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Air Traffic Smoothness as a Universal Measure for Air Traffic Quality Assessment

Piotr Andrzej Dmochowski[a]*, Jacek Skorupski[b]

[a]Polish Air Navigation Services Agency, Wieżowa 8, 02-147 Warszawa, Poland
[b]Warsaw University of Technology, Koszykowa 75, 00-662 Warszawa, Poland

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Abstract

Air traffic in European airspace is coordinated centrally by the air traffic flow management services – Network Management Operation Centre (NMOC). Their main task is to compare resources (number and capacity of air traffic control sectors) and needs (size of the planned and actual traffic). If it is found that the planned traffic exceeds the capacity of available airspace, corrective actions should be carried out. They consist in changing the takeoff time, or changing aircraft routes so as to avoid congested sectors or even cancelling the flight. Unfortunately, determining only the traffic volume is not sufficient to identify the needs, because very important are also: aircraft trajectories, manoeuvres performed, types of aircraft, their speed and other restrictions. Indeed, these factors determine the possibility to control the traffic by air traffic controllers. This makes it necessary to seek another indicator characterizing the traffic that must be handled. The paper proposes to use the notion of air traffic smoothness as a new, universal measure for characterizing the quality of air traffic. It can also serve as a measure of the traffic volume in the control sector or even as a traffic safety measure. The concept of smoothness is easier to use than the notion of the traffic complexity, which is increasingly being used, e.g. in the assessment of the capacity of the sector. The paper presents a new method for determining the air traffic smoothness, which uses both flight plans, their current implementation and the so-called favourable flight plans. On the basis of the measured data it is shown how to calculate the traffic smoothness for selected sectors. Indicating directions of further planned research, calculations were made to determine the relationship between the air traffic smoothness and its volume, which in turn may allow the use of the concept of smoothness to determine the capacity of control sectors and supporting air traffic flow management services.

Keywords: air traffic control; traffic safety; traffic complexity modelling.

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* Corresponding author
E-mail address: p_a_dmochowski@o2.pl

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1. Introduction

Air traffic flow management in European airspace works in a centrally coordinated way. Flight parameters defining a four-dimensional trajectory of aircraft are reported before flight to Network Management Operation Centre (NMOC) in Brussels in the form of a formalized sheet of a flight plan. NMOC deals with initial coordination of air traffic flow. It aims to minimize the number and the time of aircraft delays and at the same time to increase the airspace capacity. Simultaneously, NMOC services strain to increase the safety of air traffic and the effectiveness of air traffic flow. In the case when:

- the submitted flight plan does not collide with other plans,
- flight does not go through the sectors in which the air traffic volume is close to their capacity,
- the weather conditions are good,

then a flight is carried out according to its planned trajectory. But when at least one of these conditions is not fulfilled, then a submitted flight plan is modified. It is NMOC's task in cooperation with Air Operators (AO) and Flow Management Position services (FMP) which deal with the air traffic flow in the airspace through which a passage is planned. Generally, the possible modifications are: to delay the takeoff (so-called slot allocation) or to change the route in order to bypass the airspace sectors which generate restrictions (so-called re-routing). In critical cases a flight can even be cancelled.

2. Air traffic and measures of its assessment

Nowadays, one of the key parameters which enables a proper organization of the traffic itself and the work of ground services – is the traffic volume in the air traffic control sector. This term is not unequivocal. It can be understood as a flight intensity i.e. the number of aircraft coming into the sector in one unit of time (Eurocontrol 2013b). The essence of this approach is to show the total number of aircraft under control. It can be also defined as traffic density which means the number of aircraft in the sector weighted by the time spent in the sector in one unit of time (Skorupski 2008). Selecting one of these approaches depends on the purpose of the research.

2.1. Air traffic control (ATC) sector capacity

The term of the sector capacity is an example of a very important value describing the ability to handle aircraft in the sector in the context of air traffic volume. General definition of the sector capacity defines it as the maximum number of aircraft which can be safely handled in one unit of time according to international rules. In the case of ATC area sector which is the topic of this paper, the time of a controller occupancy in one unit of time is a numerical parameter which is the measure of the sector capacity. It depends highly on the traffic volume. It is obvious that heavy traffic needs more time to be served by a controller. An excessive increase of traffic volume can lead to the failure of safety measures. Thus some barriers are imposed on the traffic volume. The barrier corresponds to a maximum controller occupancy time. It is supposed that at this limit traffic volume the controller occupancy time does not exceed 70% of an hour, which is considered as a safe value (Majumdar et al. 2005).

Thus, in the case of ATC area sector a factual limitation is the air traffic safety, expressed by a controller's ability to handle a certain number of aircraft. Stating in a more or less arbitrary way, the limit value of a controller's occupancy time, one obtains the corresponding limit value of traffic volume.

2.2. The quality of air traffic

With reference to airports, an important parameter which depends on the traffic volume is the average delay for a single air operation. Similarly to ATC area sector capacity an increase of traffic causes an increase of the average delay. Thus, we can determine a barrier for an increase of traffic volume for which we state that an average delay does not exceed a permitted value (Dmochowski, Malarski 2004; Skorupski 2004). The similar approach is used, for example, when stating the capacity of a passengers' check-in system.

We can see that in the above example the factual limitation is the quality of traffic described by a delay of taking off and landing aircraft. Stating arbitrarily the boundary value of delay we obtain a corresponding boundary traffic volume (or a maximum number of passengers in the check-in system). This limitation is also, to some extent, the emanation of a desire to ensure safety. This is because a big average delay for an operation can mean that some aircraft stay in the air for too long. This in turn can influence their safety when we consider a necessary fuel level.

Another traffic quality indicator which depends on its volume can be, for example, a cost. So far, cost effectiveness has been used incidentally in air traffic management although it is a principal measure of the effectiveness of air carriers' activity. But it can be proved that the air traffic service cost depends on its volume and its organization (Banaszek 2014). It can be expected that in future the cost effectiveness in relation to one operation will be treated as a limitation for traffic volume, similarly as now it is the controller's occupancy time or an average delay for one operation.

Another similar future criterion of assessing air traffic management organization process can be environmental nuisance. Here we can show that it also is a function of the traffic volume as well as its organization (Płanda, Skorupski 2014). It is highly possible that in the future the amount of harmful substance emission (total or in some chosen points) will be a criterion deciding about permitted traffic volume.

2.3. Air traffic complexity

As one can see from the above analysis, the air traffic volume is practically a key parameter which measures different aspect of air traffic organization. But as it has already been mentioned it is not a unequivocal term. It has different definitions which are used depending on specifically stated needs. It causes that it is not an ideal indicator despite it is commonly in use.

In recent years, researchers and practitioners use the term of traffic complexity more often than traffic volume (Rahman et al. 2012). It is a result of looking for indicators which will better characterize all phenomena taking place in air traffic. These indicators, similarly to traffic volume, could be used to managing the traffic. Complexity of air traffic is defined similarly to traffic intensity. But when it is calculated some additional parameters are considered. They are: the number of conflict situations to solve, the number of transfer of control between the sectors, changes of aircraft direction or speed inside the sector, situations when aircraft trajectories intersect each other or weather conditions (Eurocontrol 2006, 2013a). Kopardekar et al. (2008) determined the maximum accepted air traffic complexity and its connection with the sector capacity with the use of simulation experiments and the observation of activities of a real controller. Some models in which the controller's workload has been correlated with the traffic intensity and traffic complexity were also compared. The determined R^2 factor was used to analyze this correlation. This factor for the model of intensity was 0.65 while for the model of complexity it was 0.74. It indicates that application of traffic complexity is more beneficial when we want to calculate the sector capacity.

Far more general understanding of the term of traffic complexity was presented by Histon et al. (2001). While the possibilities of handling a traffic situation in the sector were analyzed, some features (shapes) of airspace and operation limitations understood as restrictions imposed on possible controller's activities were taken into consideration.

The term of traffic complexity is more and more widely used for describing the traffic processes and also in research on air transport optimisation in TMA area (Netjasov 2004) as well as for airport traffic (Krstic, Tosic 2010).

3. Air traffic smoothness as a measure of its quality

Traffic volume is an independent variable for many dependences extremely important for modern air traffic engineering. These include: traffic volume – controller workload, traffic volume – average delay. They are stochastic by nature but can be easily defined as probabilistic relationships (Skorupski, Stelmach 2008). Other dependences, for example, traffic volume – ATC services cost effectiveness or traffic volume – environmental nuisance are not known analytically and have become the goal of research being carried out in scientific centres. But yet intuitive knowledge about these relationships allows to undertake some activities which let us increase the traffic in the area control sector and move forward barriers mentioned above. General increase of air traffic is a fact, so

ATC services and the sectors they handle must be ready to accommodate it. For example it is possible to increase the traffic volume in a sector by decreasing the time for ground-air transmission by introducing new communication means. Thanks to this the controller's workload is reduced and at the same time the traffic volume may be increased. It works similarly when more advanced surveillance systems or controller decision supporting system are applied.

The term of air traffic smoothness can also be used to assist the air traffic management services. On the one hand, traffic smoothness depends on its volume (Dmochowski et al. 2014). This means that in air traffic management it can be used in a similar way as the controller workload or the average delay per operation. But on the other hand, the smoothness characterizes the traffic itself. One can see that both controller workload and average delay for an airport operation is the function of traffic smoothness. The similar dependence can be observed for other mentioned above future limitation factors – cost effectiveness or environmental nuisance. They both depend on the traffic volume but also on the traffic smoothness. It clearly shows that research on traffic smoothness has a big importance not only in the context of looking for indicators and methods of the traffic quality assessment but also in the context of attempts to optimize its organization. It can be noticed that traffic smoothness has a similar sense as the above mentioned term of traffic complexity which is recently often used for a similar goal. But the smoothness seems to be easier to apply in practice.

4. A method for smoothness calculation with regard to so-called favourable flight plans

The method of determining air traffic smoothness presented in this paper is based on the description of the structure of ATC area sector in the form of grid of active and non-active airspace points presented in (Dmochowski, Skorupski 2013a, b) where:

- a flight plan is the information on an intended flight delivered to air traffic services two days before the day of operation,
- a current flight plan is understood as a flight plan with changes resulting from ATC clearances,
- a favourable flight plan is understood as a flight plan in which flight parameters take safe values and are beneficial from the flight economy point of view.

This approach allows to define air traffic smoothness in the sector in a numerical way through comparison of flight plans with their current and favourable equivalents. It is made on the base of defined numerical values of disturbances of distance, flight level and the time of the flight (Table 1).

Table 1. The rules of flight parameters disturbances assessment.

The range of flight parameters disturbances				
Distance [NM]	0–4	5–9	10–19	>20
Flight level [FL]	0–9	10–19	20–29	>30
Time [min]	0–0.9	1–1.9	2–2.9	>3
Disturbance assessment	0	1	2	3

NM – nautical mile = 1852 m

FL – flight level = 100 feet = 30.48 m

For *j*-th aircraft, distances between points taken from a flight plan and a current flight plan are marked as d_j, from a flight plan and a favourable flight plan are marked as e_j, and from a favourable flight plan and a current flight plan are marked as f_j. Figure 1 shows it in a simplified way.

Calculating of the smoothness for an aircraft consists of comparing and combining the values of variables d_j, e_j and f_j in each step of the analysis. The steps t_i, t_{i+1}, ... (Figure 1) are defined in accordance with the density of the grid of active and non-active points specified in the area sector model. The way of combining the assessments into the smoothness values is presented in Table 2.

If any of d_i, e_i or f_i parameters reaches the value of 3 or more then smoothness equals 0. The rules presented in Table 2 allow to determine the smoothness for *j*-th aircraft $s_i(d_i, e_i, f_i, t_i$ in each step t_i (the measurement point). This action is repeated for all aircraft in a considered sector. For each step, received results are summed and divided by a total number of aircrafts J, which gives average smoothness in a given step t_i:

$$S(t_i) = \frac{\sum_j^J s_j(d_j, e_j, f_j, t_i)}{J}. \tag{1}$$

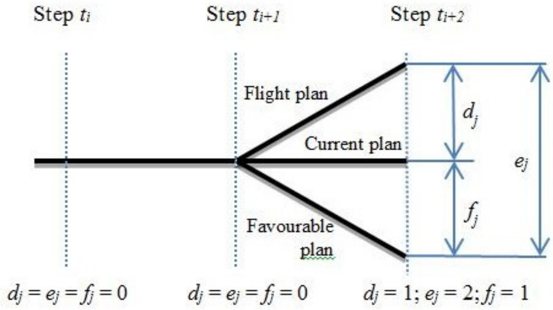

Fig. 1. A scheme of defining d_j, e_j and f_j parameters.

Table 2. The smoothness s_j of j-th aircraft in i-th step.

d_j	0	0	1	1	1	1	2	0	2	2
e_j	0	1	1	0	2	1	1	2	2	0
f_j	0	1	0	1	1	2	1	2	0	2
Smoothness s_j [0.01]	100	85	80	75	55	50	45	25	20	15

Next, smoothness values from all steps are summed up and divided by the number of steps I. Eventually traffic smoothness in the sector in the examined period is expressed by a formula

$$F = \frac{\sum_{i=1}^{I} S(t_i)}{I}. \tag{2}$$

This method allows to take into account all important parameters: the flight direction, the flight level and the time of the passage. The choice of steps (measurement points) depends on granularity of active and non-active points grid in the sector model that has been used.

5. Measurements and calculations of real air traffic smoothness in chosen sectors in FIR Warsaw

To illustrate how the method of air traffic smoothness assessment works, some measurements of real air traffic in ATC area sectors in Flight Information Region (FIR) Warsaw have been taken in January 2014. Three combined ATC sectors consisting of two elementary sectors were chosen (Figure 2):

- SE (north–east – “Suwałki–Siedlce”),
- BG (north–west – “Bałtyk–Grudziądz”),
- TC (south–west – “Łódź–Trzebnica”).

An example fragment of data with the results of the smoothness calculations for the TC area sector taken on the 22nd January 2014 is presented in Table 3. It shows measurement for 15 minutes of traffic where the step of measurements equals to one minute. The presented data consist only of four out of forty seven aircraft which were present in the examined sector at that time.

Total smoothness for period from 19.50 to 20.04 calculated according to formula (2) was 0.564. The step of one minute causes that a model grid of active and non-active points is very dense and gives a big accuracy of measurements. But at the same time these measurements are very time consuming. For the same data a three minute step gives average smoothness of 0.57 and a five-minute step gives 0.561 which can be regarded as equivalent results.

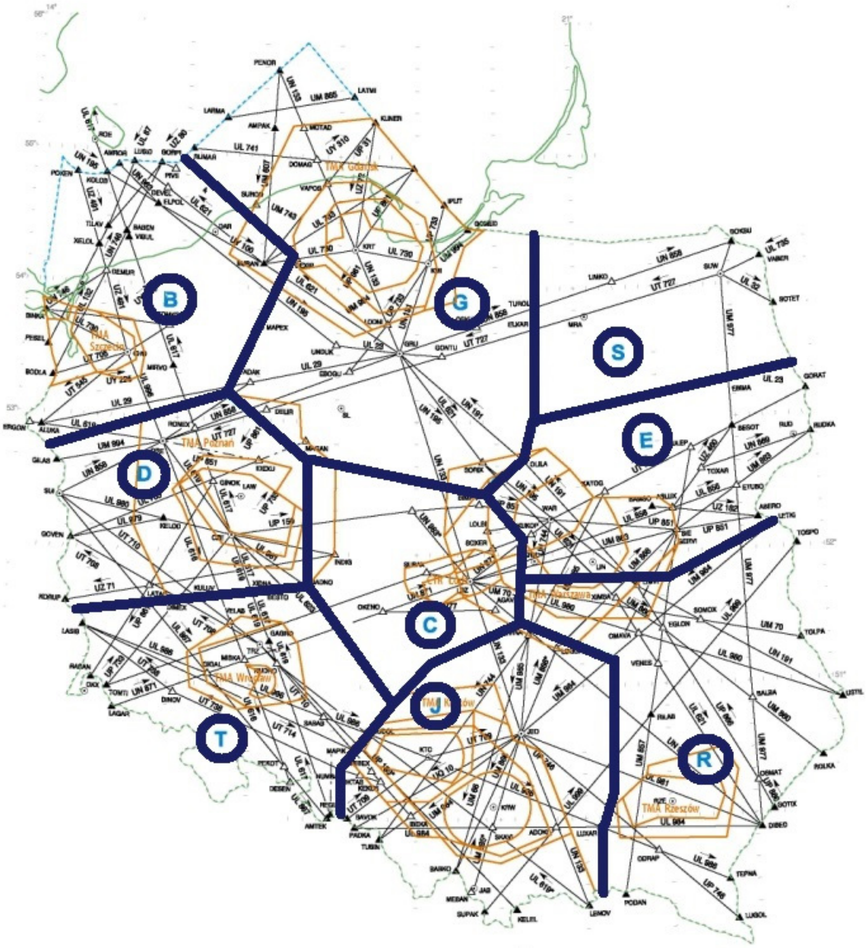

Fig. 2. ATC area control sectors in FIR Warsaw.

Thus, density of the points grid is not the key value for the accuracy of the results. Suggested in the literature (Ruiz *et al.* 2013) using the very dense grid seems to be useless and it does not bring any improvement of accuracy. However, it significantly increases computational complexity.

To show the relationship between the traditional definition of the traffic volume and the proposed in this paper idea of traffic smoothness, Table 4 presents some comparative results of measurements and calculations. The same data for TC, SE and BG area sectors as presented in table 3 were used.

One can clearly see that there is a close dependence between the traffic volume in the sector and the traffic smoothness. For a small traffic volume (observed in sector SE) the traffic smoothness is the biggest. For the bigger traffic intensity (observed in sectors TC and BG) traffic smoothness is slightly smaller.

Table 3. Calculation of air traffic smoothness in area sector TC.

Call sign	Parameters	Measurement point															Average for flight
		19:50	19:51	19:52	19:53	19:54	19:55	19:56	19:57	19:58	19:59	20:00	20:01	20:02	20:03	20:04	
N223 AF	d	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	75
	e	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	f	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
	s [0.01]	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	
CSA 5PC	d	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	e	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	f	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	s [0.01]	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	
LOT 3859	d	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	69
	e	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	
	f	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	s [0.01]	80	80	80	80	80	80	80	80	80	80	80	80	80	80	20	
RYR 541H	d	3	2	2	2	2											12
	e	0	0	0	0	0											
	f	3	2	2	2	2											
	s [0.01]	0	15	15	15	15											
Average for the point [0.01]		66	73	65	65	65	66	64	58	58	48	53	47	57	59	53	**56.4**

Table 4. Relationship between the traffic volume and the traffic smoothness.

Sector	Grid density	Traffic volume	Traffic smoothness
TC	1	10.65	0.57
	3	10.75	0.57
	5	11.42	0.56
Sector	Grid density	Traffic volume	Traffic smoothness
SE	1	6.13	0.72
	3	6.40	0.72
	5	6.58	0.71
Sector	Grid density	Traffic volume	Traffic smoothness
BG	1	11.75	0.63
	3	11.95	0.64
	5	12.75	0.64

However, further research into comparison of the traffic smoothness for different traffic volumes for the same sector is of course necessary. Comparisons between different sectors as presented in this paper are not enough to formulate more general conclusions.

6. Conclusions

1. In this paper a possibility to use the air traffic smoothness as a universal parameter which characterizes its quality has been presented. Along theoretical considerations we have also shown practical usefulness of this

notion. And thus we have proposed the method to define and calculate the smoothness which takes into account flight plans, their current realization as well as so-called favourable flight plans. The latter relate to, for example, to the direct trajectories linking the input and output points of the sector.

2. Some calculations of the traffic smoothness made with the use of the proposed method are also presented. They indicate that the traffic smoothness can become the universal measure of its quality.
3. Additionally, we have analyzed numerical dependences between the air traffic smoothness and the traffic volume. In spite of the fact that measurements were taken during a light traffic and in winter time, this relationship is clearly seen.
4. The density of the active and non-active airspace points grid is not the key value for the accuracy of the results. Using the very dense grid seems to be useless and it does not bring any improvement of accuracy. However, it significantly increases computational complexity.
5. However, presented results do not yet allow to derive far-reaching conclusions as for the details of this relationship. The research is being still carried out. Its next step will be an attempt to use the smoothness to support air traffic flow management.

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