

## The problem of determining traffic volume in a restricted traffic area

## Problem wyznaczania wielkości ruchu w ograniczonej przestrzeni ruchowej

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### Abstract

One of the most common problems in the process of traffic management is the determination of the proper traffic volume. On the one hand there is a tendency of increasing traffic volume – it brings profits to all subjects involved in the transportation process. On the other hand there is a tendency to decrease traffic volume – it assures better safety. It is necessary to solve the problem of finding a compromise between those tendencies. Solving this problem is possible, based on developed methods of safety dimensioning that use the concept of traffic smoothness for quantitative evaluation of traffic safety level. In the paper the concept of those methods is explained. Besides, presented are results of simulation research on the relation between traffic smoothness and the safety level in a restricted control sector. Although the paper presents the implementation (examples) of the problem in the air traffic management, similar procedures and methods may be applied to the marine traffic.

**Słowa kluczowe:** bezpieczeństwo ruchu, płynność ruchu

### Abstrakt

Jednym z najważniejszych problemów w procesie zarządzania ruchem jest kwestia wyznaczenia właściwego natężenia ruchu. Z jednej strony pojawia się tendencja do zwiększania ruchu – daje to korzyści (zyski) wszystkim podmiotom biorącym udział w procesie transportowym. Z drugiej jednak strony pojawia się dążenie do zmniejszenia ruchu – co zapewnia większe bezpieczeństwo. Konieczne jest więc rozwiązanie problemu wyznaczenia kompromisowej wielkości ruchu. Możliwe staje się to w oparciu o opracowanie metod wymiarowania bezpieczeństwa, bazujących na pojęciu płynności ruchu, dlatego możliwe jest liczbowe wyrażenie poziomu bezpieczeństwa. W artykule przedstawiono koncepcję tych metod oraz wyniki symulacyjnego badania zależności płynności i poziomu bezpieczeństwa w ograniczonym sektorze kontroli. Podano implementację przykładu w zarządzaniu ruchem lotniczym, ale podobne procedury i metody mogą być używane także w ruchu morskim.

## Introduction

In the transportation process several groups of participants can be identified, e.g.: carriers, traffic managers, passengers. All of them are interested in the best possible use of the traffic space (roads, airspace, waterways), resulting in the largest possible volume of traffic. In such a situation carriers take advantage of considerable flexibility in planning timetables of their transports, which in turn

enables them to offer a large number of frequent and regular connections, and at the same time to optimize them to anticipated users' needs [1]. Passengers also take advantage in the form of numerous connections they can choose from, adjusted to their preferences in terms of place and time of departure. Moreover, profits of port or airport operators are directly proportional to the number of ships or aircraft and passengers served [2].

However, restrictions imposed by the traffic regulations make an uncontrolled increase of traffic volume impossible. The regulations are aimed at keeping safety at an appropriately high level. Incessant increase of traffic volume can result in lowered safety level – e.g. greater workload for an air traffic controller may increase a probability of errors [3]. Congestions appear in port areas, which are connected with periods of waiting for port entry. This, in turn, complicates the traffic situation and increases a probability of an accident, etc. [4].

These two contradictory tendencies induce the issue of compromising the traffic volume – largest possible volume at the maximum level of safety. The problem is very difficult to be solved analytically, because experiments on actual traffic to obtain necessary data are not possible. Therefore, simulation methods of investigation, supported by herein presented methods of investigating the traffic safety, based on the concept of traffic smoothness, allows developing an expedient algorithm for determining the best possible traffic volume.

The algorithm is based on simulation experiments and observed empirical relationship indicating that both smoothness and security, referred to traffic volume, have one maximum. Additionally, smoothness maximum is “outpacing” security maximum, which enables determining the best possible volume of the traffic in a given sector.

The idea behind the method is explained for air traffic in a control sector, but for any other types of transport that operate in a restricted traffic area a similar approach is possible.

### The subject and the tool of investigation

The research aimed at determining an expedient volume of traffic in a given sector. It was carried out for the air control sector Suwałki (EPWWS), a typical sector containing one intersection of several routes with different categories. For the needs of simulation experiments, an adequate model of the sector was developed as well as computer program implementing the model, which was used as the research tool.

Modeling of traffic processes in the sector was undertaken, in this particular case, for investigating the traffic safety. An air traffic controller is responsible for this aspect. Following assumptions and simplifications were accepted for the sake of imitating his actions:

- the actions of the controller consist of: confirming entry into the sector, confirming exiting the sector, ordering change of flight level, ordering change of flight velocity, ordering change of flight route;

- time periods for carrying out particular controller’s tasks are defined and unalterable; this time is spent on: analysis of a problem and working out a decision, sending an instruction by the radio and confirmation of its reception by the aircraft commander;
- aircraft are handled according to specific waiting algorithm;
- at any given moment only one aircraft is handled;
- conflict situation is resolved by appropriate maneuver of the aircraft which provoked the situation;
- each aircraft should be served at least twice – immediately after entering and about three minutes before exiting the sector.

Details of the model were omitted. The program implementing the model consists of five modules:

- *engine* – responsible for supervising of the simulation process and realizing simulation of aircraft movements;
- *controller* – realizing an air traffic controller tasks, in particular handling a sequence of flights through the collision point of the sector – intersection of air routes;
- *CFMU* – responsible for modifications of flight plans that resulted from the coordination of the aircraft flows in the European framework [5];
- *engine ATC* – responsible for the simulation of operational control of the air traffic and generating decisions made to avoid collision situations;
- *mConstans* – consisting of fixed aircraft characteristics, shape of the sector and other fixed data.

In the simulation experiment described below and its subsequent conclusions, so-called “dangerous flights” play a significant role. They are a consequence of a conflictsolving procedure followed by the controller. A general scheme of proceeding by a simulated controller can be summed up to three situations:

- *solve conflict SUW* – means a situation when an aircraft is in conflict situation with another aircraft on the intersection of air routes in SUW point;
- *solve conflict BOKSU* – means a situation when an aircraft is in conflict situation with another aircraft at an intersection of air routes at BOKSU point;
- *solve conflict SUCCESSOR* – means a situation when an aircraft is in conflict situation with its successor; decision is taken in a different manner than in cases *solve conflict SUW* and *solve conflict BOKSU*.

## The concept of air traffic smoothness

As a general measure of traffic smoothness, relation between the number of disturbed flights  $LZ$  and overall number of flights  $LS$  is proposed [6]. As a disturbed flight is understood a flight with parameters (altitude, velocity, time of control point passage etc.) changed for reasons of air traffic safety, e.g. necessity of avoiding dangerous storm areas. Any flight can be disturbed only to a certain level. This conclusion is the basis for employing methods of smoothness measurements presented below.

Let us mark a planned movement trajectory of  $i$ -th aircraft in control sector as  $\mathbf{M}_{P_i}^*$ . It is usually an optimal trajectory in terms of fuel consumption, time of passage and flight characteristics of a given aircraft.  $\mathbf{M}_{P_i}^*$  trajectory is determined by an arranged sequence of aircraft positions, determining locality of waypoints on flight route, times of their passage and velocity vectors at the time of passing waypoints. Thus we get

$$\mathbf{M}_{P_i}^* = \langle [\mathbf{W}_1^*, \mathbf{V}_1^*, t_1^*], [\mathbf{W}_2^*, \mathbf{V}_2^*, t_2^*] \dots [\mathbf{W}_{N_i}^*, \mathbf{V}_{N_i}^*, t_{N_i}^*] \rangle \quad (1)$$

where:  $\mathbf{W}_i^*$  – vector of planned position of an aircraft in  $i$ -th waypoint,  $\mathbf{V}_i^*$  – vector of planned velocity of an aircraft in  $i$ -th waypoint,  $N_i^*$  – number of waypoints for  $i$ -th aircraft.

For a given period of time (e.g. 24 hours) a flight plan is a set of planned trajectories  $\mathbf{M}_{P_i}^*$  for all aircraft:

$$\mathbf{FP}^* = \{\mathbf{M}_{P_i}^*\} \text{ for } i = 1, \dots, LS \quad (2)$$

A flight plan can be disturbed by numerous external factors of random character: meteorological, traffic etc. The actual realization of a flight plan for  $i$ -th aircraft will be marked as  $\mathbf{M}_{P_i}$ . It is defined by a sequence of actual position points with actual time of passage and velocity vector in time of passage of these points:

$$\mathbf{M}_{P_i} = \langle [\mathbf{W}_1, \mathbf{V}_1, t_1], [\mathbf{W}_2, \mathbf{V}_2, t_2], \dots, [\mathbf{W}_{N_i}, \mathbf{V}_{N_i}, t_{N_i}] \rangle \quad (3)$$

where:  $\mathbf{W}_i$  – vector of actual position of an aircraft in  $i$ -th waypoint,  $\mathbf{V}_i$  – vector of actual velocity of an aircraft in  $i$ -th waypoint,  $N_i$  – number of actual waypoints for  $i$ -th aircraft.

If  $\mathbf{M}_{P_i}^* = \mathbf{M}_{P_i}$  we say that flight of  $i$ -th aircraft was consistent with a flight plan (smooth).

Of course, when considering the  $\mathbf{M}_{P_i}^*$  and  $\mathbf{M}_{P_i}$  equations, allowing some tolerance is necessary, especially with regard to time of flight at respective waypoints.

The flights, which are characterized by  $\mathbf{M}_{P_i}^* \neq \mathbf{M}_{P_i}$  will be called disturbed flights. Most typical cases of disturbed flights are as follows: delaying of flight, change of flight altitude, change of flight route (shortened or lengthened route, partial or complete change of a route except departure and arrival points), performing unplanned maneuvers.

## Dimensioning of traffic safety using the concept of smoothness

The smoothness of traffic can be a basis for traffic safety estimation in a longer time perspective. As was mentioned above, the air traffic is initially planned. As a result, a set of flight plans  $\mathbf{FP}^*$  is created. The flight plans are initially coordinated, which means that the possibility of collision, when all aircraft are flying according to their plans, is eliminated. It also means that for all aircraft included in the plans and for every waypoint on the route all needed separations are assured. It is then obvious that such traffic is entirely safe. Every disturbance, mentioned above, generated by external factors, is dangerous to the traffic. It is then indispensable for an air traffic controller to take actions to solve a potentially dangerous situation. Decisions taken under stress and a lack of time could put things on the wrong track. Additionally, such actions distract the controller's attention from other tasks and could also be a threat to safety. Of course, the seriousness of this threat depends on many factors, such as the controller's workload, his experience and professional qualifications etc. It can then be accepted that the threat to safety is proportional to the degree of smoothness disturbance. So, to employ the concept of smoothness to estimate safety it is necessary to assign a dimension smoothness. Two approaches are possible: binary and multivalent [7].

In either of the cases the measure of smoothness is a relation between the number of smooth (undisturbed) flights and the number of all flights:

$$F = \frac{LS - LZ}{LS} = 1 - \frac{LZ}{LS} \quad (4)$$

## Dimensioning with the binary function

The binary function estimate is the simplest, but very effective approach to dimensioning smoothness in terms of safety, as the results of modeling

experiments show. It is then assumed that a flight is smooth if its whole actual trajectory is consistent with the planned one and non-smooth in opposite case:

$$SB_{P_i} = \begin{cases} 1, & \text{for } \mathbf{M}_{P_i}^* = \mathbf{M}_{P_i} \\ 0, & \text{for } \mathbf{M}_{P_i}^* \neq \mathbf{M}_{P_i} \end{cases} \quad (5)$$

where  $SB_{P_i}$  denote smoothness of  $i$ -th aircraft.

Let us denote the number of disturbed (non-smooth) flights in a given time as  $LB_Z$

$$LB_Z = \sum_{i=1}^{LS} (1 - SB_{P_i}) \quad (6)$$

Finally, smoothness in the binary method equals:

$$FB = 1 - \frac{LB_Z}{LS} \quad (7)$$

#### Dimensioning with the multivalent function

Smoothness disturbances are not equal. A two-minutes delay at a control point is significantly less important than avoiding a certain area of the airspace because of heavy weather conditions prevailing in this area. It is then possible to estimate smoothness, applying a method alternative to the binary one.

One can analyze the compatibility with planned flight trajectory of every aircraft and for every defined waypoint. The smoothness of  $i$ -th aircraft in  $k$ -th waypoint can be described as:

$$SW_{P_i}^k = \begin{cases} 1, & [\mathbf{W}_k, \mathbf{V}_k, t_k] = [\mathbf{W}_k^*, \mathbf{V}_k^*, t_k^*] \text{ for } i\text{-th aircraft} \\ 0, & [\mathbf{W}_k, \mathbf{V}_k, t_k] \neq [\mathbf{W}_k^*, \mathbf{V}_k^*, t_k^*] \text{ for } i\text{-th aircraft} \end{cases} \quad (8)$$

The smoothness of  $i$ -th aircraft then equals:

$$SW_{P_i} = \frac{\sum_{k=1}^{N_i} SW_{P_i}^k}{N_i} \quad (9)$$

and  $LW_Z$  indicator defining the number of disturbed flights:

$$LW_Z = \sum_{i=1}^{LS} (1 - SW_{P_i}) \quad (10)$$

Finally, the smoothness in the multivalent method takes a similar form as before and equals:

$$FW = 1 - \frac{LW_Z}{LS} \quad (11)$$

#### Dimensioning with the multivalent weighed function

Going further, one can dimension the smoothness taking into account the influence of various smoothness disturbances on the safety. In such case we can apply the weighed method of dimensioning traffic smoothness.

Let us assume that there is a set of possible types of disturbances  $\mathbf{ZA} = \{za_1, za_2, \dots, za_B\}$  and corresponding to them a set of regulations imposed on traffic, equal to the weight of traffic smoothness disturbance  $\mathbf{WZ} = \{wz_1, wz_2, \dots, wz_B\}$ . Let us denote as  $z_b(i, k)$  the binary variable indicating if a flight at waypoint  $k$  of  $i$ -th aircraft was smooth or disturbance of  $b$ -th type occurred.

$$z_b(i, k) = \begin{cases} 1, & [\mathbf{W}_k, \mathbf{V}_k, t_k] = [\mathbf{W}_k^*, \mathbf{V}_k^*, t_k^*] \text{ for } i\text{-th aircraft} \\ 0, & [\mathbf{W}_k, \mathbf{V}_k, t_k] \neq [\mathbf{W}_k^*, \mathbf{V}_k^*, t_k^*] \text{ for } i\text{-th aircraft} \end{cases} \quad (12)$$

The smoothness of  $i$ -th aircraft in waypoint  $k$  is illustrated by this equation:

$$SWW_{P_i}^k = 1 - \frac{\sum_{b=1}^B (1 - z_b(i, k)) \cdot wz_b}{\sum_{b=1}^B wz_b} \quad (13)$$

The smoothness of  $i$ -th aircraft on the whole route is illustrated by this equation:

$$SWW_{P_i} = \frac{\sum_{k=1}^{N_i} SWW_{P_i}^k}{N_i} = \frac{\sum_{k=1}^{N_i} \left( 1 - \frac{\sum_{b=1}^B (1 - z_b(i, k)) \cdot wz_b}{\sum_{b=1}^B wz_b} \right)}{N_i} \quad (14)$$

The indicator showing the number of disturbed flights takes the form:

$$LWW_Z = \sum_{i=1}^{LS} (1 - SWW_{P_i}) \quad (15)$$

Finally, smoothness designated by the multivalent weighed method is expressed by this equation:

$$FWW = 1 - \frac{LWW_Z}{LS} = 1 - \frac{\sum_{i=1}^{LS} (1 - SWW_{P_i})}{LS} \quad (16)$$

Table 1. A structure of air routes in the simulated sector

Tabela 1. Struktura tras lotniczych w symulowanym sektorze

No of route	input	output	route1	route2	point1	point2	point3	point4	point5	point6
1	wlot4	wlot1	M857	N858	wlot4	BOKSU	SUW	MRA	OLKIN	wlot1
2	wlot4	wlot9	M857	N871	wlot4	BOKSU	SUW	wlot9	wlot9	wlot9
3	wlot2	wlot1	N858	N858	wlot2	VABER	SUW	MRA	OLKIN	wlot1
4	wlot2	wlot9	N858	N871	wlot2	VABER	SUW	wlot9	wlot9	wlot9
5	wlot5	wlot1	L32	N858	wlot5	SOTET	SUW	MRA	OLKIN	wlot1
6	wlot5	wlot9	L32	N871	wlot5	SOTET	SUW	wlot9	wlot9	wlot9

The results of measurements and the model analyses show that the first method, although simplest, very well describes the phenomena connected with the influence of smoothness on capacity. It can be explained by the fact that even one and non-significant disturbance of a planned aircraft flight trajectory necessitates constant analysis of the rest of its trajectory and influence of created deviations on keeping safe distances from other aircraft. In some cases, though, also multivalent methods can be useful in determining the traffic smoothness.

### The simulation experiment

The simulation experiment consisted of investigating the influence of traffic load changes in every entry point to the EPWS sector on smoothness and safety of the air traffic.

The following plan of experiment was adopted.

1. The aircraft notify their input on several chosen flight levels (from FL 210 to FL 280). For every aircraft notifying its presence in an entry point to the sector, flight path is developed (table 1) according to the previously given distribution of probability. The aircraft types and their flight characteristics, especially their flight velocity, ascending and descending rates are also generated at the moment of passing control after arriving at a sector border, according to the given probability distribution (table 2).

Table 2. An example of characteristics of aircraft in the input flow

Tabela 2. Przykład właściwości samolotów w przepływie wejściowym

Type of aircraft	Number	v_standard [km/h]	v1 [km/h]	v2 [km/h]	v3 [km/h]
A320	7	837	906	833	785
B727	12	874	986	869	835
B737	29	856	908	781	750
B767	6	865	908	854	818
DC10	3	902	932	818	780
TU34	5	818	856	781	735

2. The initial intensity amounts to 3.75 aircraft per hour at every entry point. Then, it is increased

by iteration at every entry point, taking successively values 4.29, 5, 6, 7.5, 10, 12, 15, 20 aircraft per hour. The time of simulation is two hours.

3. Disturbances are registered according to smoothness examined with the multivalent function. It is assumed that smoothness disturbance can occur at the central point of the sector (SUW), or at any of exit points. Similarly, smoothness can be examined with the binary method. Applying the multivalent weighed method is also possible in case of two (included in the model) types of smoothness disturbances – change of time and flight level at a selected waypoint point.

4. The violations of separation, which result from inability of solving potentially conflict situations, are also registered as well as number of service operations performed by a controller, which are necessary for serving the given traffic. This allows direct estimate of the number of flights with lower safety level and in consequence – calculating dependence between smoothness and safety of the air traffic.

5. External disturbances, such as break-downs, partial closures of air routes, difficult weather conditions etc. were not taken into consideration.

### The results and conclusions

The experiments conducted for various intensity of the air traffic show that an increase of traffic volume generates an increase of the number of smoothness disturbances. The latter increase is initially small and that is why the number of smooth flights (as perceived by the multivalent method) is also increasing. But in case of further increase, the downfall of smoothness is so great that the overall number of smooth flights decreases. The result is concordant with expectations based on theoretical considerations presented in capitel “Dimensioning of traffic safety using the concept of smoothness”. The dependence of the number of smooth flights on the traffic volume has a similar character [8].

Example results of the simulation experiments are summed up in table 3. The table presents

Table 3. Example results of simulation experiments  
Tabela 3. Przykładowe wyniki badań symulacyjnych

Input intensity [ac/h]	3.75	4.29	5	6	7.5	10	12	15	20
Global number of aircraft	64	72	82	98	122	162	193	240	319
Number of disturbed flights	6	8	12	20	32	57	80	146	235
Number of smooth flights	58	64	70	78	90	105	115	99	84
Number of safe flights	64	72	82	96	120	150	191	228	128
Number of services	134	150	177	214	273	376	461	608	724

selected results for the situation when on every of entry points the same intensity of notifications is simulated, ranging from 3.75 to 20 aircraft per hour.

The relations between the number of smooth flights and the number of safe flights and the traffic volume, in two hours research interval, are presented in figure 1.

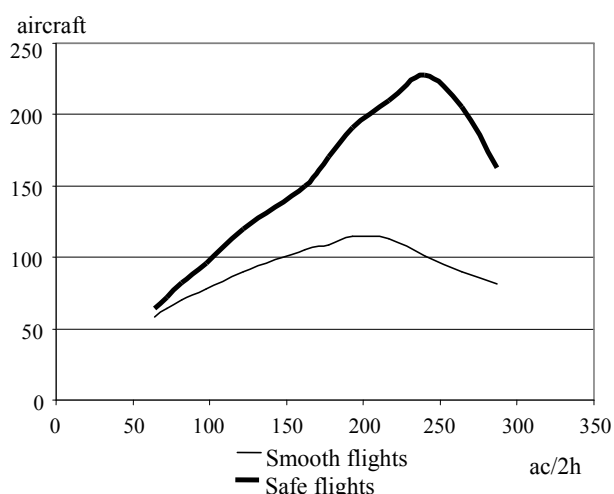


Fig. 1. The influence of traffic volume fluctuations on the smoothness and safety of traffic

Rys. 1. Wpływ wahań natężenia ruchu na jego płynność i bezpieczeństwo

The experiments conducted prove that a very interesting relationship exists, which can have considerable practical meaning. As it can be observed, both diagrams have one maximum. The maximum of smoothness occurs for smaller volume of traffic than the maximum of safety. The maximum number of smooth flights occurs for about 205 aircraft in two hours interval, whereas the maximum number of safe flights occurs for about 230 aircraft in two hours interval. The result can be explained by the fact that the applied safety procedures are redundant and even a significant number of smoothness disturbances is not yet tantamount to endangering safety.

The reciprocal shaping of these diagrams makes possible developing a heuristic algorithm for finding an expedient maximum volume of traffic in a given sector. The algorithm is based on increasing

volume of traffic and at the same time monitoring smoothness coefficient. The expedient maximum of safety occurs when traffic volume reaches the level marking the beginning of smoothness decrease. Such volume of traffic can be accepted as a maximum capacity of the control sector, taking safety into account.

The results corroborate to a certain extent the previously presented proposition about the possibility of safety estimation using the concept of smoothness. The results demonstrate that a strong correlation occurs between those values, so the smoothness coefficient (calculated with any of three methods of smoothness investigation) can be a measure of safety level.

## References

1. YU-HERN CHANG, CHUNG-HSING YEH: A New Airline Safety Index. *Transportation Research*, part B: Methodological, Elsevier, 2004, 38, issue 4, 369–383.
2. WAGUESPACK JR. B., RHOADES D.L.: Better safe than service: the relationship between service and safety quality in the US airline industry. *Managing Service Quality*, 1999, 9, issue 6, 396–400.
3. MAJUMDAR A., POLAK J.: Estimating the Capacity of Europe's Airspace Using a Simulation Model of Air Traffic Controller Workload. 80<sup>th</sup> Annual Meeting of the Transportation Research Board, Washington 2001, 30–43.
4. BAUERLE N., ENGELHARDT-FUNKE O., KOLONKO M.: On the waiting time of arriving aircrafts and the capacity of airports with one or two runways. *European Journal of Operational Research*, Elsevier, 2007, 177, issue 2, 1180–1196.
5. CFMU Operations executive summary, EUROCONTROL, 2002.
6. SKORUPSKI J.: Metody wymiarowania bezpieczeństwa ruchu lotniczego. *Prace Naukowe Politechniki Warszawskiej, Transport*, 2008, 66.
7. SKORUPSKI J.: Metoda wymiarowania bezpieczeństwa ruchu lotniczego w horyzoncie średnioterminowym. *Badania Operacyjne i Systemowe, Analiza systemowa w globalnej gospodarce opartej na wiedzy*, Wyd. EXIT, Warszawa 2006, 251–258.
8. SKORUPSKI J.: The method of designating air traffic volume in sector taking into account security aspect. *The Archives of Transport*, Warszawa 2008, 20, 3, 63–74.

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