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Air traffic smoothness as a measure of air traffic safety

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ABSTRACT: The safety of the vehicles involved in the transport process is one of the most important criteria for its assessment. There are many factors which contribute to that safety. In this paper, some problems of the work on dimensioning (quantitative assessment) of the traffic safety are presented. In the paper air traffic smoothness is considered. Some methods for smoothness dimensioning are proposed. Relation between air traffic safety and smoothness is discussed. Possibility of determining optimal air traffic volume was pointed out. On one hand there is a tendency of increasing traffic volume – it gives profits to all subjects involved in transportation process. On the other hand there is a tendency to decrease traffic volume – it gives better safety. It is necessary to solve the problem of finding a compromise between those tendencies. In the paper results of simulation research on smoothness and safety in control sector EPWWS are presented.

1 INTRODUCTION

In the air transport several groups of participants can be singled out, among others: air carriers, airspace managers, airport managers, passengers. All of them are interested in best possible use of the airspace, resulting in largest possible volume of the air traffic. In such a situation the air carriers take advantage of considerable flexibility in planning timetables of their flights, which in turn enable them to perform large number and frequency of connections and at the same time to adjust them in best possible way to anticipated users needs. The passengers also take advantage in the form of numerous flights in their disposition, adjusted to their preferences in terms of place and time of departure. And profits of airspace and airport managers are directly proportional to number of aircraft and passengers served.

However restrictions imposed by the regulations of air traffic make uncontrolled increasing of air traffic volume impossible. The regulations are aimed at keeping safety at appropriately high level. Incessant increase of traffic volume can result in lowering of safety level – for example greater workload for a controller increase probability of mistakes. The congestions appear in the airports areas, which are generating waiting periods for landing. This in turn complicates the traffic situation and increase probability of occurring danger of an air accident etc.

These two contradictory tendencies are inducing question of compromising volume of the air traffic - largest possible, but in the same time assuring maximal level of safety. The problem is very difficult for analytic solution, especially because experimenting on actual air traffic with the aim of obtaining necessary data is not possible. Applying simulation methods of investigation, supported by developed and summarily presented in the article methods of investigating the air traffic safety, based on notion of traffic smoothness, allows developing expedient algorithm for designating best possible traffic volume.

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

2 THE NOTION OF AIR TRAFFIC SMOOTHNESS

The notion of the traffic smoothness as a measuring tool of estimating traffic quality was verbally formulated in (Węgierski 1971). The formalized representation of connections between smoothness and intensity of the traffic was presented in (Woch 1983), initially for rail traffic then in the following years for generally perceived traffic flow. The road to modification of transport networks in aspects of the traffic smoothness and connections between smoothness and safety of traffic was open.

Direct transferring of traffic smoothness definition, employed in the road transportation, is not possible because of the air traffic peculiarities. For example, stopping an aircraft in midair is impossible. The same is true for keeping a distance between vehicles in the road traffic, which can vary according to changes of vehicles average velocity. In the air traffic distance between aircraft is strictly determined by the regulations and cannot be smaller than so-called minimal separation.

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

Let's mark planned movement trajectory of *i*-th aircraft in control sector as $\boldsymbol{M}^*_{P_i}$. It is usually optimal trajectory because of fuel consumption, time of passage and flight characteristics of given aircraft. $\boldsymbol{M}^*_{P_i}$ trajectory is designated by arranged sequence of an aircraft positions, determining locality of characteristic points of a flight's route, times of their passage and velocity vectors at time of passage. So

$$\mathbf{M}^*_{P_i} = \left\langle \left[\mathbf{W}^*_1, \mathbf{V}^*_1, t^*_1\right], \left[\mathbf{W}^*_2, \mathbf{V}^*_2, t^*_2\right], \ldots, \left[\mathbf{W}^*_{N_i}, \mathbf{V}^*_{N_i}, t^*_{N_i}\right] \right\rangle \quad (1)$$

where:
$\boldsymbol{W}_i^*$ - vector of planned position of an aircraft in *i*-th point of a route,
$\boldsymbol{V}_i^*$ - vector of planned velocity of an aircraft in *i*-th point of a route,
N^*_i – number of defined route points for *i*-th aircraft.

For given time (for example 24 hours) a foreseen flight plan is a set of planned trajectories $\boldsymbol{M}^*_{P_i}$ for all aircraft:

$$\boldsymbol{FP}^* = \left\{\boldsymbol{M}^*_{P_i}\right\}, \text{ for } i=1,\ldots,LS \quad (2)$$

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

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

where:
$\boldsymbol{W}_i$ – vector of actual position of an aircraft in *i*-th point of route,
$\boldsymbol{V}_i$ – vector of actual velocity of an aircraft in *i*-point of route,
N_i – number of actual route points for *i*-th aircraft.

If $\boldsymbol{M}^*_{P_i} = \boldsymbol{M}_{P_i}$ we say that flight of *i*-th aircraft was consistent with a flight plan (smooth). Of course, when talking about $\boldsymbol{M}^*_{P_i}$ and $\boldsymbol{M}_{P_i}$ equation, allowing some tolerance is necessary, especially with regard to time of flight at respective points (Skorupski 2004).

The flights, which are characterized by $\boldsymbol{M}^*_{P_i} \neq \boldsymbol{M}_{P_i}$ we will call disturbed flights. Most typical cases of disturbed flights are as follows: delaying of flight, change of flight level, change of flight route (shortening of a route, extension of a route, partial or complete change of a route except departure and arrival points), performing unplanned maneuvers or any combination of those disturbances types.

3 DIMENSIONING OF TRAFFIC SAFETY WITH EMPLOYING THE SMOOTHNESS NOTION

The smoothness of traffic can be the basis for the traffic security estimate in longer time perspective. As was mentioned above, the air traffic is initially planned. As a result a set of flight plans $\boldsymbol{FP}^*$ is created. The flight plans are initially coordinated, which means that possibility of collision, when all aircraft are flying according to their plans, is eliminated. It means also that for all aircraft included in the plans and for every point on an air 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 potentially dangerous situation. Decisions taken in stress and lack of appropriate time conditions could be wrong. Additionally, such actions reverse 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 size of 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 smoothness notion to safety estimate it is necessary dimensioning the smoothness. Two approaches are possible: binary and multivalent.

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

$$F = \frac{LS - LZ}{LS} = 1 - \frac{LZ}{LS} \tag{4}$$

3.1 *Dimensioning with the binary function*

The simplest, but very effective – as the results of modeling experiments show – approach to dimensioning smoothness, from security aspect point of view, is applying the binary function estimate. It is then assumed that a flight is smooth if it's whole actual trajectory is consistent with the planned one and non-smooth in opposite case:

$$SB_{P_i} = \begin{cases} 1, \text{for } \boldsymbol{M}^*_{P_i} = \boldsymbol{M}_{P_i} \\ 0, \text{for } \boldsymbol{M}^*_{P_i} \neq \boldsymbol{M}_{P_i} \end{cases} \tag{5}$$

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

Let's mark by LB_Z number of disturbed (non-smooth) flights in given time

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

Finally, smoothness for the binary method equals:

$$FB = 1 - \frac{LB_Z}{LS} \tag{7}$$

3.2 *Dimensioning with the multivalent function*

The smoothness disturbances are not equal. Two minutes delay at a control point is significantly less important than avoiding certain area of the airspace because of intensive weather phenomena taking place in this area. It is then possible to estimate smoothness, applying other method than binary.

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

$$SW^k_{P_i} = \begin{cases} 1\ if\ \left[\mathbf{W}_k, \mathbf{V}_k, t_k\right] = \left[\mathbf{W}^*_k, \mathbf{V}^*_k, t^*_k\right] \\ 0\ if\ \left[\mathbf{W}_k, \mathbf{V}_k, t_k\right] \neq \left[\mathbf{W}^*_k, \mathbf{V}^*_k, t^*_k\right] \end{cases} \tag{8}$$

The smoothness of i-th aircraft equals then:

$$SW_{P_i} = \frac{\sum_{k=1}^{N_i} SW^k_{P_i}}{N_i} \tag{9}$$

and LW_Z indicator designating number of disturbed flights:

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

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

$$FW = 1 - \frac{LW_Z}{LS} \tag{11}$$

3.3 *Dimensioning with the multivalent weighed function*

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

Let's assume that there is a set of possible types of disturbances $\boldsymbol{ZA} = \{za_1, za_2, \ldots, za_B\}$ and corresponding to them a set of regulations imposed on traffic, equaled to weight of traffic smoothness disturbance $\boldsymbol{WZ} = \{wz_1, wz_2, \ldots, wz_B\}$. Let's mark by $z_b(i,k)$ binary variable indicating if flight at point k of i-th aircraft was smooth or disturbance of b-th type occurred.

$$z_b(i,k) = \begin{cases} 1\ if\ \left[\mathbf{W}_k, \mathbf{V}_k, t_k\right] = \left[\mathbf{W}^*_k, \mathbf{V}^*_k, t^*_k\right] \\ 0\ if\ \left[\mathbf{W}_k, \mathbf{V}_k, t_k\right] \neq \left[\mathbf{W}^*_k, \mathbf{V}^*_k, t^*_k\right] \end{cases} \tag{12}$$

The smoothness of i-th aircraft in point k of it's route is illustrated by equation:

$$SWW^{k}_{P_i} = 1 - \frac{\sum_{b=1}^{B}\left(1 - z_b(i,k)\right)\cdot wz_b}{\sum_{b=1}^{B} wz_b} \qquad (13)$$

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

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

The indicator showing number of disturbed flights takes form:

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

Ultimately, smoothness designated by the multivalent weighed method is illustrated by equation:

$$FWW = 1 - \frac{LWW_Z}{LS} = 1 - \frac{\sum_{i=1}^{LS}\left(1 - SWW_{p_i}\right)}{LS} \qquad (16)$$

The results of measurements and the model analyses show that first method, although simplest, very well describe the phenomena connected with influence of smoothness on capacity (Skorupski 2007). It can be explained by the fact that even one and non-significant disturbance of planned aircraft flight trajectory result in necessity of constant analysis of the rest of it's trajectory and influence of arisen deviations on keeping safe distances from other aircraft. In some cases, though, also multivalent methods can be useful in designating the traffic smoothness.

4 THE SUBJECT AND THE TOOL OF THE INVESTIGATION

The research aimed at designating expedient volume of the traffic in given sector was carried out for control sector Suwałki (EPWWS), singled out as a typical sector containing one intersection of several air routes with different categories (fig.1).

Due to safety requirements is not possible to experiment on real traffic. Therefore for the needs of simulation experiments, an adequate mathematical model of the sector was developed as well as computer program realizing the model, which was used as the research tool.

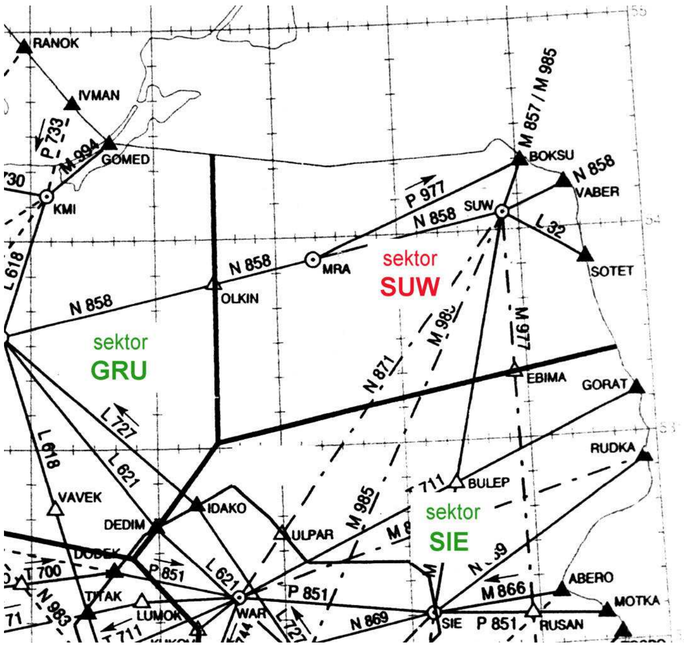

Figure 1. Control sector EPWWS in Flight Information Region FIR Warsaw.

Modeling 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 entering 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; a time period contains: analysis of a problem and working out a decision, sending an instruction by the radio and confirmation of it's receiving by aircraft commander,
- aircraft are serviced according to specific waiting algorithm,
- in any given moment only one aircraft is serviced,
- conflict situation is resolved by appropriate maneuver of the aircraft which provoked the situation,
- every aircraft should be serviced at least two times – immediately after entering and about 3 min. before exiting the sector.

Details of the model and software performing the simulation in this article have been omitted. The program realizing 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 servicing sequence of flights through collision point of the sector - intersection of air routes,
– *CFMU* – responsible for modifications of the flights plans resulted from coordination of the aircraft flows in ATFM framework,
– *engine ATC* – responsible for the simulation of operational controlling of the air traffic and determining decisions avoiding collision situations,
– *mConstans* – consisting of fixed aircraft characteristics, shape of the sector and other fixed data.

In below described simulation experiment and it's subsequent conclusions, so-called "dangerous flights" play significant role. They are consequence of realized by a controller procedure of solving a conflict situation. General scheme of proceeding by a modeled controller can be summed up to three situations:
– *solve conflict SUW* – means a situation when an aircraft is in conflict situation with other aircraft on intersection of air routes in SUW point (fig. 1),
– *solve conflict BOKSU* - means a situation when an aircraft is in conflict situation with other aircraft on intersection of air routes in BOKSU point (fig. 1),
– *solve conflict SUCCESSOR* – means a situation when an aircraft is in conflict situation with it's successor; decision is taken in a different manner than in cases *solve conflict SUW* and *solve conflict BOKSU*.

The relation between the number of undisturbed flights and the total number of flights is of empirical nature and was identified on the basis of measurements within a certain area of Polish airspace (namely TMA Warsaw). The empirical relations concerning traffic smoothness observed for air traffic show some similarity to other branches of transportation. In particular, the relation between the number of undisturbed (smooth) flights and the traffic intensity is somewhat similar to the theoretical relation between the expected traffic smoothness and its density, which was developed using agglomerated queuing process method (Malarski et. al, 1998, Skorupski & Dmochowski, 2005). In both cases, the theoretical one developed for road traffic and the empirical one for air traffic discussed in this paper, one can find the optimum traffic density/intensity with respect to smoothness.

5 THE SIMULATION EXPERIMENT

The simulation experiment consisted of investigating influence of traffic load changes in every entry point to sector EPWWS on smoothness and security 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 it's presence in entry point to the sector, flight path is developed (Table 1) according to previously given distribution of probability. The aircraft types and their flight characteristics, especially their flight velocity, ascending and descending pace are also generated in the moment of passing control after arriving at sector's border, according to given probability distribution. (Table 2).
2. Initial intensity amounts to 3,75 aircraft per hour on every entry point. Then, it is increased by iteration on every entry point, taking successively values 4,29, 5, 6, 7,5, 10, 12, 15, 20 aircraft per hour. Time period of simulation amounts to 2 hours.
3. The disturbances are registered according to smoothness examined with multivalent function. It is assumed that smoothness disturbance can occur in central point of the sector (SUW), or in any of exit points. Similarly, smoothness can be examined with the binary method. Applying multivalent weighed method is also possible in case of two, included in the model, types of smoothness disturbances – change of time and flight level in selected route's point.
4. The violations of separation, resulted 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 servicing given traffic. This allows direct estimate of number of flights with lower security level and in consequence – calculating dependence between smoothness and security 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.

Table 1. Exemplary structure of air routes in simulated sector

No of route	input	output	point 1	point 2	point 3	point 4	point 5
1	wlot4	wlot1	wlot4	BOKSU	SUW	MRA	wlot1

2	wlot4	wlot9	wlot4	BOKSU	SUW	wlot9	wlot9
3	wlot4	wlot8	wlot4	BOKSU	SUW	wlot8	wlot8
4	wlot4	wlot7	wlot4	BOKSU	SUW	wlot7	wlot7
5	wlot4	wlot6	wlot4	BOKSU	SUW	EBIMA	wlot6
6	wlot2	wlot1	wlot2	VABER	SUW	MRA	wlot1
7	wlot2	wlot9	wlot2	VABER	SUW	wlot9	wlot9
8	wlot2	wlot8	wlot2	VABER	SUW	wlot8	wlot8
9	wlot2	wlot7	wlot2	VABER	SUW	wlot7	wlot7
10	wlot2	wlot6	wlot2	VABER	SUW	EBIMA	wlot6
11	wlot5	wlot1	wlot5	SOTET	SUW	MRA	wlot1
12	wlot5	wlot9	wlot5	SOTET	SUW	wlot9	wlot9
13	wlot5	wlot8	wlot5	SOTET	SUW	wlot8	wlot8
14	wlot5	wlot7	wlot5	SOTET	SUW	wlot7	wlot7
15	wlot5	wlot6	wlot5	SOTET	SUW	EBIMA	wlot6

Table 2. Exemplary characteristics of aircraft in input flow.

Type of aircraft	Number	v_standard [km/h]	v1 [km/h]	v2 [km/h]	v3 [km/h]
A300	4	856	893	857	800
A310	3	856	900	833	780
A320	7	837	906	833	785
A330	2	865	930	865	815
A340	2	884	919	867	820
B727	12	874	986	869	835
B737	29	856	908	781	750
B747	9	911	943	900	850
B757	6	856	934	854	825
B767	6	865	908	854	818
DC10	3	902	932	818	780
DC9	7	884	946	874	825
EM145	4	818	904	753	720
MD11	1	911	939	874	840
TU34	5	818	856	781	735

6 THE RESULTS AND THE CONCLUSIONS

The experiments conducted for various intensity of the air traffic show that increase of traffic volume is generating increase of number of smoothness disturbances. The latter increase is initially small and that's why 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 is decreasing. The result is concordant with expectations based on theoretical considerations. The dependence of the number of smooth flights from volume of traffic has similar character.

The exemplary results of the simulation experiments were summed up in Table 3. The table presents selected results for the situation when on every of entry points the same intensity of notifications is simulated, fluctuating from 3,75 to 20 aircraft per hour.

Table 3. Exemplary results of simulation experiments

Input intesity [ac/h]	3,8	4,3	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

The dependencies of the number of smooth flights and the number of safe flights from the volume of traffic, in 2 hours research interval, were presented in fig.2.

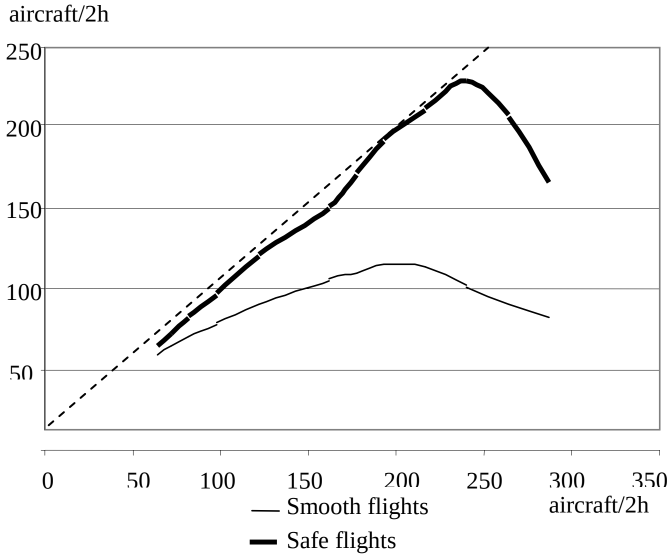

Figure 2. Influence of traffic volume fluctuations on smoothness and safety of the traffic

The experiments conducted prove that very interesting dependency exists, which can have considerable practical meaning. As can be observed, both diagrams have one maximum. Maximum of smoothness occur for smaller volume of traffic than maximum of safety. Maximal number of smooth flights occur for about 205 aircraft in 2-hours interval, whereas maximal number of safe flights occur for about 230 aircraft in 2-hours interval. The result can be explained by the fact that applied safety procedures are redundant and occurring even significant number of smoothness disturbances is not yet tantamount to endangering security.

The reciprocal shaping of these diagrams makes possible developing heuristic algorithm for finding expedient maximal volume of traffic in 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 reach the level, which designate beginning of smoothness decreasing. Such volume of traffic can be accepted as maximal capacity of control sector, taking into account security aspect.

Quantitative assessment of the traffic safety is absolutely necessary as the key criterion for evaluation of flight plans, airspace organization, traffic control procedures, etc. No optimization is possible with respect to any aspect of the air transportation without proper numerical evaluation of the effects of the intended modernization projects on the traffic safety.

The results obtained confirm, in certain extent, previously presented proposition about possibility of security estimate with the aid of smoothness notion. The results demonstrate that strong correlation occurs between those values, so smoothness coefficient (calculated with the aid of any of three methods of smoothness investigation) can be a measure of security level.

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