INTRODUCTION

According to common understanding, the transportation is considered safe unless disturbed by any dangerous events (collisions, accidents). Usually, there is no quantitative assessment of the level of safety. The traffic safety may be analysed on a macro- or microscale. On a microscale, the safety is the same as the static/dynamic safety defined below. It consists in geometric and dynamic relations between aircraft, which constitute the basis for the assignment of the numerical safety rating to individual traffic situations. The safety defined and determined in such a manner may be used in the analysis and design of current operation control systems related to air traffic. In our research project financed by Supreme Research Committee in Poland we have developed many methods and tools for investigation of the so defined safety. The project results, however, are not discussed here; for their detailed presentation see (Skorupski et al. 2001).

On a macroscale, we propose to analyse the safety using the traffic smoothness concept. Such safety is related to traffic considered in the long run and may be useful in the organisation and long-term planning of air transportation systems. A concept of research on the smoothness approach to the traffic safety dimensioning will be presented later in this paper.

Methods presented in this paper may be extremely useful in supporting air traffic controller work. Any time, when a so-called conflicting situation occurs in the airspace there are many ways to solve the problem, for instance by changing the cruising speed or flight level. Each way results in different traffic situation with different safety level. As far as now controller has no way to compare his decisions according to the resulting safety level. Methods mentioned in this paper are developed to support the air traffic controller in performing such comparison and let him undertake better decision.

GENERAL DEFINITIONS

Due to its nature, the air traffic is subject to initial planning and coordination or, using terminology derived from other branches of transportation, it is routed traffic. Generally, the routed traffic is defined as any movement of objects according to a predefined schedule which assigns a route in space-time to each object. Any service aircraft must have a flight plan before it takes off. Such plan determines in detail the flight trajectory, specifying the points on the ground to be flown over, altitude and expected flight time. Thus, it is a flight route in four dimensions.

While developing a flight plan, one has to consider, first of all, the aircraft flight characteristics, such as fuel consumption at different altitudes, optimum cruising speed, maximum and minimum flight altitude, etc. In addition, one has to account for traffic restrictions resulting from the air corridor
system, air traffic regulations and already planned flight routes.

Flight plans are developed in such a manner as to ensure that the flight of the aircraft is undisturbed, i.e. that any changes in the flight parameters (altitude, speed, direction) result from landscape features or the above-mentioned aircraft flight characteristics and traffic regulations only. Air traffic, however, is a highly dynamic and variable process; it is significantly affected by numerous external disturbances, especially related to weather conditions as well as traffic congestion next to airports or critical airway nodes. Flight plans are developed in advance, which differs considerably, e.g. from six or one month to one day. Consequently, one has a different chance to predict disturbances or congestion and modify the flight plan accordingly to ensure that the flight is undisturbed, i.e. that there are no changes to the flight parameters due to the current control by air traffic controllers.

Pursuant to international air traffic regulations (ICAO, 1989), under all and any conditions there should be a buffer zone (or separation) around each plane to prevent aircraft collision in the air or in the maneuver field.

Such separations are to be maintained by air traffic controllers and pilots. It is assumed that the air traffic is safe if the separations are not violated. And this is usually the case in real life traffic: the separations are maintained and the traffic is safe in that sense (especially that the above-mentioned flight plans are designed to maintain the separations). Still, there are some aircraft crashes due to reasons other than a technical failure or pilot fault, but rather related to traffic organisation and control.

2.1 Traffic Space

The traffic space means a certain 3D region in the air space or 2D region in the ground space. It marks the set of allowable points which can be reached by aircraft. Each time any plane leaves that space, it is a violation of air traffic regulations, which results in a significant decrease in the traffic safety. In case of the air traffic, the traffic space is determined by the relevant international regulations and standards. Identifying the traffic space with the controlled flight space (within which all service aircraft flights take place), let this space be denoted by $S_{FIR}$ and let it correspond to the given flight information region (FIR):

$$S_{FIR} = \sum_i S_{AWY}^i \cup \sum_i S_{RL}^i$$

(1)

where: $S_{AWY}^i$ - airway $i$, $S_{RL}^i$ - airport area $i$

The airport area, in turn, may be defined as follows (Skorupski, 1997):

$$S_{RL} = S_{TMA} \cup S_{CTR} \cup S_{TX} \cup S_{TS}$$

(2)

where:

- $S_{TMA}$ – airspace in which the aircraft descend before landing and climb after take off, corresponding roughly to the terminal area (TMA);
- $S_{CTR}$ – runway space in which the aircraft take off and land, corresponding roughly to the airport control zone (CTR);
- $S_{TX}$ – ground area in which the aircraft taxi after landing and before take off;
- $S_{TS}$ – ground area in which the technical maintenance and repairs of the aircraft are performed.

2.2 Controlled Object

In case of air traffic, the term controlled object is ambiguous and hard to define; also the influence on such object, speaking strictly, cannot be called control. However, we will refer to it as control in this paper. We also assume that the controlled object is the set of all aircraft within the traffic space. It is a non-uniform object, which consists of many component objects with their own autonomous control systems.

2.3 Aircraft Position

The momentary position of the aircraft is characterised by vector $P = [W,V]^T = [x,y,z,v_x,v_y,v_z]^T$, which describes the aircraft position in the traffic space, $W=[x,y,z]^T$, and the speed vector components along each axis, $V=[v_x,v_y,v_z]^T$. As by nature the air traffic is a dynamic process, the vector $P$ is a certain function of time $P(t)$, referred to as the flight trajectory or actual flight route of the aircraft. Usually, the concept of the planned/actual flight route is used. In the practice of air traffic control services, the planned flight routes are determined by specifying the subsequent points to be reached by the aircraft, without defining the detailed trajectory between such points:

$$M_w = \{W^1,W^2,\cdots,W^N\}$$

(3)

where $N$ – the total number of the points defined on the route.

Alternatively, one may specify the time in which the subsequent points are to be reached:

$$M_w(t) = \begin{bmatrix} x^1(t_1) & x^2(t_2) & \cdots & x^N(t_N) \\ y^1(t_1) & y^2(t_2) & \cdots & y^N(t_N) \\ z^1(t_1) & z^2(t_2) & \cdots & z^N(t_N) \end{bmatrix}$$

(4)

It is equivalent to specifying (at least roughly) the climb/descent characteristics or simply the air speed. Thus, it is equivalent to defining the route through an ordered sequence of aircraft positions:
of values of the vectors \( \mathbf{v} \) and the planes \( xy, xz \) and \( yz \) respectively. Then:

\[
\begin{align*}
\cos \varphi &= \frac{(v_x)^2 + (v_y)^2}{\sqrt{v_x^2 + v_y^2 + v_z^2}}, \\
\cos \psi &= \frac{(v_y)^2 + (v_z)^2}{\sqrt{v_x^2 + v_y^2 + v_z^2}}, \\
\cos \zeta &= \frac{(v_z)^2 + (v_x)^2}{\sqrt{v_x^2 + v_y^2 + v_z^2}}.
\end{align*}
\]

Let \( n \) denote the resultant speed vector:

\[
|\mathbf{v}| = \sqrt{(v_x)^2 + (v_y)^2 + (v_z)^2}
\]

Let \( \varphi, \psi, \text{ and } \zeta \) be the angles between the vector \( \mathbf{v} \) and the planes \( xy, xz \) and \( yz \) respectively. Then:

\[
\begin{align*}
\cos \varphi &= \frac{(v_x)^2 + (v_y)^2}{\sqrt{v_x^2 + v_y^2 + v_z^2}}, \\
\cos \psi &= \frac{(v_y)^2 + (v_z)^2}{\sqrt{v_x^2 + v_y^2 + v_z^2}}, \\
\cos \zeta &= \frac{(v_z)^2 + (v_x)^2}{\sqrt{v_x^2 + v_y^2 + v_z^2}}.
\end{align*}
\]

2.4 Traffic Situation
The traffic situation at instant \( t_0 \) is defined as the set of values of the vectors \( \mathbf{P}(t_0) \), \( i=1, \ldots, \text{LS} \), where \( \text{LS} \) is the total number of aircraft within the traffic space (LS evolves over time):

\[
\mathbf{SR}(t_0) = \{ \mathbf{P}_1(t_0), \ldots, \mathbf{P}_n(t_0) \}
\]

The traffic situation \( \mathbf{SR}(t_0) \), as defined above, is in fact a static momentary projection of the set of all trajectories \( \mathbf{P}(t) \) traced at instant \( t_0 \). The traffic situation is a basic term used in the air traffic control, both in the process of developing and making decisions and traffic safety evaluation. Air traffic controllers use momentary aircraft position data obtained by means of position reports or radar techniques for the purpose of the analysis which leads to decision making. The traffic situation data obtained in the above-mentioned manner as well as the predicted (forecasted) future parameters constitute the basis for the determination of control signals \( \mathbf{X}_{\text{ATC}} \). As for the traffic safety evaluation by the traffic analyst, the traffic situation constitutes the basis for the calculation of all parameters which affect such evaluation.

2.5 State of Environment
The environment state at instant \( t_0 \) is characterised by vector \( \mathbf{SO} \), which includes weather data, traffic space equipment data as well as information on control methods, traffic space shape, etc.

\[
\mathbf{SO}(t_0) = \{ \mathbf{S}_m(t_0), \mathbf{S}_w(t_0), \mathbf{S}_{\text{ATC}}(t_0), \mathbf{S}_p(t_0), \mathbf{S}_w(t_0) \}
\]

2.6 Traffic Process
The traffic situation is a temporal variable, too. So, one can refer to a certain transition function which transforms a traffic situation at instant \( t_i \), \( \mathbf{SR}(t_i) \), into another traffic situation at instant \( t_j \), \( \mathbf{SR}(t_j) \). This function is called the traffic function, traffic process or simply traffic.

\[
\{ \mathbf{SR}(t_i), \mathbf{SO}(t_i), \mathbf{X}_{\text{ATC}}(t_i) \} \xrightarrow{f_{\text{SR}}} \mathbf{SR}(t_j)
\]

The traffic process depends on the assumed flight trajectories (routes) of individual aircraft, the state of environment and the control vector generated by the air traffic control system (ATC system). Thus, it depends on both controlled and uncontrolled factors.

2.7 Traffic Safety
The traffic safety is a feature of the traffic situation and state of environment. One can refer to static safety \( \mathbf{B}_S \) at instant \( t_0 \) or dynamic safety \( \mathbf{B}_D \), which depends on the changes of the traffic situation, environment state and control signals \( \mathbf{X}_{\text{ATC}} \).

\[
\{ \mathbf{SR}(t_0), \mathbf{SO}(t_0) \} \xrightarrow{b_S} \mathbf{R}_s
\]

\[
\{ \{ \mathbf{SR}(t_i), \mathbf{SO}(t_i), \mathbf{X}_{\text{ATC}}(t_i) \} \xrightarrow{f_{\text{SR}}} \mathbf{SR}(t_j) \} \xrightarrow{b_D} \mathbf{R}_s
\]

Static safety \( \mathbf{B}_S(t_0) \) is a function which associates the traffic situation and environment state at instant \( t_0 \) with a positive real number, while dynamic safety \( \mathbf{B}_D \) associates the traffic process (which transforms the traffic situation and environment state at instant \( t_i \) into the traffic situation at instant \( t_j \)) with a positive real number.

2.8 Traffic Control System
The traffic process \( f_{\text{SR}} \) may be influenced from the outside in order to achieve the assumed objectives, i.e. to make the actual traffic situations \( \mathbf{SR}(t_i) \) consistent with the requirements of the control body. The state of environment is considered a disturbance to this process.

In air traffic control it is usually not required to reach any set traffic situation. It would be very difficult to define such objective, not to mention its achieving. Partial objectives, which can be characterised by certain aggregated criteria, are specified instead. One may assume that the given criterion value corresponds to certain utility (expressed nu-
merically). The utility function is different for each criterion used for the evaluation of the traffic (traffic control process); it is also subjective, as it depends on the preferences of the individual controller.

The evaluation of the achievement of partial objectives using utilities of individual criteria constitutes the basis for defining the objective function:

$$\max z = u_1(c_1) + u_2(c_2) + \ldots + u_n(c_n).$$

where: $c_i$ – $i$th criterion for the traffic process evaluation; $u_i(c_i)$ – utility of the $i$th criterion (Coombs, 1993).

The superior objective of air traffic control services is to minimise or maximise such objective function. It is not possible to determine function $z$ in a definite way, as it is subjective. However, one may assume that the utilities related to partial objectives are monetary values which are additive. Then, the objective is to maximise the sum of all utilities:

$$\max z = u_1(c_1) + u_2(c_2) + \ldots + u_n(c_n).$$

One may further assume that the objectives of air traffic control services is to minimise or maximise such objective function. It is not possible to determine function $z$ in a definite way, as it is subjective. However, one may assume that the utilities related to partial objectives are monetary values which are additive. Then, the objective is to maximise the sum of all utilities:

In order to avoid such problems, we propose to introduce and analyse a concept of the safety of the air traffic, as the flight safety referred to above is just one aspect of the traffic safety.

3.1 Geometrical methods of safety dimensioning

The traffic safety deals with the problems of collision-free, efficient and low-cost performance of many flights within finite airspace and airport maneuver fields. It also deals with situations which do not pose direct danger themselves, though their superposition and multiplication can lead to accidents or catastrophes. In such approach, the air traffic safety may be considered an element of the air traffic quality assessment (of quantitative rather than qualitative character). Once such definition of the air traffic safety and the methods to determine it are developed, one can provide a numerical assessment of any traffic situation and compare it with others. Thus, such approach enables one to determine the optimum strategy with respect to safety, as any control decisions may be expressed through corresponding traffic situations, which in turn may be rated in terms of traffic safety.

Safety in the field of transportation cannot be overestimated. As for now, there are no effective methods and tools for the air traffic safety dimensioning (i.e. quantitative assessment). It seems that two issues should be pursued in parallel. First, the investigation and comparison of traffic situations, which is useful for the analysis and design of air traffic operating control systems and procedures.

The concept of geometrical methods is based on the following algorithm:

1. Decomposition of traffic situation to suitable for analysis - $n$-groups of aircrafts.
2. Determining of possible interactions between aircrafts.
3. If there exists any risk between the aircrafts – determining the weights of hazardous interactions.
4. Computing the level of safety of isolated $n$-group.
5. Calculating the relative weights of each $n$-group in the whole traffic situation.
6. Computing the safety of whole traffic situation.

Basing on this algorithm we developed several practical methods for dimensioning of air traffic.

3 TRAFFIC SAFETY

The air traffic safety is a complex and multifold concept. Most often, the safety in aviation is deemed to be the safety of the flight (of one or more aircraft). In such approach one usually considers the technical reliability of the plane subassemblies and its impact on the risk of dangerous events, such as defects, crash/accident preconditions, etc. In addition, one analyses the human factor impact on the flight safety, taking into account the abilities and skills of pilots and ground maintenance personnel, as well as the efficiency of people responsible for flight supervision (Jazwinski & Borgon, 1989).
3.2 Traffic smoothness

Second, further research based on the traffic smoothness concept, which should provide a global picture of the air transportation safety and may be used e.g. for the analysis and strategic planning of the air transport infrastructure development.

Despite many similarities to the railway or road traffic, the air traffic is significantly different. The key differences include the fact that 3D analysis is required and that one cannot ‘stop’ individual vehicles (and consequently the whole traffic flow).

Although there are some holding procedures to make the aircraft wait, e.g. until the runway is cleared before landing, holding is not the same as waiting or stopping in case of ground traffic. Consequently, there is no maximum traffic density \( k_{\text{jam}} \) (as denoted by D. Heideman (1996), which would be of similar importance for the air traffic smoothness. Unlike road traffic, the expected flow speed does not exist, as this speed is imposed by the control body (air traffic controller) on the basis of the predefined flight plans. Also the stream density is determined by the existing international air traffic regulations adopted by ICAO.

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, Dmochowski & Skorupski, 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.

4 CONCLUSIONS

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

Some general definitions and ideas of air traffic safety dimensioning pointed in this paper may help in development of practical methods that may be useful in practice. Some of those methods were also mentioned here. We have developed computer tools that implement those methods and they are already in the phase of practical tests. Those tests prove that they have practical importance. Results are obtained on-line, even in complicated traffic situations. We hope that those methods will be used in air traffic controllers work in future.

REFERENCES