AIR TRAFFIC COMPLEXITY AS A SAFETY PERFORMANCE INDICATOR

Jelena DJOKIC, Hartmut FRICKE, Michael SCHULTZ, Christoph THIEL

Abstract: Numerous studies emphasize the significant influence of air traffic complexity on controller’s workload and consequently on the overall safety level. This paper describes a detailed investigation into these air traffic complexity metrics. The evaluated data originate from traffic samples of a recently conducted real-time simulation in air traffic control at EUROCONTROL CRDS Budapest. In these traffic samples both flight characteristics of individual aircraft and the interactions between pairs of aircraft were taken into consideration. With an attempt to quantify potential changes of the safety level, relevant indicators as the position, collision- respectively conflict probabilities were used. A traffic simulation environment was developed in order to determine these quantitative criteria more accurately. Additional emphasis was put onto the consideration of actual navigation performance of each aircraft to allow correlating air safety with performance based navigation (PBN) concepts.

Keywords: Air Traffic complexity, safety, collision probability, Actual Navigation Performance (ANP).

1 INTRODUCTION

According to the air traffic analyses in the last decade, continuous growth was anticipated in the long term, at least until 2030. Nevertheless, since august 2008 situation surprisingly evolved in the opposite direction for the first time since 2002. While in 2007 a growth of 5% was recorded, in 2008 it reached only 0.4% as a consequence of the global financial crisis and economic downturn. However, on the daily basis, traffic went three times beyond the numbers recorded in 2007 [1].

Taking all this into consideration, greater ATC flexibility is needed for handling all possible future scenarios efficiently, while at least maintaining, rather improving, safety level according to SES key performance indicators [2]. Therefore, numerous studies investigate into enhanced automation, tools and procedures to achieve this goal. Even so, it is very difficult to measure the safety “performance” of ATC, since safety is the absence of accidents, and it is hard to measure absence [3]. Therefore, it is sought for an indicator of safety that would reflect quantified characteristic able to capture variations in safety assessment through different traffic scenarios in order to provide enough data for anticipation and mitigation of safety critical events.

This paper deals exclusively with the endangering of the involved air traffic expressed through the factors defined in order to capture complexity of the traffic and as a specific level of risk or safety for an aircraft conflict or accident per period of time [4].

Numerous studies investigate into safety through controller’s workload, as prime factor driving safety, determined by both directly measurable air traffic factors (number of aircraft in the sector, speed, distance between aircraft, etc.) and controller’s activity mediated by the controller’s abilities, age, fatigue, level of experience, etc. [5]. As the investigation into the correlation between subjective controller workload and safety level was previously conducted and strong connection was found [6] this paper focuses only on air traffic complexity as the objectively measurable prime driver of subjective controller workload and collision probabilities as an attempt to quantify the changes in air traffic safety level.

Therefore, a detailed investigation into these air traffic complexity metrics and collision probability is described, followed by an analysis of their relationship. Moreover, the objective of the current study is to investigate into their interdependencies and examine whether they contribute to the overall safety as two separate independent entities, or they could be considered as unity in which they are partially congruent in depiction of the air traffic complexity.

2 COMPLEXITY

As the number of aircraft within a sector here called ‘sector load’ is increasing, the routine tasks associated with handling each aircraft safely (monitoring, communication and coordination) are increasing accordingly. Still, the level of difficulty experienced by the controller depends on other traffic factors beyond the sector load. These traffic factors refer both to the flight characteristics of each aircraft in the sector individually and the interactions between different aircraft.

Flight characteristics of the aircraft are referred to as the transition factors which relate to instantaneous changes of the state and position of the aircraft, e.g. changes in altitude, heading and speed. In this manner, interactions between aircraft can be captured by the degree of disorder among aircraft, i.e. the variability in headings and speeds.

The straightforward factor derived from the sector load taking into consideration changes in horizontal and vertical distances between aircraft within time, is called ‘density’. Nevertheless, density itself is not affecting controllers feeling of difficulty of the situation as much as if aircraft are converging.
or diverging. In case of convergence, potential conflicts can emerge driven by sensitivity of both the relative distance and transition factors of the aircraft in the sector.

Though significant number of studies (see [7] for a recent review) considers ATC complexity matter, with many complexity factors proposed, there is still no set of comprehensive and generally accepted measures recognized.

This study presents a list of complexity factors selected from the literature on the basis of continuously recognized relevance (importance) and detailed calculation formula reported.

There are 14 selected complexity factors listed in Table 1, for which more thorough review readers are referred to the indicated source literature, since their detailed description and explanation is out of the scope of this paper.

![Table 1 List of the complexity factors](image)

### Table 1 List of the complexity factors

<table>
<thead>
<tr>
<th>Complexity Factors</th>
<th>Used in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 number of aircraft</td>
<td>[9], [11], [13]</td>
</tr>
<tr>
<td>2 number of climbing aircraft</td>
<td>[9], [11], [13]</td>
</tr>
<tr>
<td>3 number of descending aircraft</td>
<td>[9], [11], [13]</td>
</tr>
<tr>
<td>4 number of aircraft with lateral distance between 0-25nm and vertical separation less than 2000ft above 29000ft</td>
<td>[11], [10]</td>
</tr>
<tr>
<td>5 variance of ground speed</td>
<td>[9], [11], [13]</td>
</tr>
<tr>
<td>6 density indicator (mean)</td>
<td>[8], [12], [13]</td>
</tr>
<tr>
<td>7 variability in headings (track disorder) (mean)</td>
<td>[8], [12], [13]</td>
</tr>
<tr>
<td>8 variability in speed (speed disorder) (mean)</td>
<td>[8], [12], [13]</td>
</tr>
<tr>
<td>9 divergence between pairs of aircraft (mean)</td>
<td>[8], [12], [13]</td>
</tr>
<tr>
<td>10 convergence between pairs of aircraft (mean)</td>
<td>[8], [12], [13]</td>
</tr>
<tr>
<td>11-12 sensitivity indicator (a/c converging-mean; a/c diverging-mean)</td>
<td>[8], [12], [13]</td>
</tr>
<tr>
<td>13-14 insensitivity indicator (a/c converging-mean; a/c diverging-mean)</td>
<td>[8], [12], [13]</td>
</tr>
</tbody>
</table>

### 3 SAFETY CORRELATOR MODEL

The Safety Correlator (SC) is a fast- and real-time simulation tool, which calculates a Risk index – the ‘Level of Safety’ (LOS) – on the basis of the quantitative criteria collision and conflict probability, where the collision probability is defined as the probability of a collision of two aircraft within the terminal area (TMA). The second metric, the conflict probability, is expressed as the probability of a contact or penetration of a predefined safety zone around two aircraft. As the basic principles of the underlying model are comprehensively explained in [14] and [15], the following section only gives a short introduction to the theoretical background.

The RTCA CD&R Working Group has defined the term „Protected Airspace Zone“ (PAZ) in its work about collision and conflict probability [16]. The PAZ represents airspace around aircraft in which no other aircraft shall penetrate. The dimension and shape of this safety zone has obviously a significant impact onto the resulting conflict probability. For this reason, the PAZ chosen from the RTCA CD&R Working was modified as follows to achieve an appropriate and still conservative metric for safety measurement: The original PAZ consists of a cylinder with a radius equal to the separation minima. So, each separation infringement leads mandatorily to a conflict. This modus operandi would lead to an excessive large conflict probability in the here observed airspace with its characteristic high traffic density. The consequently extended safety zone used here is illustrated in Figure 1.

The dimensions of this safety zone are deduced from the dimensions of the aircraft, from the values of the actual navigation performance of the reference aircraft, and from the velocity difference to the potential conflict partner, the intruder aircraft. The ANP values (differentiated in longitudinal, lateral, and vertical direction) are used analogue to the RNP values [17] as the standard deviation $\sigma$ of a normal probability density function (PDF) to calculate the position probability by integration. The calculation refers to a space grid of pre-defined, three-dimensional raster elements in which the observed airspace is subdivided. A raster element represents the two dimensional integration boundaries when calculating the position probability of each aircraft every time interval. This is a valid simplification as a raster element corresponds to the dimension of the largest aircraft within the observed airspace. During each simulation cycle (typically this equals one second in real time) the assumed position for each reference aircraft in the observed airspace is calculated for all raster elements.

Because of the chosen probability approach, it is virtually possible, that an aircraft is expected in multiple raster elements. At this, the probability
decreases heavily with increasing distance of the raster element to the reference position of this aircraft with respect to its actual navigation performance, modeled through the PDF. So, it is necessary to calculate the conflict probability for every possible spatial configuration of any pair of aircraft. The sum of these conflict probabilities is the probability of a conflict between that pair of aircraft. The described model is implemented as a prototype called Safety Correlator (SC) using the JAVA programming language. Beside modules for modeling the ANP of each individual aircraft and the modules for calculating the conflict probabilities, the SC also features a graphical “radar screen like” user interface. With this interface, the user is able to set the operational and technical constraints and to review the results of the calculations as a histogram “conflict probability over time”. Furthermore, the SC has standard interfaces to connect to external sources of traffic data (e.g., radar data using the ASTERIX protocol).

4 THE REAL-TIME SIMULATION EXPERIMENT

4.1 Simulation

The data used for the analysis were collected during a two week IAA RTS1 (Irish Aviation Authority Real Time Simulation 1) real-time simulation experiment that aimed at investigating the operational feasibility, efficiency and benefits of solutions based on a package of modifications in the provision of the IAA Air Traffic Service (ATS) in the Shannon Control Area (CTA) below FL245; so in the low airspace [18].

For the present investigation, IAA RTS1 data was reduced to the busiest sector of the considered airspace (SHLOW). As a baseline, data was used from a scenario in which no operational changes were introduced, thus reflecting the current situation but with varying traffic load over time. Data was so used from 13 exercises, each lasting 1 hour and 20 minutes in total, out of which approximately one hour was recorded.

4.1 Complexity and Safety measures

The flight plans and flown trajectories were used as input data for both the complexity factors calculations and the conflict and collision probability over time as a technical safety indicator. In particular the following data was used: Position of the aircraft (latitude, longitude and altitude), speed, heading and the next waypoint within a sector. Synchronously to the SC collision probability calculations, the complexity factors were updated every 5 seconds. This was achieved with additional software that was developed for this experiment. So a completely synchronised data set was obtained for the experiment declaring evolving complexity and safety metrics over time.

5 STATISTICAL EVALUATION AND RESULTS

The data used for the statistical analysis were derived from the recordings of the exercise covering a 1 hour timeframe divided in 5 second time steps. This lead typically to 9,360 measurements for each indicator (12 measurements/minute → 12 × 60 = 720 measurements/hour → total: 720 × 13 exercises = 9,360). However, due to recordings that had duration longer than 1 hour in some exercises, the overall set comprised 9,573 measurements, forming the basis for the statistical analysis presented next.

5.1 Application of the Principal Component Analysis

As the initial set of the chosen complexity factors aimed at capturing to a large extent all aspects of
complexity, a high dimensionality was reached, being difficult to analyse. Further, interdependencies were expected to exist between the variables.

Therefore, a Principal Component Analysis (PCA) was performed on this set of complexity factors trying to keep most of the (expected) information of the original set of variables while reducing its absolute number. The PCA is a method to reduce data dimensionality by performing a covariance analysis between factors.

Principal components with an Eigenvalue higher than 1 were extracted and subsequently rotated using the VARIMAX method. The rationale for using the criterion of an Eigenvalue>1 lies in fact that such a component is accounting for a significant variance in the overall data set. Consequently, components with Eigenvalues less than 1 were considered to be neglected and were not retained. Beside that “importance judgement”, the VARIMAX rotation invokes an orthogonal rotation resulting in independent components.

There were 4 principal components extracted as the result of this statistical method. They accounted for 77.6% of the total variance in the overall data set. Table 1 displays these components sorted by descending Eigenvalues. It further depicts the percentage of variance they are accounting for. As the loading is equivalent to the correlation between that factor and its component, the factor with the highest loading generally leads the interpretation of the component.

<table>
<thead>
<tr>
<th>Components</th>
<th>Eigenvalue</th>
<th>% of Variance</th>
<th>Cum. % of Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp.1</td>
<td>5.543</td>
<td>35.591</td>
<td>35.591</td>
</tr>
<tr>
<td>Comp.2</td>
<td>1.950</td>
<td>17.930</td>
<td>53.521</td>
</tr>
<tr>
<td>Comp.3</td>
<td>1.740</td>
<td>12.429</td>
<td>65.950</td>
</tr>
<tr>
<td>Comp.4</td>
<td>1.630</td>
<td>11.645</td>
<td>77.595</td>
</tr>
</tbody>
</table>

Comp.1 – aircraft distribution – highly correlated to the density factor and the number of aircraft in the sector (0.953 and 0.942 respectively).

Comp.2 – aircraft transitioning – component that is strongly related to the variance of the ground speed on one side (0.830) and the number of climbing aircraft (0.777).

Comp.3 – convergence – this component describes convergence between aircraft in the sector as it shows relation to both the convergence factor and the insensitivity factor associated to the convergence between aircraft (0.963 and 0.966 respectively).

Comp.4 – divergence – analogously to the previous component, but in the opposite direction this component relates to divergence factor and associated insensitivity (0.957 and 0.954).

In a second step of the analysis the correlation between complexity factors and the collision probability taken from the SC as safety indicator was examined. In order to reveal this relationship, a second PCA application was performed. The hypothesis for this step was: If those two entities to a certain extent describe the same aspect of safety – i.e. the complexity of the instantaneous geometry of the air traffic situation, the consideration of the collision probability as additional factor would reach a higher percentage of the total variance contained in the factor set (at 77.6% with the 1. PCA process). Additionally, the collision probability would contribute with a given loading on one of the components and by that reveal its interdependence with specific complexity factors with loadings within the same component. On the other hand, if those two entities refer to different aspects of safety, the total variance would be less.

Therefore, the same procedure to extract the relevant components was performed (Eigenvalues>1, VARIMAX rotation). Interestingly, with the same 4 principal components a lower value of the total variance in the metrics, now found with 72.95% did result, each of it contributing as follows:

<table>
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<tbody>
<tr>
<td>Comp.1</td>
<td>5.598</td>
<td>37.318</td>
<td>37.318</td>
</tr>
<tr>
<td>Comp.2</td>
<td>1.953</td>
<td>13.021</td>
<td>50.339</td>
</tr>
<tr>
<td>Comp.3</td>
<td>1.741</td>
<td>11.603</td>
<td>61.942</td>
</tr>
<tr>
<td>Comp.4</td>
<td>1.651</td>
<td>11.004</td>
<td>72.946</td>
</tr>
</tbody>
</table>

However, the collision probability factor did not provide loading on any of the extracted components.

Table 3 Results of the PCA performed on 14 complexity factors and collision probability

<table>
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6 CONCLUSIONS

With an attempt to quantify characteristics able to capture variations in safety of air traffic operations through different traffic scenarios, two aspects were investigated: Complexity of the
instantaneous geometry of the traffic situation on one side and so-called collision/conflict probability on the other side. Further, in order to investigate into their interdependencies and examine whether they contribute to the overall safety as two separate independent entities, or they can be treated as unity as being partially congruent in depiction of the air traffic complexity, a two-step Principal Component Analysis (PCA) analysis was performed. In the first step, the PCA was performed using the initial set of complexity factors without collision probability as a baseline scenario, while in the second step the conflict/conflict probability factor was considered additionally. The intention of the first PCA was to reveal interdependencies within the set of complexity factors and consequently, reduce its dimensionality. The second PCA intended to investigate the level of correlation between the baseline complexity factors and the conflict/conflict probability.

The analysis resulted in the extraction of the same components in both steps of the analysis, but with a lower total variance for the second one. Additionally, the conflict/conflict probability factor did not add any loading on any of the derived components. As the loading is equivalent to the correlation between that factor and the component, it can be concluded that there is no interdependency between components identified based on the complexity factors and the conflict/conflict probability factor. It also explains that conflict/conflict probability does not give added information to the complexity of the air traffic situation, but targeting another scope of the safety assessment.

Namely, based on the analysis performed on the available dataset, the conclusion drawn out is that each of them captures different aspects of safety and provides separately added value in quantification of the changes in the safety level. Further research into both complexity and conflict/conflict probability is recommended, as well as a deeper investigation into their correlation with the changes in safety level.

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References


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