# Simulation studies of airborne ADS-B applications

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## Abstract
This paper presents the research which includes simulation, analysis, approbation and demonstration of new airborne communication, navigation and surveillance (CNS) functions. During the research In-Trail Procedure (ITP), Flight-Deck Interval Management (FIM) procedure and Airborne Conflict Management (ACM) procedure were developed. To study various aspects of advanced airborne procedures fast-time simulation in automatic mode and real-time human-in-the-loop simulation were performed. The objects of the research were air traffic characteristics and main partisipants of air traffic management system: air trafiic controllers and aircraft crew. Simulation was conducted using the research Stand for hardware-in-the-loop and human-in-the-loop simulation of Air Traffic Management System, which integrates mathematical models and simulators including aircraft and ATC models, cockpit simulators and ATC workstations.

## 1. Introduction

Because of airspace congestion and constantly increasing air traffic the development of new ADS-B applications is relevant nowadays. Such applications are expected to benefit the air traffic system by enhancing accuracy of transmitted data and situational awareness of pilots and air traffic controllers. New technologies make it possible to delegate some operations from ATC to pilot, decreasing ATC workload. Because of this fact, new airborne CNS procedures, such ITP, FIM or ACM, appear. But before exploitation new airspace technologies require preliminary approbation and studies.

Research and development of ADS-B applications are conducting all over the world nowadays. Global Air Navigation Plan ICAO declares main trends for modernization of ATM system, which includes new ADS-B applications. Various studies of ADS-B applications are organized by EUROCONTROL (Europe) and FAA and NASA (USA). Radio Technical Commission for Aeronautics (RTCA) has already developed standards for new airborne procedures. At the same time the avionics manufacturing companies, such as Thales, Honeywell, Rockwell Collins, etc., has already designed new avionics solutions. In other words, the whole world is preparing to implement new procedures into air traffic system.

Global harmonization has a trend to spread new technologies and ideas all over the world and soon will bring them to Russian Federation. Using advanced technologies and procedures can bring serious benefits to such a vast airspace with long-distance routes, unique structure and features. That is why simulation and research studies of advanced procedures are up-to-date in our country.

The main goals of the presented work are:

- demonstration and research of pilot and ATC cooperation during CNS procedures performance;
- development and research into pilot and ATC interfaces;
- performance approbation of airborne procedures in high air traffic conditions with the impact of random factors;
- getting the quantity characteristics of performance changes caused by using CNS procedures;
- comparison of airborne CNS procedures and standard procedures.

The main objects of researches are pilots, aircrafts and air traffic controllers. Such characteristics as pilot and controller workload, fuel consumption and average delays were estimated. Changes in air traffic performance characteristics, such capacity, safety, ecology, also were under review.

To assess the influence on air traffic characteristics advanced ADS-B-based functions were compared with corresponding standard functions. ITP was compared with standard flight level change procedure, FIM procedure was compared with standard ATC interval management functions, and ACM procedure was compared with standard ATC conflict management functions.

The method of the research is the simulation, which was performed in two modes : fast-time automatic mode without human interaction and real-time human-in-the-loop mode with pilot and ATC interaction.
The instrument of the research is the research Stand for hardware-in-the-loop and human-in-the-loop simulation of Air Traffic Management System (KIS UVD), which was developed in Russian Federation State Research Institute of Aviation Systems (GosNIIAS) for demonstration, simulation and research of new technologies in air traffic management system.

## 2. ADS-B airborne procedures

The present research includes simulation, analysis, approbation and demonstration of new airborne communication, navigation and surveillance (CNS) functions. The following prototypes of airborne procedures were developed for the simulation tool:

- **In-Trail Procedure (ITP)**, which enables aircraft that desire flight level changes in procedural airspace to achieve these changes on a more frequent basis, thus improving flight efficiency while maintaining safe separation from other aircraft;
- **Flight-Deck Interval Management (FIM)** procedure, a set of airborne capabilities designed to support a range of interval management operations whose goal is precise inter-aircraft spacing.
- **Airborne Conflict Management (ACM)** procedure, which enables aircraft to detect, prevent and resolve air traffic conflicts, thus performing self-separation.

### 2.1 In-Trail Procedure (ITP)

In-trail Procedure allows changing flight level in one-direction flow in procedural airspace on a more frequent base. Figure 1 demonstrates the idea of the procedure.

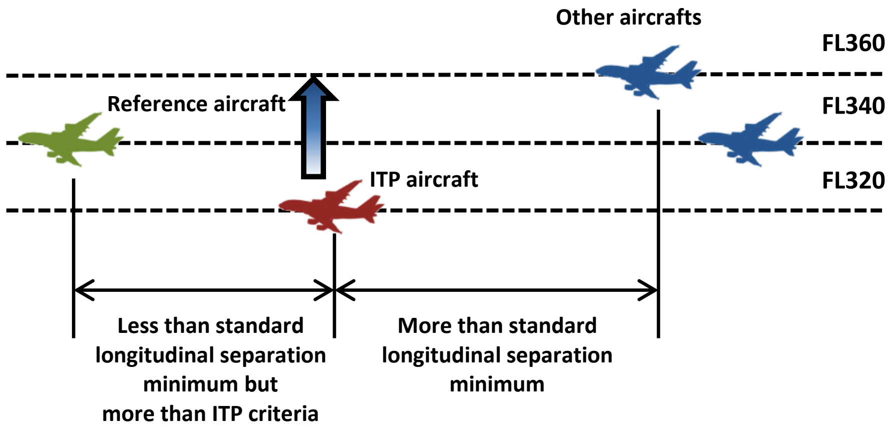


Figure 1: In-Trail Procedure

In case of advanced procedure flight level change is possible when standard separation criteria are not fulfilled, but the ITP criteria are fulfilled. The separation minimum is significantly reduced from 80 NM down to 15-20 NM.
The interaction between ATC and pilot during ITP procedure is described in the RTCA document DO-312 [7]. Pilot sets desired flight level and checks ITP criteria, which includes distance, equipment and altitude aspects. If ITP criteria are fulfilled pilot sends ITP request with information about reference aircraft, distance to it and desired flight level. At first ATC checks if the standard separation minimum with all aircrafts will be maintained during the maneuver. If not, ATC checks ITP criteria. If ITP criteria are fulfilled he allows performing flight level change using ITP. Pilot checks the answer, repeats checking ITP criteria just before the maneuver and (if fulfilled) performs ITP and makes report when achieves desired flight level.
ITP was compared with standard flight level change procedure. During this procedure pilot doesn’t have information about surrounding aircrafts. So he sends the request without preliminary checking. ATC allows flight level change only if standard separation is fulfilled.
ITP was studied by Chartrand R. C. at al in [14] and by Carey B. in [15]. It was already aprobated in the North Atlantic area and showed wide prospects.

## 2.2 Flight-Deck Interval Management (FIM)

Flight-deck interval management procedure is an airborne procedure for longitudinal interval management toward reference aircraft. This interval can be achieved by speed maneuver or turn maneuver. All calculations for the manoeuvres take place on-board. Figure 2 illustrates the idea of the FIM procedure.
Principal document for FIM procedure is the RTCA document DO-328 [9]. The FIM procedure is initiated by ATC. Controller sets the reference aircraft, Interval Management (IM) aircraft, which has to perform manoeuver, and required time interval. After that he sends the command to perform speed maneuver. Avionics calculate needed speed and pilot checks, if it is possible according to aircraft performance characteristics. If not, pilot informs ATC. Then ATC sends the command to perform turn maneuver. Avionics calculate necessary data and pilot checks if it is possible. If yes, pilot performs turn maneuver and reports when passes start point, turn point and merge point.
During the standard interval management procedure all calculations take palace on ground. If speed maneuver is impossible, ATC sends command to go to holding zone.
FIM procedure was studied by J. Thipphavong at al in [16] and T.J. Callantine at al in [17].

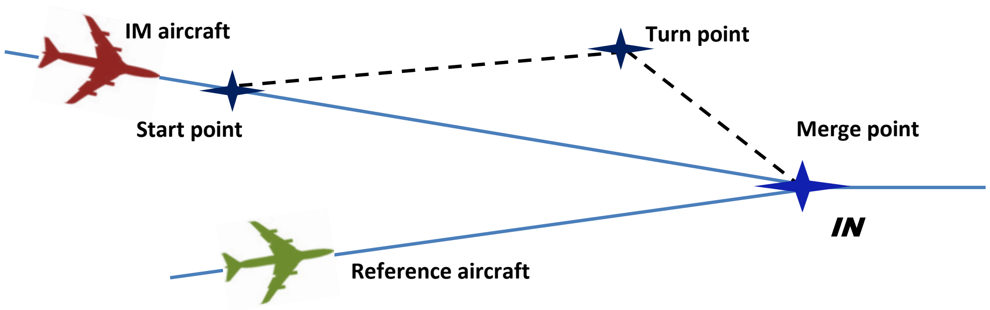


Figure 2: Flight-Deck Interval Management procedure

## 2.3 Airborne Conflict Management (ACM)

Airborne Conflict Management procedure is airborne conflict prediction, detection and resolution by self-separation.
The illustration of self-separation is performed on the Figure 3. The idea of this method is to prevent crossing of protection zones and at the same time to minimize the deviation from the route. Operational concept for the ACM application presents in RTCA document DO-263[11].
ACM procedure can be performed in the defined airspace area (e.g. sector). When aircraft enters this sector pilot checks if aircraft is prepared for self-separation. If yes, pilot requests self-separation. ATC checks, if it is possible to perform self-separation. If yes, allows to do it. Later in case of potential conflicts pilot performs self-separation. At the border of the sector he requests ATC control.
During standard procedure ATC sends commands for conflict resolution. For example – command to change flight level. Pilot performs only ATC commands.
Conflict Detection and Resolution methods were widely studied by K.Billimoria, et al. [18], M. Eby [19], K. Zeghal [20], E. Wallace and I. Kelly [21].

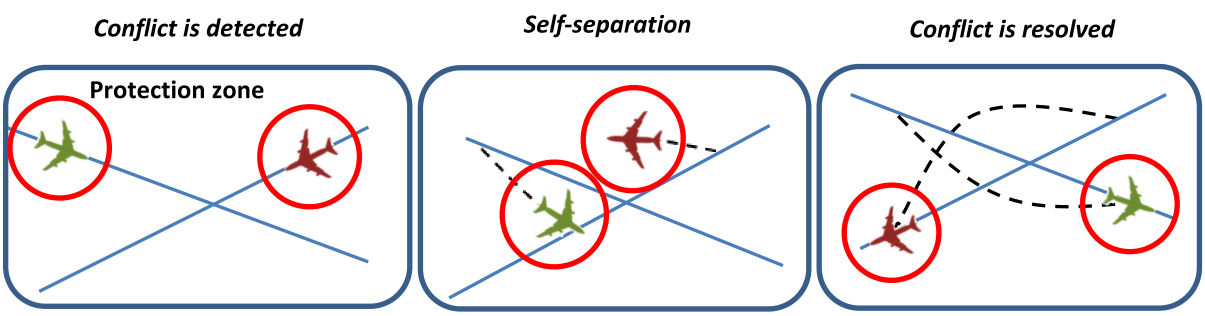


Figure 3: Airborne Conflict Management procedure

## 3. Simulation and Research tool

The research tool used in the study is the Stand for hardware-in-the-loop and human-in-the-loop simulation of Air Traffic Management System (KIS UVD). This stand was developed in Russian Federation State Research Institute of Aviation Systems (GosNIIAS). The stand is designed for

- research of airborne and ATC procedures;
- demonstration of airborne and ATC procedures;
- testing of pilot and ATC human-machine interfaces;
- estimation of potential benefits of new airborne procedures;
- testing of advanced technologies of air traffic management systems (e.g. flow management technologies).

The stand allows conducting distributed simulation across multiple host computers or workstations. Stand components involved in the simulation can be located even in different cities. Configuration of models or workstations involved in the simulation may vary depending on the research goals. The stand can include both mathematical models and human-in-the-loop simulators (e.g. cockpit simulator, ATC workstation, etc.). All components interact through the protocol based on TCP/IP. Involved components should be connected to server host. The server synchronizes components and manages the simulation process. This server is called The Research Manager Workstation. This workstation is a core of the stand. The Research Manager Workstation allows

- to create, configure simulation scenarios;
- to set preferences of models and workstations for current experiment;
- to control the simulation process (2D and 3D visualization);
- to analyse results of simulation, generate reports.

Simulation scenarios include information about airspace structure, flight plans, meteodata, start and end time of simulation, settings of ATC workstation and much more other information. This large amount of information is stored in the common database. All components can be connected to the database, but it is not necessarily, since at the start of the simulation The Research Manager Workstation sends basic information about the scenario to all components. At the current time the following mathematical models and workstations are developed and can be connected to the stand (both own and third-party developments) for simulation (figure 4):

1. Three different cockpit simulators (DKS IMA, Sukhoi Superjet, Irkut MC-21);
2. Two Air Traffic Controller’s workstations – real workstations from Moscow Air Traffic Control Centre;
3. Air Traffic Flow Management workstation – real workstation from Main Air Traffic Management Centre of Russian Federation;
4. AMAN workstation – Arrival flow management position;
5. DMAN workstation – Departure flow management position;
6. A-SMGCS workstation – Advanced Surface Movement Guidance & Control System;
7. Ground vehicles model;
8. Ground surveillance model;
9. Ether model;
10. Weather model;
11. Air traffic model;
12. ATC system model;

Depending on the stand configuration the simulation can be conducted in two modes: real-time mode and fast-time mode. Real-time mode is used for human-in-the-loop demonstrations and experiments, fast-time mode is used for fast multiple run simulation without human interaction.

## 4. Simulation studies

The research of advanced airborne procedures was conducted by means of simulation in real-time and fast-time modes. During real-time human-in-the-loop simulation the stand is configured of research manager workstation, ATC workstation, cockpit simulator and air traffic model. In this mode all operations of pilot and ATC are performed by corresponding operators. During the research the interaction between participants of procedures were demonstrated and different pilot and ATC interfaces were approbated.

In fast-time mode the simulation of each advanced procedure and corresponding standard procedure was performed. After multiple run simulation with statistics collection the comparative analysis was made. The research of each ADS-B procedure in fast-time mode consisted of the following stages: preparation stage, simulation and data processing.

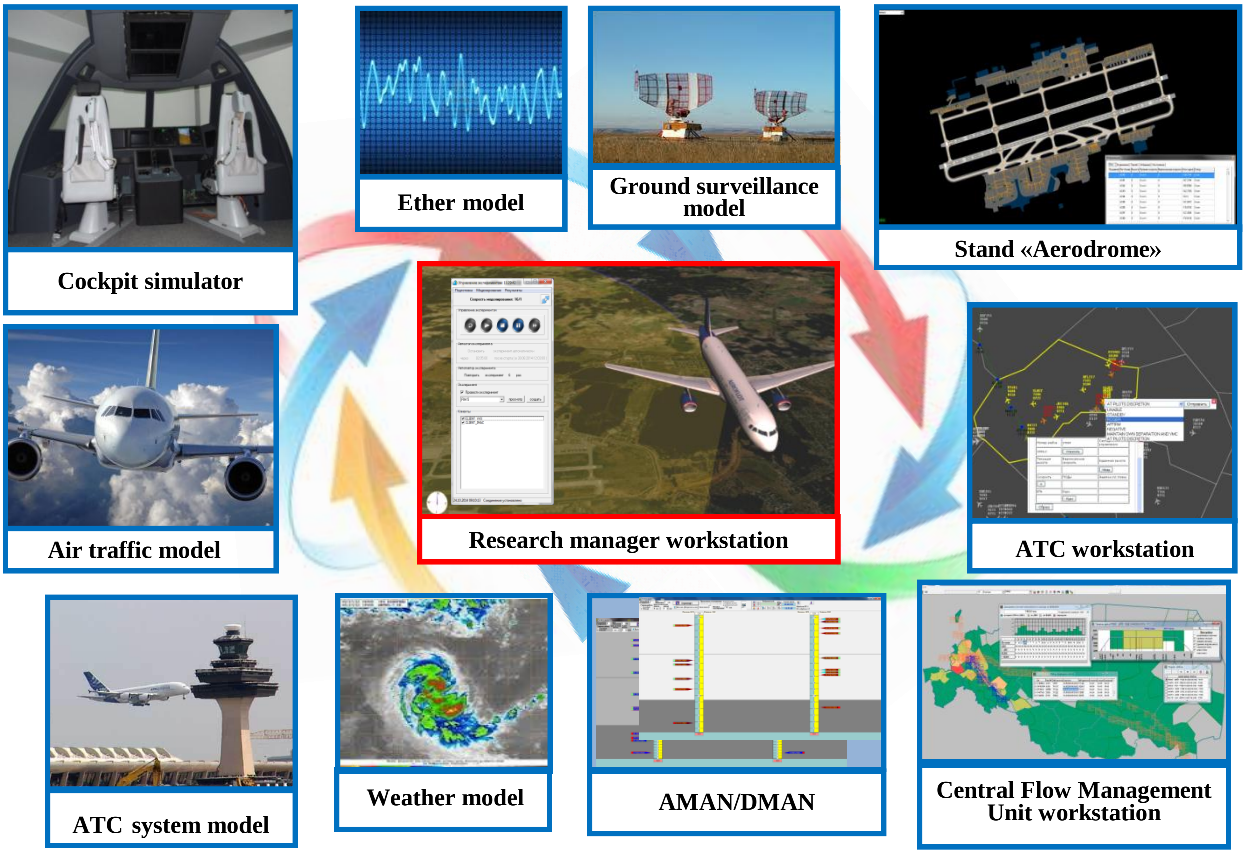


Figure 4: The research Stand for hardware-in-the-loop and human-in-the-loop simulation of Air Traffic Management System (KIS UVD)

## 4.1 Preparation stage

The first stage of the research is preparation stage, during which the scenario is constructed. The research manager

- chooses or creates new air traffic flow using prepared library of flights (for each aircraft sets time of departure, flight level, equipment);
- configures the stand depending on the simulation mode and research goal;
- sets parameters of simulation process;
- sets parameters of random factors.

The optional random factor is the time of departure from the airport. This factor changes relative aircrafts position and causes changes in the performance and the results of the procedures. The departure time was set as a random value with normal distribution with mean as scheduled time and variance chosen by research manager: $N \sim (T_{plan}, \sigma)$.

For the research of CNS procedures the special scenarios with high density air traffic were created. It was assumed that all aircrafts are equipped with all necessary avionics (ADS-B IN and OUT, ITP, FIM, ACM avionics).

For ITP the airspace under Khabarovsk and Irkutsk ATC centres was chosen. It was assumed that chosen airspace was under procedural control. The main features of this airspace are long distance routes and high density traffic from Europe to Asia. Also one-direction air traffic flow was created.

For FIM procedure air traffic flow included potential conflict situations at the merge point. As a merge point the enter point "IN" to the Moscow terminal area was chosen. Studied airspace has a high congestion most of the time.

For ACM procedure the airspace under Kirov ATC centre was chosen. Several domestic and international routes cross in the chosen sector. High density air traffic on one flight level was created, so during the simulation process a lot of potential conflicts, which needed detection and resolution, accrued.

## 4.2 Simulation

The next stage is the simulation process. Two sets of runs for each CNS and standard procedures in equal conditions were conducted. For the further analysis the exchanged CPDLC messages report is creating and metrics are calculating during the runs. The simulation can be conducted in real time mode or in fast time mode with different timescale. As a result of random factors impact the performance of advanced procedures was different in each run.

The research manager can control the simulation process and watch in 2D and 3D modes. The following information is visualised:

- the map with Russian Federation air structure;
- aircraft position in each moment;
- flight number, altitude and ground speed for each aircraft;
- exchanged CPDLC messages.

Figure 5 presents the 2D visualisation of the airspace and air traffic flow for FIM procedure.

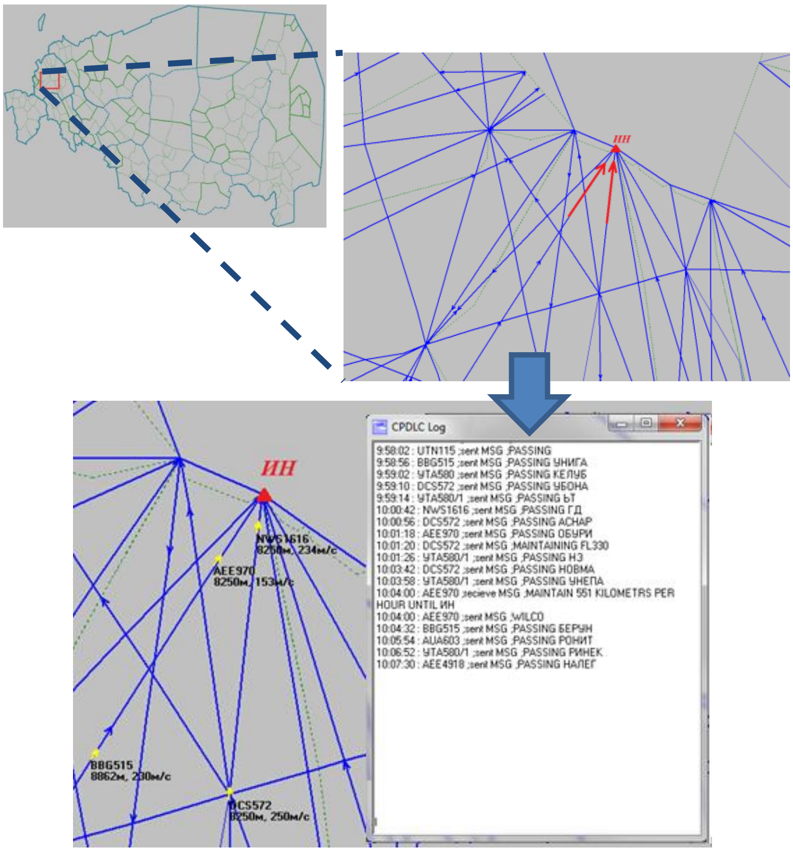


Figure 5: 2D visualisation of the airspace and air traffic flow for FIM procedure

## 4.3 Data processing

The last stage is data processing. The research manager analyses results, constructs diagrams and makes conclusions. Table 1 presents metrics, calculated during simulation process. These metrics were chosen a result of analysis of a big variety of researches [15-21], international conferences [1-3, 16-17] and documents [12]. Metrics refer to the main performance characteristics such airspace access, capacity, procedures efficiency, environment and safety. These metrics are calculated according to Eurocontrol Base of Aircraft Data [13]. Figure 6 presents the example of constructed diagrams – number of flight level changed per run during ITP and standard flight level change procedure.

Table 1: Performance characteristics and metrics

| Performance characteristics | Metrics |
|---|---|
| Airspace access | 1. Percentage of requested flight level versus rejected flight level |
| Airspace capacity | 1. Number of aircrafts in airspace segment per hour<br>2. Number of ATC operations<br>3. Number of aircrafts being under the ATC control at one time<br>4. Number of aircrafts under ATC control per hour |
| Efficiency | 1. Kilograms of fuel per flight<br>2. Average delay caused by queuing and interval management<br>3. Number of exchanged CPDLC messages<br>4. Number of sending to holding zones<br>5. Number of deviations from a route and average time of deviations |
| Environment | 1. Kilograms of CO2 emissions |
| Safety | 1. Number and degree of conflicts<br>2. Number and average time of separation violations<br>3. Number of detected and resolved potential conflicts |

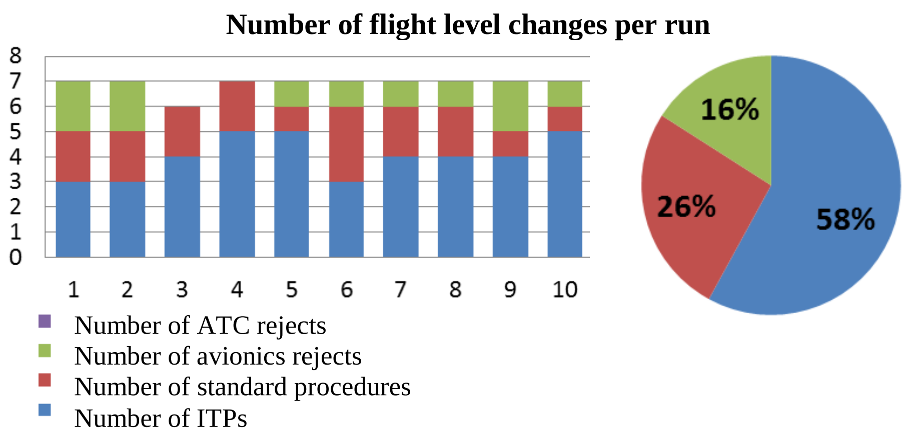


Figure 6: The example of constructed diagrams

## 5. Simulation results

The following results were obtained by simulation using prepeared scenarios.

1. The In-Trail Procedure
    - makes flight level changes more frequent: using ITP procedure flight level change is possible in 84% cases, using only standard procedure it is possible in 55% cases. It increase the access and capacity of airspace;
    - reduces fuel consumption at the average rate of 117 kg per 2 hours. It is equivalent to 369 kg of CO2 emissions;
    - decreases pilots and ATC workload: decreases the number of exchanged CPDLC messages and the number of ATC operations at the average rate of 27%.
2. The FIM procedure
    - decreases the ATC workload, number of interval management operations reduced by 48%. With FIM procedure ATC does not calculate speed and holding zone operation parameters;
    - increases the number of CPDLC messages connected with reports;

- reduces fuel consumption in average on 22,6 kg per one aircraft, reduces CO2 emissions in average on 71,3 kg;
- reduces delays in average on 35 seconds (6%).

3. The ACM procedure
- decreases the ATC workload, number of conflict management operations reduced by 25%, time consumed on conflict management procedures reduced by 40%, time consumed on all procedures reduced by 18,5%;
- does not lead to serious changes in fuel consumption and CO2 emissions;
- does not lead to serious delays in the sector;
- increases the number of potential conflicts, so requires additional research of influence on safety.

## 6. Conclusion

The research of advanced airborne CNS procedures was conducted by the research Stand for hardware-in-the-loop and human-in-the-loop simulation of Air Traffic Management System (KIS UVD) in 2013-2014. As part of the research the following CNS procedures were reviewed: ITP (In-Trail Procedure), FIM (Flight-Deck Interval Management), ACM (Airborne Conflict Management).
During real-time human-in-the-loop simulation the following participants were involved: ATC workstation operator and operator of the advanced cockpit simulator (called DKS IMA). Fast-time simulation in automatic mode was conducted without operator’s participation.
During the work:
- the cooperation of pilot and ATC during advanced CNS procedures was approbated;
- the human-machine interfaces of CNS procedures for pilot and ATC were tested;
- CNS procedures in high air traffic conditions with the impact of random factors were tested;
- the quantity characteristics of changes caused by using new CNS procedures were calculated;
- CNS procedures were compared with standard procedures.

The results of research showed prospects of using new CNS procedures and the need of future researches. The work showed that research stand can be used for simulation and research of airborne and ATC procedures.
The future research trends are:
- the research of airborne procedures in different air traffic intensity and in conditions where one part of aircrafts is equipped with ADS-B, ITP, FIM, ACM avionics and another part is not equipped;
- the research of FIM procedure on STAR;
- the simulation and research of other ADS-B-based procedures (ASIA, SURF);
- the research into airborne procedures, connected with weather hazard avoidance;
- the research into airborne procedures using the real air traffic.

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