A FAST-TIME SIMULATION STUDY OF SHARED AIRCRAFT INTENT INFORMATION

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Abstract

The combination of flight management systems with data links could make aircraft intent information in the form of accurately predicted trajectories available to both ground-based air traffic control systems and other aircraft. The chief benefit to be expected from this capability is that it could make feasible the use of automated tools for detecting aircraft conflicts and for proposing resolution manoeuvres for such conflicts (automated CD&R tools).

The INTENT Project, jointly funded by the European Commission and a Consortium of research organizations and industry, is studying the question of how the level of sharing of aircraft intent information might affect air traffic management (ATM) system design and traffic-handling capacity. The study reported here is the fast-time simulation component of the INTENT Project.

This paper presents results on human workload for three different ATM operational concepts for use of intent-enabled automated CD&R tools in en-route airspace, and interprets these in terms of traffic handling capacity. The results indicate a potentially large capacity benefit for systems where aircrews supported by automated CD&R tools have the main responsibility for ensuring safe separation. The paper also presents some results on the effect of intent-based CD&R on flight efficiency.

Introduction

The combination of aircraft flight management systems with air/ground or air/air data links could make aircraft intent information in the form of accurate predicted trajectories for the next 20 or more minutes available to both ground-based air traffic control systems and other aircraft. This capability might reasonable be expected to have a significant effect on the mode of operation and performance of future air traffic management (ATM) systems.

The INTENT Project, initiated in 2001, is studying the question of how the level of sharing of aircraft intent information might affect ATM system design and traffic-handling capacity of en-route airspace. The project is funded jointly by The European Commission and an international consortium[1] of research organizations and industry, and is being carried out by this consortium.

The fundamental processes involved in keeping aircraft safely separated are: checking predicted separations to find potential infringements of separation rules, known as conflict detection (CD), and finding manoeuvres that avoid such infringements, known as conflict resolution (CR). In today's systems air traffic controllers carry out these processes mentally, but the availability of accurately predicted trajectories 20 or more minutes ahead could make feasible the use of automated tools for predicting conflicts and for proposing possible resolutions to controllers or pilots; these tools are collectively referred to as automated CD&R. The INTENT Project has assumed that most of the benefit to be derived from shared aircraft intent information will arise from the fact that it enables use of automated CD&R. The project is comparing three distinct operational concepts in which shared aircraft intent information might enable the use of such tools:

[1] The consortium comprises Stichting Nationaal Lucht- en Ruimtevaartlaboratorium (NLR), QinetiQ, Office National d'Etudes et de Recherches Aerospatiales (ONERA), Eurocontrol, Delft University of Technology, Rockwell-Collins France, Smiths Aerospace, AIRBUS, European Cockpit Association, Association of European Airlines. For further details see the project website at www.nlr.nl/public/hosted-sites/intent/intent.htm

1. A concept where air traffic control is done by ground-based controllers using highly structured airspace with airways, much as today, but with the addition of automated CD&R tool support for controllers.
2. As 1, but with all traffic flying direct routes instead of using airways.
3. A concept where aircrew (supported by automated CD&R) rather than ground-based controllers have the main responsibility for maintaining safe separation. This concept also assumes all direct routes.

Computer simulation is the chief method being used to make comparisons between these operational concepts. Three phases of simulation were planned:

1. A series of real-time part-task simulations involving qualified pilots and air traffic controllers, to demonstrate some automated CD&R techniques, and to establish some human workload models.
2. A series of fast-time simulations to collect data over a much larger airspace and a much larger set of traffic scenarios than would be practicable in real-time simulation.
3. A series of full-task real-time simulations to demonstrate and further explore the options that look most promising from the fast-time simulations.

The two real-time phases are being undertaken by NLR in The Netherlands and the fast-time phase is being undertaken by QinetiQ in the UK. Delft University of Technology, ONERA and The Eurocontrol Experimental Centre have all made substantial inputs to the design of the simulations and the concepts to be simulated.

The remainder of this paper will be concerned with the fast-time simulations, but it will be necessary to quote some results from the real-time part-task simulations.

Airspace Capacity

At peak times the ATM systems in many parts of Europe operate at or close to capacity. One indication of this phenomenon is the frequency of occurrence of air traffic flow management delays (ground holding delays). In 2001 approximately 20% of flights in Europe suffered such delays, and approximately 80% of the delay arose from airspace rather than airport causes [1]. Although there has been a temporary halt to traffic growth, Eurocontrol's current medium term forecast [2] predicts growth in the region of 3.4% per annum for most of the current decade. In recent years traffic-handling capacity has increased slightly faster than traffic volume, mainly through reorganization of airspace, but such reorganization cannot be repeated indefinitely, so there is on-going interest in technological means of increasing airspace capacity. Shared aircraft intent information is potentially one such means.

It is now almost universally accepted that the primary cause of current capacity limits in en-route airspace is controller workload. When a present-day system is operating at capacity air traffic controllers only just have enough time to do all the things that must be done: detecting conflicts and taking avoiding action, communicating with aircraft, co-ordinating with neighbouring sectors, maintaining situation awareness etc.; they do not have enough spare time to handle additional flights safely. So the INTENT Project has chosen to tackle the airspace capacity problem via controller/pilot workload.

The project used its real-time part-task simulations [3, 4] to develop statistical models of controller and pilot workload, and these models were inputs to the fast-time simulation phase being described here. The general approach to model development was to ask controllers and pilots participating in the real-time part-task simulations to rate their workload on a scale of 1 to 5 at 2-minute intervals, and to look for correlations between these instantaneous self assessment (ISA) scores and various traffic complexity factors. The complexity factors considered included Dynamic Density and its components [5] and the Delahaye complexity metrics [6]. The chosen models are summarized in Table 1. Each model was also provided with a limiting value indicating where workload becomes unacceptably high.

Table 1. Controller and Pilot Workload Models

planning controller	$W_{PC} = a_1 + a_2\, DE + a_3\, OUT - a_4\, TO$
tactical controller	$W_{TC} = b_1 + b_2\, N + b_3\, N^- - b_4\, TO$
flying pilot	$W_{FP} = c_1 + c_2\,\mathrm{CON} + c_3\,\mathrm{H} - c_4\,\mathrm{C}$
non-flying pilot	$W_{NP} = d_1 + d_2\,\mathrm{CON} - d_3\, I + d_4\,\mathrm{X}$
Where the symbols have the following meanings	
N	number of flights in sector at end of 2-minute period
N^-	number of flights in sector at end of previous 2-min period
OUT	number of flights that left the sector during 2-minute period
TO	= 1 if CD&R tool is in use, = 0 otherwise
X	number of other aircraft in a specified volume surrounding the subject aircraft
CON	number of conflicts involving subject aircraft in last 2 mins
I	= 1 if intent information is in use, = 0 otherwise
H	the CD&R time horizon in minutes
DE	the Delahaye density evaluated with $\alpha = 3.0$
C	the contribution of the subject aircraft to the Delahaye Convergence metric, evaluated with $\alpha = 0.1$
a_i, b_i, c_i, d_i	constant coefficients

The Fast-time Simulations

Some Assumptions

Modern flight management systems can predict aircraft trajectories very accurately, so the simulations assumed that ground-based control systems and aircraft receiving intended trajectories had completely accurate knowledge of those trajectories out to some time horizon (20 minutes was the maximum horizon used). Features of data communications systems (delay, message formatting, numbers of trajectory change points, etc.) were not simulated.

It was assumed that conflict-avoiding action requested by ground controllers or taken by aircrew was initiated immediately. This assumption might at first be found surprising, but it should be remembered that the large majority of conflicts were detected at the time horizon for intent information which had values between 5 and 20 minutes in the simulations performed.

Airspace

The airspace used for the fast-time simulations was a region of Western Europe bounded by the meridians at 0° and 16° East, and by the parallels at 47° and 52° North. Within this region there were nine sectors of *measured* airspace as shown in Figure 1; the rest of the region was considered *feed* airspace. The measured airspace included all flight levels at and above flight level 245; the feed airspace extended down to ground level.

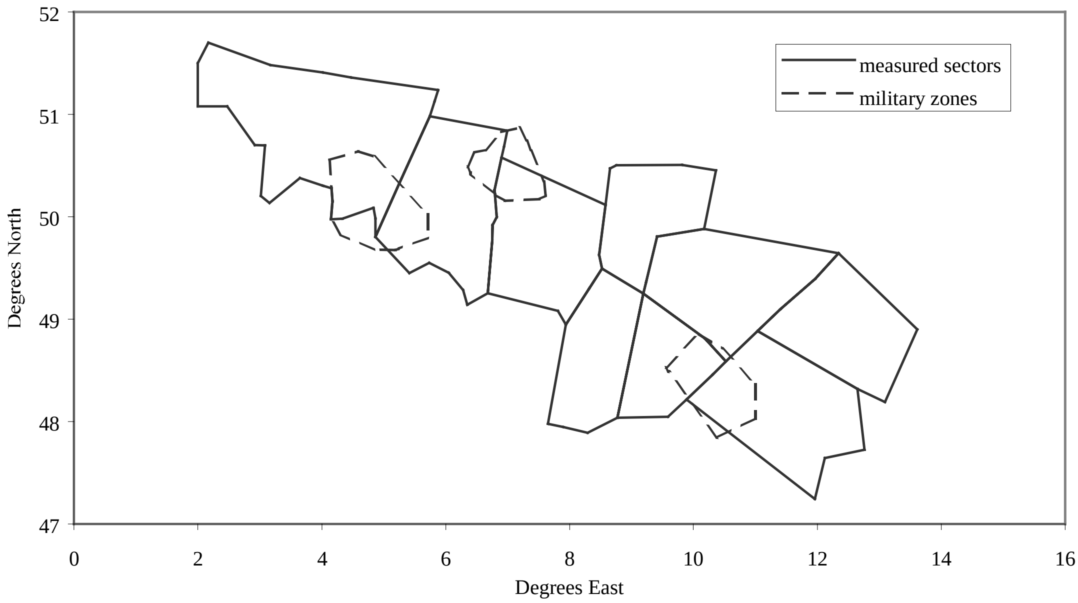

Fig. 1. The Airspace Simulated

The feed airspace had two important functions:

1. To get the traffic entering the measured airspace into a state typical of what would be produced by ATM systems operating in neighbouring airspace. In particular, flights should not be in conflict when entering the measured airspace.
2. To provide an environment for CD&R operations in the measured airspace. If, for example, the time horizon for intent information was set to 15 minutes, an aircraft might be 120 miles and/or 30,000 feet away from the start of conflict at the time of detection. Although a detected conflict could be close to ground level, the simulation restricted resolution to those above flight level 120 because lower levels were considered to be the province of terminal rather than en-route operations.

For the two operational concepts involving ground-based control, workload metrics were calculated for each sector in the measured airspace. For the concept involving airborne CD&R, sectors were not used directly, but the outer boundaries of the sectors shown in Figure 1 were still used to define measured airspace.

It was assumed that there were three military zones in operation that must be avoided by all civilian traffic, as shown in Figure 1. These significantly constrained the routes flown and the options available for conflict resolution.

Traffic

Traffic samples for the simulations were produced by the method developed by Eurocontrol's CARE INTEGRA Project, [7]. According to this method, a statistical summary of traffic flows called a Traffic Pattern Description (TPD) is produced by analysing historical traffic data, and individual pseudo-random traffic samples are generated from the TPD by a Traffic Sample Generator program. The INTEGRA method has two important advantages: once a TPD has been produced, as many different and independent samples as required can be generated simply by using different random number seeds; and the generation process can easily be scaled to produce different traffic densities.

TPDs for the INTENT simulations were produced by analysing archived flight plan data from Europe's Central Flow Management Unit for a six-week period in the summer of 2000. Two TPDs were produced, one representing morning peak conditions, the other representing afternoon/evening peak conditions. Three 11-hour traffic samples were generated from each TPD for each of the traffic densities required. No data was collected for the first hour of each sample; this period allowed the simulated system to make the transition from no traffic to peak conditions. Thus 60 hours of data was collected for each combination of experimental conditions.

Experience from the part-task real-time simulations suggested that, in the ground-based control concepts controllers were slightly overloaded at 1.7 times 2000 traffic levels, but that in the airborne CD&R concept pilots were not overloaded at 4 times current levels. Therefore the project chose to use traffic densities of 1.0, 1.3 and 1.7 times 2000 levels for the former and 1, 2 and 4 times 2000 levels for the latter.

Conflict Detection

In addition to intent-based automated CD which was the primary focus, two other forms of CD were simulated for purposes of comparison. These were: manual CD to represent what controllers do without automated tool support, and state-based CD to represent a possible alternative automated CD tool for use by aircrews.

The fast-time simulator was set up to test for conflicts every 10 seconds of simulated time. The intent-based CD process is in principle straight-forward: consider each distinct pair of flights in turn, step along the predicted trajectories for the pair by equal time steps, calculate and test the separation after each step. However this process requires a significant amount of computation and in fact dominates simulation run time. To illustrate this point, at Summer 2000 traffic density there are about 400 flights in our simulated airspace which means that there are about 80,000 distinct aircraft pairs, and with a time horizon for intent information of 15 minutes there are 90 steps for each pair.

The conflict detection process can be speeded up considerably by the following observation: if a pair of flights was conflict free to the time horizon after the previous time step and neither flight has deviated from its intended trajectory, then it is only necessary to test the separation of the pair at the time = now + horizon. This approach was implemented, and did make a substantial difference to simulation run time.

For manual CD it was assumed that controllers know the intended path of a flight from the filed flight plan and current clearances, and have some knowledge of its position and speed from radar tracking. Manual CD was modelled in much the same way as intent-based CD, but horizontal and vertical speed uncertainties were included, so that more situations were treated as conflicts than in the intent-based case. The time horizon used for manual CD was 10 minutes.

For state-based CD it was assumed that each aircraft knows the position and velocity vector of every other aircraft, but does not know in advance about changes in velocity vectors. The approach of stepping along predicted trajectories was again used, but in this case the predicted trajectory was a segment with constant velocity vector. It was necessary to check the whole segment from current position to time horizon (and not simply the point at the time horizon) every time an aircraft's velocity vector changed.

Experience from the part-task simulations suggested that for the ground-based concepts, the precise value of the intent horizon had little effect, whereas for the airborne concept it did have a significant effect. Consequently two CD&R scenarios were simulated for the ground-based concepts, no intent (manual with a 10 minute time horizon) and intent information with a 15 minute time horizon, and four CD&R scenarios were simulated for the airborne concept, no intent (state based with a 5 minute time horizon) and intent information with horizons of 5, 10 and 20 minutes.

Conflict Resolution

A fairly simple form of conflict resolution was simulated. Each conflicting pair was treated as follows:

1. A set of rules was applied to determine which aircraft should manoeuvre, allowing the other aircraft to continue without manoeuvring. If no resolution was found by manoeuvring this aircraft

then an attempt was made to find a resolution by manoeuvring the other member of the pair.

2. An attempt was made to find both a vertical manoeuvre and a horizontal manoeuvre that would resolve the conflict. If both were found, then a random choice with equal probabilities was made between them.
3. When searching for resolutions, three tests were applied to each resolution considered:
    a. Does it resolve the conflict being considered?
    b. Is it conflict free, i.e. does it generate any new conflicts and does it resolve all other conflicts in which the subject aircraft is involved?
    c. Does it violate any military zones?

The rules used to determine which aircraft to manoeuvre were as follows:

1. If one member of the pair is involved in more conflicts than the other, then it is chosen to manoeuvre.
2. Otherwise, if both aircraft are in different phases of flight, then a climbing aircraft is chosen to manoeuvre in preference to a cruising or descending aircraft, and a cruising aircraft is chosen in preference to a descending aircraft.
3. Otherwise, if both aircraft are in the same phase of flight then the one furthest from the conflict (the one with the highest ground speed) is chosen to manoeuvre.

When trying to find a vertical manoeuvre to resolve a conflict, the manoeuvres considered depended upon the state of the aircraft to manoeuvre. If the aircraft was in the climb or descent phase at the onset of conflict, then the type of resolution considered was temporarily stopping-off the climb or descent at a level intermediate between the aircraft's current altitude and its altitude at the onset of conflict. If it was in cruise but near top of descent, then the type of resolution considered was early or late descent. If it was in cruise and not near top of descent, than an attempt was made to find a new cruise level by considering levels below and above its current level in increasing steps from its current level.

When trying to find a horizontal manoeuvre to resolve a conflict, the first resolution considered was skipping the next waypoint and going directly to the following one. If this was unsuccessful, then vectoring by increasing amounts each side of the aircraft's current track was considered.

Simulation Software

The project made use of a package of software called FLAME (FLexible Airspace Modelling Environment) which was developed by QinetiQ for ATM research applications. It has previously been used for several such applications including [8, 9]. FLAME simulates the movement of flights through airspace, collects statistics on quantities of interest, and provides traffic displays for scenario validation purposes. The chief benefit of FLAME for the present application is that it is more a kit of parts for building simulations than a monolithic simulator, so that for example, required CD&R methods and required workload metrics could easily be built into it.

Results

Controller Workload

Workload was computed for planning and tactical controllers in the two ground-based operational concepts (airways and all-direct-routes) by using the models summarized in Table 1 above. Workload values were calculated every two minutes for each of the sectors in the measured airspace and statistics were accumulated throughout the measured time of each simulation run. Obviously it is peak and near-peak workload that is of the most interest, so the 95th percentiles of workload scores were accumulated; these percentiles were estimated without storing individual observations by using the methods of Jain and Chlamtac [10]. Resulting percentiles for planning and tactical controllers averaged over the three busiest sectors and the six simulation runs for each set of experimental conditions (direct/airways routeing and intent time horizon) are shown in Figures 2 and 3.

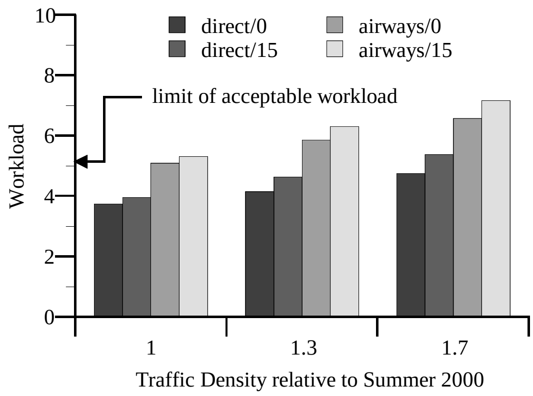

Fig. 2. 95th Percentiles of Workload Scores for Planning Controllers

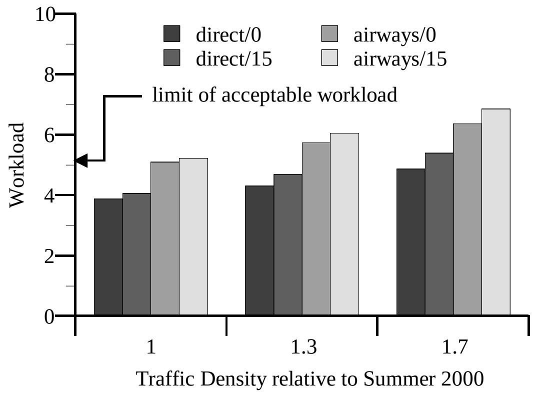

Fig. 3. 95th Percentiles of Workload Scores for Tactical Controller

The following conclusions can be drawn from the graphs in Figures 2 and 3:

1. Workload for both controllers is higher in airspace structured with airways than in airspace where all traffic flies direct routes.
2. Workload for both controllers is a little higher with automated CD&R support than without it.
3. With airways and no automated CD&R, workload is at the limit of acceptability for the Summer 2000 traffic density; with all-direct-routes it almost reaches the limit at 1.7 times this traffic density.

The first conclusion is not too surprising because airways tend to concentrate traffic into smaller volumes of airspace than direct routes, and is consistent with the results from some previous studies [9]. The third conclusion concurs with experience from the part-task simulations. However the second conclusion is surprising and requires explanation.

We believe that at least part of the cause of conclusion 2 is as follows: In the simulations, intent-based CD&R assumed exact knowledge of future aircraft trajectories whereas manual CD&R assumed significant uncertainties in this knowledge. This difference causes the manual CD&R to treat more situations as conflicts and take resolution action than the intent-based CD&R. Extra resolutions in the feed sectors cause some flights not to enter the measured sectors which otherwise would have done so (they are either given lower cruise levels or are vectored horizontally). Thus, for the same traffic sample, the measured sectors have lower aircraft counts with manual CD&R than with intent-based CD&R. This leads to an apparent reduction in workload for the manual case.

The conclusion from this part of our study must be that, if there is a workload and capacity benefit for ground-based controllers from automated CD&R enabled by shared aircraft intent information, then it is a very small benefit.

Pilot Workload

Workload was computed for the flying and non-flying pilots in the airborne CD&R operational concept using the models indicated in Table 1 above. Workload scores were calculated every 2 minutes for each aircraft in the measured airspace and statistics were accumulated throughout the measured time of each simulation run. Again, the 95th percentile of workload observations was estimated as described for controller workload above, and percentile values obtained were averaged over the six simulation runs for each intent time horizon. Results for the flying and non-flying pilots are shown in Figures 4 and 5.

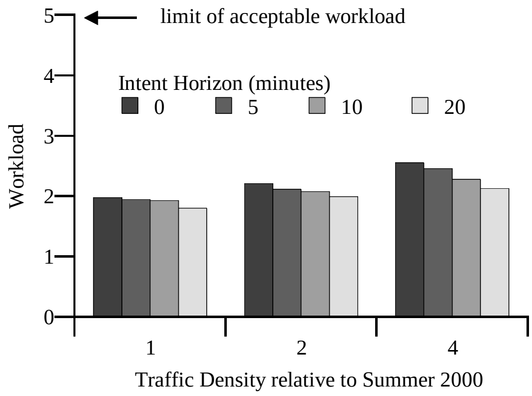

Fig. 4. 95th Percentile of Flying Pilot Workload

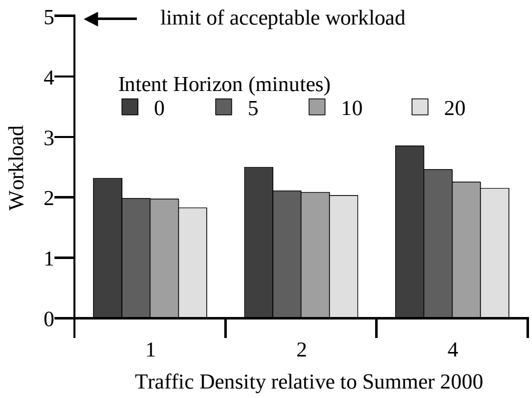

Fig. 5. 95th Percentile of Non-flying Pilot Workload

The main conclusions that can be drawn from the graphs in Figures 4 and 5 are:

1. For a given traffic density, workloads for both pilots are less with intent-based CD&R than without it.
2. Workloads for both pilots tend to decrease slightly as the intent time horizon is increased.
3. Even at four times the traffic density for Summer 2000, the workloads for both pilots are well below the acceptable limits.

Comparing Figures 2 and 3 with Figures 4 and 5, it is striking that with intent information, pilot workload scores are about half the acceptable limits with four times the Summer 2000 traffic, whereas controller workload scores exceed the limits with 1.7 times this traffic density. The comparison suggests that an ATM system for en-route airspace where aircrews supported by appropriate automation have the main separation responsibility has a much greater traffic-handling capacity than one where ground-based controllers supported by similar tools have that responsibility. This result is of course dependent on the fidelity of the workload models of Table 1 which the present study took as inputs. However, the workload models would need to be in error by very large amounts to reverse the conclusion about relative airspace capacities.

In one sense the airspace capacity result is not surprising. If human workload is at the heart of the airspace capacity problem, then distributing the work of a pair of sector controllers over 20 or more pairs of pilots is likely to produce only a small workload increment for each pilot. A great deal of research remains to be done to show that complete delegation of separation responsibility is a viable concept, but this result gives a strong incentive to do that research.

Flight Efficiency

The resolution of conflicts leads to aircraft flying routes or flight levels that differ from those originally planned, and this in turn leads to additional flight time and fuel consumption. Our simulations accumulated statistics on additional flight time and distance, and on a rough estimate of additional fuel consumption compared with originally planned routes. Figure 6 shows the means and 95th percentiles of additional time as a function of traffic density and intent horizon for simulations of the airborne CD&R concept; results for additional distance and fuel consumption follow similar patterns and are not shown.

From Figure 6 it can be seen that the additional flight time caused by conflict resolution is reduced by nearly 50% by use of intent information compared with the no-intent case. The additional time then increases slightly as the intent horizon is increased; however this latter effect is so small that it is probably an artifact of the experimental setup.

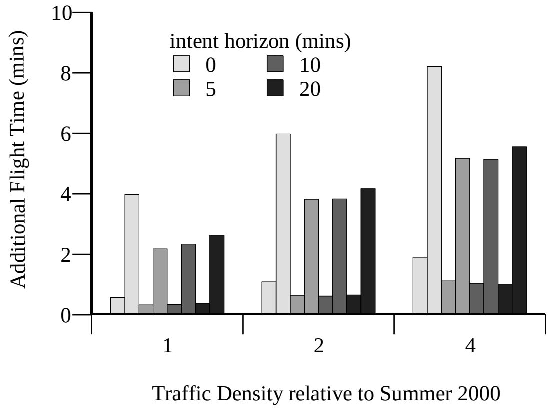

Fig. 6. Means (short bars) and 95th percentiles (long bars) of additional flight time caused by conflict resolution

Additional flight time increases as traffic density is increased because the probability of a flight having a conflict is increased, and because the difficulty of finding a conflict-resolving manoeuvre is increased. For a traffic density of 4 times that for Summer 2000, the mean additional flight time is about 1 minute and the 95the percentile is about 5 minutes.

Concluding Remarks

This paper has described a fast-time simulation study of automated CD&R enabled by shared aircraft intent information, which was carried out as part of the INTENT Project, jointly funded by the European Commission and an international consortium of research organizations and industry. The study focused on human workload and airspace capacity for three different operational concepts.

The most striking result from the study is the following: If aircrews supported by automated CD&R tools have the primary responsibility for maintaining safe separation, pilots are far from being overloaded when the traffic density is 4 times that of Summer 2000, whereas if ground-based air traffic controllers supported by similar automated tools have this responsibility as today, they are clearly overloaded at 1.7 times the traffic density for Summer 2000; compare Figures 2 and 3 with 4 and 5. As pointed out above, this result depends on the fidelity of the workload models used, but the models would need to be in error by very large amounts to negate it completely. The result makes a very strong case for further research into ATM systems where aircrews have the primary responsibility for ensuring safe separation.

Workload scores for both flying and non-flying pilots are reduced by intent-based CD&R compared with state-based CD&R (the no-intent case). Workload scores tend to decrease as intent time horizons are increased, but this is a small effect, so in practice intent horizons are likely to be determined by factors other than workload (such as communications range).

Investigation of the ground-based operational concepts suggests that, in the airspace simulated, use of all direct routes generates less controller workload than use of airways. There is no evidence from the simulations that use of automated CD&R tools increased airspace capacity by reducing controller workload.

Results were presented for additional flight time caused by conflict resolution, Figure 6. Additional flight time was reduced by nearly 50% by use of intent-based CD&R compared with state-based CD&R (the zero-intent case in the figure). Additional flight time was affected only very slightly by the intent time horizon used.

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