Assessing the Impact of Varied Speed Profiles on Airborne Spacing in a Full Flight Simulator

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This paper reports on an experiment conducted with airline pilots on a full flight simulator. The objective was to assess the effect of different positions in chain of aircraft under airborne spacing. Pilots reported several benefits: improved situation awareness, reduction of communications, and better accuracy of achieved spacing. They reported however an increase of workload, requiring for most of them an automatic mode. Despite the basic assistance provided, pilots could maintain the spacing well within tolerances (5 seconds), with on average one action per minute, but with unnecessary speed changes. The relation between required performance and cost induced will be further investigated.

Acronyms

- ADS-B = Automatic Dependant Surveillance – Broadcast
- ASAS = Airborne Separation Assistance System
- FAF = Final Approach Fix
- FMS = Flight Management System
- IAF = Initial Approach Fix
- IAS = Indicated Airspeed
- MCDU = Multipurpose Control Display Unit
- ND = Navigation Display
- PF = Pilot Flying
- PFD = Primary Flight Display
- PNF = Pilot Not Flying

I. Introduction

Airborne spacing involves a new allocation of tasks between controller and flight crew envisaged as one possible option to enhance the management of arrival flows of aircraft. It relies on the ability of the controller to task the flight crew to maintain a given spacing with respect to the preceding aircraft. The motivation is neither to transfer problems nor to give more freedom to the flight crew, but to identify a more effective task distribution beneficial to all parties without modifying responsibility for separation provision 1. Airborne spacing assumes air-to-air surveillance (ADS-B) along with cockpit automation (ASAS). No significant change on ground systems is initially required.

Airborne spacing for arrival flows of aircraft was initially studied from a theoretical perspective through mathematical simulations, to understand the intrinsic dynamics of in-trail following aircraft and identify in particular possible oscillatory effects 2,3,4. The pilot perspective was addressed through human-in-the-loop simulations 5,6,7 and flight trials 8. The flight trials were conducted in the terminal areas on in-trail situations, with different speed control modes (from manual with the support of display cues to a fully automatic). The spacing task was performed successfully with a limited impact on workload but a perceived head-down time higher. The air traffic control perspective was considered through model-based and human-in-the-loop simulations 9,10,11.

The work performed so far at the EUROCONTROL Experimental Centre allowed developing and refining a set of spacing instructions for sequencing and merging arrival flows of aircraft. To gradually assess their operational feasibility, potential benefits and limits, two streams of air and ground experiments are conducted 12,13,14. The previous air experiments showed the feasibility of the spacing task from a flight crew perspective in nominal

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conditions. The air experiment conducted in 2003 considered the complete descent phase with a target under conventional control. The subsequent air experiment conducted in 2004 aimed at going a step further by considering the target being itself under airborne spacing. Despite a workload increase due to the basic cockpit assistance currently provided, the spacing task was still found acceptable and feasible by flight crew. While the immersion of the flight in a realistic air traffic situation enabled to reach a reasonable level of realism, the use of a part task cockpit simulator was found too restrictive by pilots to fully gain confidence on the impact on their tasks.

An experiment took place on a A330 full flight simulator at the Technical University of Berlin in March 2005. Beyond the technical challenge of porting the spacing interface and the air traffic control environment in a simulator certified for training purposes, the objective was, as in 2004, to assess the effect of different positions in the chain, in simulating varied target speed profiles. The paper presents the main findings from this experiment. It is organised as follows: the two next sections will present the spacing instructions and the cockpit interface. The two following sections will briefly describe the technical environment and the simulator characteristics. The next ones will present the experiment design and setup and the main findings.

II. Spacing Instructions

The controller tasks involve sequencing aircraft with the same strategies as today. When appropriate, he/she can task the flight crew to execute an instruction with respect to a designated aircraft (target). Three spacing instructions are proposed and can be applied throughout the arrival sectors, from top of descent down to final approach. These instructions require aircraft to achieve or maintain a particular spacing on common or converging trajectories (Figure 1). For example, with a “heading then merge”, the task of the flight crew is defined as follows: (1) in order to achieve the desired spacing, the flight crew flies an initial heading issued by the controller, and initiates the resume action when the desired spacing is achieved; (2) in order to maintain the desired spacing, the flight crew adjusts the aircraft speed. It should be noticed that the aircraft is not following the target – it is on his own navigation or on vector as instructed by the controller.

As for any standard instruction, the use of spacing instructions is at the controller’s discretion, and he/she can decide to end it at any time. The flight crew can only abort a spacing instruction in case of a problem onboard such as a technical failure. The controller should respect the same conditions as today for sequencing, e.g. compatible aircraft speeds. The use of spacing instructions is composed of three phases: (1) target identification, in which the controller designates the target aircraft to the flight crew, (2) issuing of the spacing instruction, and (3) termination of the spacing instruction. An example dialogue between controller and pilot is as follows:

1. Controller designates the target aircraft using e.g. transponder code (“XYZ, select target 4522”)
2. Flight crew identifies target aircraft (“XYZ, target 4522 identified, 8 o’clock, 30 miles”)
3. Controller confirms the identification (“XYZ, target 4522 correct”)
4. Controller, when appropriate, issues the spacing instruction (“XYZ, continue present heading then merge WPT 90 seconds behind target”)
5. Flight crew continues on heading, then initiates direct when spacing achieved (“XYZ, merging WPT”), then adjusts speed to maintain 90 seconds
6. Controller, when appropriate, cancels spacing (“XYZ, cancel spacing, speed 180 knots”)

![Figure 1. Spacing instructions.](image-url)
III. Cockpit Interface

From the beginning, it was decided to solely rely on graphical cues to support the use of spacing instruction in the cockpit, without any automatic mode (no coupling to the autopilot or to the Flight Management System). The motivation was twofold. Firstly to understand what flight crew could achieve in a manual (“selected”) mode, and secondly to restrict the modifications required during initial phases of implementation.

An initial design of the ASAS interface has been proposed in 2000 and was constantly refined following pilot suggestions. The ASAS features consist in new MCDU pages for data input, and new graphical indications on the ND to visualise the target and to allow the flight crew to perform the necessary actions (direct-to and speed adjustments). On the ND, the ASAS features are (Figure 2):

- **Target aircraft**: The head of the target symbol (triangle) represents the position of the target and the symbol is pointing in the direction of the target heading. The associated data tag provides information on the relative altitude (e.g. –26 for 2600ft below) and on the vertical trend of the target (e.g. ↓ for descending).

- **Reference line**: To highlight the current spacing situation (“merge” versus “remain”), a reference line (double dashed line) links ownship and target aircraft via the merging point in a “merge” situation and through own trajectory in “remain” when under lateral navigation or directly in “remain” when under heading selected.

- **Predicted spacing**: A broken arrow with an arc (\(\rightarrow\)) indicates the geographical position at which the spacing will be acquired.

- **Spacing scale**: Indicates current and required spacing, spacing trend, closure rate, and tolerance margin. It is centred on the current spacing value (yellow line) with lower spacing values at the top of the scale and higher spacing values at the bottom. The range of the scale was set at 2×4 seconds. The current spacing value is indicated in seconds at the left of the scale. The required spacing is materialised by a magenta symbol (triangle) when within scale range, and by the textual value (displayed either at the top or the bottom of the scale depending whether it is smaller or larger than current spacing) when outside range. The spacing trend (green arrow) represents the projected spacing in one minute. The limits of tolerance margin (±5s) are materialised by amber rectangles (caution zone).

- **Suggested airspeed**: Corresponds to the speed value computed by the system in order to acquire and then maintain the required spacing. It is filtered and rounded to multiple values of 5kt. The suggested speed is displayed in green when nominal, in amber when the use of flaps becomes necessary and in red when its value gets outside the flight envelope. When a difference of more than 7kt is detected between the current and the suggested IAS, the header of the suggested speed starts blinking.

- **ND system pilot prompts**: Depending on situations, specific advisory caution or warning messages may be displayed at the bottom of both ND and MCDU.

Tolerance margins were set to ±5s for caution and ±10s for warning.

![Figure 2: ASAS features on ND (left) and detail of the spacing scale (right).](image-url)
IV. Full Flight Simulator and Technical Environment

The simulator (Figure 3) is an Airbus A330 full-flight simulator located in Berlin at ZFB (Zentrum für Flugsimulation Berlin). This simulator manufactured by CAE is certified JAR Level D for training and includes full motion (with six degrees of freedom) and a wide visual display (EP1000CT) for the external view. Besides its use for training, this simulator can also be used as a Scientific Research Facility (SRF). In that case, the simulator uses a second host computer based on IBM RISC 6000 with an ATM network and different research capabilities. This simulator reproduces the complete flight controls, panels, displays and systems of a real aircraft, allowing pilots to perform all the usual flight tasks in automatic or manual. An instructor panel placed in the back of the simulator gives control on external parameters such as the technical status of the aircraft, the atmospheric conditions (e.g. wind, visibility, wind-shear…) and the ground infrastructure (e.g. glide slope inoperative).

The host computer of the SRF offers different programmers’ interfaces in the domains display development, flight management and flight control and guidance. For this purpose the functionality of the original hardware is substituted by software modules which are extendable and modifiable. The following aircraft systems are completely available as software modules:

- Electronic Flight Instrument System and Display Management Computers (EFIS/ DMC),
- Flight Management System (FMS),
- Flight Guidance and Envelope System (FGES) including Autopilot and Autothrust.

![Figure 3: A330 Full-Flight Simulator.](image)

The development team faced several heavy problems during the coding, testing and debugging phase. Mainly it was caused by the complex environment of the Scientific Research Facility and the given processing and network technology compared to the high requirements in precision of ASAS. The flight simulator was set up in 1993. Compared to state-of-the-art technology the processing power of the IBM Risc 6000 Model 580 is relatively low. Also the Ethernet network is using a 10 MBit transfer rate.

Real-time systems using the “Hardware-in-the-Loop”-concept have some disadvantages. Delayed or wrong information can disturb the original hardware. In the case of scarce processing time and loss of network communication caused this effect resulting in unexpected failures of avionic systems like TCAS or GPWS (Ground Proximity Warning System). In addition, high update rates compelled by ASAS of original parts especially like the MCDU can downgrade their functionality. For example, the MCDU seems to work slowly.

Also a disordered communication in a Distributed Simulation Environment with external simulations like the traffic generator can produce unforeseeable functional distortions.

The main technical problems lay in the following fields:

- Scarce spare time (CPU time for processes on the same simulation host but outside the main simulation) caused by the used processing technology and an average CPU load factor of 70 % in full flight mode produced limitations. The time consuming functions for precise calculation of range and bearing and extrapolation algorithms used most of the spare time.
- So called “overruns” occurred due to the high processing time demand. An overrun occurs if the execution time of the synchronous process exceeds the basic frame time of a real-time simulation.
• One stable time reference had to be introduced, because the time reference system was sometimes disturbed by overruns or the synchronisation process with the simulation. This led to drifting times between the master clock and the external clock.
• The existing traffic simulation software GATS (Generic Air Traffic Simulation) by ILR/ TUB had not met the specification of the project. The introduction of new software with higher precision and variable update rate had been necessary. The new tool was then used for experiments.
• Problems with the calculation of suggested speed arose. The atmospheric compensation due to the different altitudes was not accurate enough because of inaccurate entry values available in the simulation. An alternative calculation method had to be found and verified.
• The software FMS as a data source was not always reliable or available along a simulation run. A busy status had to be identified and the resulting information had to be buffered and filtered. In addition, the software FMS had to handle new waypoints. Not all functions are supported for new waypoints in general. A modification of the data base was not available in the development and preparation phase.
• New waypoints, scarce spare time, overruns and design problems of the software FMS also had impact on the stability and reliability of lateral revisions.
• The introduction of a new visual system had had impact on the scenario preparation phase. Many features of the visual scenarios had to be corrected after the installation of the system.

The project schedule had foreseen one major milestone, the so called dress rehearsal, which was performed on the 25th of February 2005. On that day the team was able to come to a decision if a Go or No-Go situation could be detected for the experiments. Due to the fact that all problems were solved, bypassed or minimized if still existing a Go was decided and experiments could be prepared.

V. Experiment Design and Setup

A. Objective
The main objective of the experiment was to assess the effect of airborne spacing in a chain of aircraft, from top of descent down to final approach. A secondary objective for the project, purely technical, was the porting of the spacing interface developed on the EUROCONTROL part task cockpit simulator along with the air traffic control environment, in a full flight simulator certified for training purposes.

B. Scenarios
To vary the position of the aircraft in the chain of aircraft under spacing, we simulated varied target speed profiles with different initial conditions. Among the main factors having an impact, a combination of the following was used:
• The initial spacing deviation which would necessitate speed changes from the crew in order to acquire the required spacing,
• The difference of flight level between own aircraft and the target which could impact the speed profile as one aircraft might be in vertical evolution whereas the other is not.
• The reaction time of the crews from preceding aircraft to changes in suggested airspeed.
• The difference in deceleration capacity of the target aircraft.

Four different scenarios were simulated:
• Scenario 1: The target is under conventional control (standard deceleration capacity). The initial spacing was larger than required.
• Scenario 2: The target speed profile in cruise is representative of a chain effect (4 aircraft with initial spacing alternatively too small then too large). Preceding pilots had a quick reaction time and thus could anticipate the speed reductions.
• Scenario 3: The target is flying at lower higher altitude (~4000ft) and has a strong deceleration capacity in descent representative of a short haul aircraft using speed brakes.
• Scenario 4: The target speed profile in cruise is representative of a chain effect (2 aircraft with relative altitude alternatively higher then lower). The target aircraft has a smooth deceleration capacity in descent representative of a long haul aircraft.
C. Participants and Schedule

The simulation took place in Berlin between March 7th and 18th 2005. It involved five crews of two pilots from Lufthansa which participated each during two days (four hours on the simulator each day). Among the 10 participants, 3 were captains and 7 first officers. The age ranges from 29 to 58 (mean 40), experience from 4500 to 23000 hours (mean 8270), experience with Airbus from 4500 to 13500 hours (mean 5270). The program covered a general briefing, initial training through replays of typical situations, four training runs on the simulator and four measured runs for each crew, enabling pilots to alternate functions (PF and PNF). Each run lasted about 1 hour. A general debriefing concluded each session.

D. Airspace

The simulated airspace came from the one used in the 2003 ground experiment (derived from Paris area). The airspace was adapted to airborne spacing by adding standard trajectories from the initial approach fix (IAF) to the final approach fix (FAF). Flights consisted of arrivals to (pseudo) Paris Orly (LFPO) and Charles De Gaulle (LFPG) airports, with four flight phases: cruise, initial descent (from top of descent to IAF), initial approach (from IAF to FAF) and final approach (from FAF to full stop landing). The flights were comparable and lasted about 35 minutes of flight time.

Recordings from the 2003 ground experiment were used to simulate the environment. Each flight was immersed in a traffic recorded, thus providing realistic voice communications (and party-line), the display of TCAS traffic when within range and the visual display of the target aircraft. For the aircraft replaced in a given scenario by the full flight simulator, pilot communications were omitted and the recorded positions were removed. Consequently, the radio party-line included all the voice communications and in particular instructions for the cockpit simulator. Although all ATC instructions were recorded, a pseudo-controller was present on the frequency in order to confirm the target positioning made by the crew, re-issue an instruction in case it was missed or misunderstood, and answer any possible request from the crew (e.g. “requesting descent”).

E. Flight Crew Tasks

Flight crews were tasked to fly the simulator as they would do in a regular flight, performing their usual tasks, including communications with ATC and checklists. Automatic Terminal Information Service (ATIS), navigation charts, and checklists were provided. Given the phase of flight, flight crews were also tasked to take the last ATIS and perform their arrival preparation and briefing.

To ensure the stability of the simulation platform, the flights were conducted in fuel freeze, which means that the crews were not required to monitor fuel. As the descent mode has an effect on the deceleration capacity of the aircraft, it was also decided to harmonise the descent profiles among crews in order to control the number of experimental variables. Crews were asked to systematically use an “open descent” mode and did not need to monitor their vertical profile. There was an exception in the last measured run during which they had an altitude constraint to meet and for which they needed to manage their descent profile. In addition, it should be stressed that pilots were not authorised to modify route or change altitude, unless explicitly instructed by the controller.

The spacing task consisted in acquiring and maintaining a given spacing (“merge” 90s with a tolerance of ±5s to a point located 20NM upstream the IAF), then when the target aircraft passes the IAF, maintain it (“remain” mode) until reaching the FAF. The task was handled through adjustments of the selected speed on the flight control unit (FCU) with the support of the display cues. There was no managed spacing mode. Concerning the flight task distribution, following today’s practices, it was suggested that the PNF would perform the input of data in the MCDU and that the PF would make the necessary speed adjustments to perform the spacing task. Both pilots would monitor the spacing.

VI. Main findings

The main findings are presented in three parts: human factors, discussing the comments and workload assessment; human activity relying on the analysis of speed actions; effectiveness addressing both achieved performance and cost induced. It should be noticed that, due to technical problems, two runs could not be considered, and for others, erroneous “jumps” of spacing value were recorded in the data and had to be removed.

A. Human Factors

The feedback was globally positive. Pilots felt their situation awareness was improved by knowing the preceding aircraft and by flying on standard trajectories. The reduction of communications was also appreciated and might benefit safety. The better accuracy of achieved spacing may allow gaining slots. According to pilots, the spacing...
task was acceptable in terms of workload. Pilots’ workload was globally moderate and did not affect their perceived level of performance. The spacing task seemed to slightly affect more the PF than the PNF. The PF still had to follow and perform the speed changes while the PNF had a lower workload due to the reduction of communications. NASA-TLX questionnaires were used to investigate pilots’ workload. This questionnaire was filled at the end of each run and addressed six dimensions: mental demand, temporal demand, physical demand, frustration and effort. Mean scores on mental and temporal demand are presented on Figure 4. This shows no clear effect of different runs. The target speed profiles did not affect the pilot workload. Indeed, during debriefing most of pilots said that they did not perceive real differences between the runs and indicated that they were just following the suggested speed and did not try to analyze the speed profile induced. Only a couple of pilots highlighted the fact that the speed reduction of the target aircraft was sometimes more difficult to follow. One pilot identified the run with the target not itself under spacing as it was receiving speed instructions.

The workload was nevertheless increased at specific moments, typically on final while PF was still performing speed adjustments and the PNF is head-down on MCDU canceling the spacing. This specific situation may impair safety. Most of the pilots required an automatic (managed) spacing mode, and in any case improvement of the spacing cues. An automatic cancel of spacing on short final (e.g. below 2000ft) was also suggested. Pilots also raised the issue of passenger comfort, variation of pitch or engine regime due to the numerous speed adjustments. Other limitations were raised in terms of level of ASAS equipped aircraft, diversified meteorological conditions (turbulences, wind…). The training of all the parties involved (pilots, controllers) to standardized procedures seemed to be a key point for many pilots.

### B. Human Activity

The impact on human activity essentially relies on the analysis of speed actions. A speed action is defined as a set of successive speed increments separated by an interval less than 5s (the value associated to the speed action is the one of the last increment). An average of 1 action per minute can be observed, with a standard deviation below 2 and a maximum value below 4 (Figure 5). No significant differences among the scenarios can be observed. This is in line with the previous experiments. It should be noticed however that there is no constant distribution over time: speed actions are induced by changes on target speed, mainly speed reductions at 250kt then 220kt.

![Figure 4. Mean score of NASA-TLX mental and temporal demand per run.](image)

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![Figure 5. Number of speed actions per minute.](image)
This means that, even if it was rather “quiet” most of the time, the two short periods corresponding to target speed reductions were more demanding. Beyond, when the number of actions appears as reasonably low, it should be mentioned that a monitoring of the suggested airspeed (and spacing scale) was still required. The impact on the monitoring activity has to be assessed.

C. Effectiveness

The effectiveness covers two aspects: the achieved performance and the cost induced.

The performance is analyzed through the achieved spacing. The spacing is only considered during the maintaining period, once it has been acquired. It can be seen (Figure 6) that the spacing was kept well with tolerance: average below 1s, standard deviation below 2s and some extreme cases never exceeding the tolerance margins (±5s). No different among the runs can be observed, except for the third one which was designed to be the most demanding one (strong deceleration of the target). These trends are consistent with the air previous experiments.

In order to provide an insight on the cost induced, we analyzed the amount of unnecessary speed changes. Typically, this includes any acceleration followed by a deceleration not caused by the target. This value is obtained by subtracting the total amount of target speed changes from that of the ownship. On average, an extra speed change of about 40kt per flight is induced (Figure 7). Two main observations can be made:

Firstly, a high disparity between the scenarios. Whereas #2 and #4 show a low cost, #1 and #3 are much costly. Although with a standard profile, #1 had the worst initial conditions, and #3, the strongest deceleration profile.

Secondly, a high disparity between crews. Two reasons can explain this: flight crew reaction time and strategy. A late reaction time requires to over or under compensate. A strategy of very accurate maintaining of the spacing imposes numerous changes. The very accurate spacing suggests that the second reason is predominant.

This is in line with observations and feedback from the pilot. The “align the bug” culture (and partly the computation of the suggested airspeed) induces pilots to keep 90s as much as they can. It should be noticed also that, due to a short familiarization, pilots were still experimenting different strategies during the data collection.
D. In Perspective

Considering the three aspects (activity, performance and cost) in perspective, it is interesting to note that, when few differences can be observed among the crews and the scenarios, the effect of the scenarios is on mainly on the cost induced. This cost not only concerns own aircraft, but also the following ones: degrading a speed profile may result in making the spacing task more difficult to achieve for the rest of the chain. However, the spacing was maintained with a high accuracy, without taking advantage of the full range of the tolerance margins. In other words, the high performance seems to be detrimental to the cost. The trade-off between performance and cost induced still has to be reached. In addition, although necessary for final approach, the tolerance margins of ±5s are probably unnecessary for initial approach. Relaxing the margins may help further reduce the cost.

VII. Conclusion

An experiment took place on a A330 full flight simulator at the Technical University of Berlin in March 2005. Beyond the technical challenge, the objective was to assess the effect of different positions in the chain, in simulating varied target speed profiles. A total of five crews of two Lufthansa pilots participated during two sessions of four hours each. The feedback was globally positive. Pilots felt their situation awareness was improved by knowing the preceding aircraft and by flying on standard trajectories. The reduction of communications was also appreciated and might benefit safety. The better accuracy of achieved spacing may allow gaining slots. Pilots however felt an increase of workload, requiring for most of them an automatic (managed) mode for spacing, and in any case improvement of the spacing cues. They also raised the issue of passenger comfort, variation of pitch or engine regime due to the numerous speed adjustments. Most pilots did not perceive significant differences between the target speed profiles. Despite the basic assistance provided, the spacing was maintained well within tolerances (±5s), with on average one speed action per minute. However, there was a cost induced of about 40kt unnecessary speed changes. This cost not only concerns own aircraft, but also the following ones: degrading a speed profile may result in making the spacing task more difficult to achieve for the rest of the chain. The issue will be to reach the trade-off between required spacing accuracy and cost induced. In the present experiment, the spacing was maintained with a high accuracy, without taking advantage of the full range of the tolerance margins. This accuracy, although necessary for final approach, was probably unnecessary for initial approach. Relaxing the margins may help further reduce the cost. This will be investigated in a comprehensive manner through model-based simulations. The next steps will also consist in improving the suggested airspeed and investigating the use of a managed mode. Model-based prototyping are ongoing to enhance and evaluate the guidance laws. An experiment is planned on the part task cockpit simulator and then on the full flight simulator.

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