Airborne Spacing: Managed vs. Selected Speed Mode on the Flight Deck

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This paper reports on an experiment conducted with airline pilots on a fixed-based cockpit simulator. The objective was to assess the use of a speed managed mode for airborne spacing, compared to a speed selected mode. The availability of a speed managed mode reinforced the pilot acceptability. All pilots found airborne spacing feasible and compatible with their usual flying task, from cruise until automatic disengagement at 2000 feet. The speed managed mode was found as the most appropriate during the initial descent but the speed selected mode was preferred by some pilots during final approach. The spacing was well maintained below the 5 seconds tolerance margins with an average of –0.1 second and a 95% containment within ±2.5 seconds. The cost induced is in the order of 60 knots additional speed changes for the complete descent phase, with a maximum but also a minimum cost when using the speed selected mode. This raises the issue of trade-off between required performance (spacing accuracy) and cost induced (speed changes).

Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AAL</td>
<td>Above Airport Level</td>
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<tr>
<td>ADS-B</td>
<td>Automatic Dependant Surveillance – Broadcast</td>
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<tr>
<td>ASAS</td>
<td>Airborne Separation Assistance System</td>
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<td>ATIS</td>
<td>Automatic Terminal Information Service</td>
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<td>ECAM</td>
<td>Electronic Separation Assistance System</td>
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<td>FAF</td>
<td>Final Approach Fix</td>
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<td>FCU</td>
<td>Flight Control Unit</td>
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<td>FMA</td>
<td>Flight Mode Annunciator</td>
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<td>FMS</td>
<td>Flight Management System</td>
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<td>IAF</td>
<td>Initial Approach Fix</td>
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<td>MCDU</td>
<td>Multi Purpose Control and Display Unit</td>
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<td>ND</td>
<td>Navigation Display</td>
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<td>PF</td>
<td>Pilot Flying</td>
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<td>PFD</td>
<td>Primary Flight Display</td>
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<td>PNF</td>
<td>Pilot Not Flying</td>
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<tr>
<td>TCAS</td>
<td>Traffic alert and Collision Avoidance System</td>
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I. Introduction

Airborne spacing involves a new task allocation 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 both parties without modifying responsibility for separation provision. 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 sequencing and merging arrival flows of aircraft is being studied, in particular at NASA, Mitre and EUROCONTROL. The investigations initially considered the air perspective through model-based and

* Steria, Issy-les-Moulineaux, France.
human-in-the-loop simulations\textsuperscript{2,3,4,5} which showed the feasibility of the concept, mainly for in-trail situations. In addition, flight trials were conducted with experimental aircraft to confirm the results obtained\textsuperscript{6,7,8}. In\textsuperscript{6,7} trials were performed in the terminal areas, on in-trail situations with turns and wind effect, and using different speed control modes (from manual with the support of display cues to a fully automatic). The spacing task was performed successfully with a small deviation of inter aircraft spacing at runway threshold, and with a limited impact on workload although the perceived head-down time was higher. The ground perspective was also considered and a concept of operations for the terminal area has been proposed and validated through human-in-the-loop experiments\textsuperscript{9,10}.

The work performed at the EUROCONTROL Experimental Centre has allowed the development and refinement of a set of spacing instructions for sequencing and merging arrival flows of aircraft\textsuperscript{11}. To gradually assess their operational feasibility, potential benefits and limits, two streams of air and ground experiments were conducted. The previous air experiments showed the feasibility of the spacing task from a flight crew perspective with a simple assistance (graphical cues and speed selected mode). The air experiment conducted in 2004 considered the complete descent phase with the preceding aircraft (target) under airborne spacing\textsuperscript{12}. The subsequent air experiment conducted in 2005 in a full flight simulator aimed at going a step further by assessing the effect of different positions in the chain, in simulating varied target speed profiles\textsuperscript{13}. From all these experiments, pilots reported benefits in terms of situation awareness, accuracy of achieved spacing, reduction of communications, but expressed concerns in terms of fuel consumption or passenger comfort. The pilots also felt an increase in workload due to the simple assistance provided and most of them requested an automatic mode (speed managed).

An experiment took place on an Airbus A320 fixed-based cockpit simulator in November 2005. The objective was to investigate the use of a speed managed mode for airborne spacing from cruise until automatic disengagement at 2000ft. The paper presents the main findings from this experiment. It is organized as follows: the two next sections introduce the spacing instructions and the cockpit interface. The following section describes the experiment design and setup, and the next one presents 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 a spacing instruction with respect to a designated aircraft (target). Three spacing instructions are proposed and can be applied throughout the arrival sectors for sequencing and merging, 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.

![Figure 1. Spacing instructions for sequencing and merging.](image)

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”)

III. Cockpit Interface

The fixed-based cockpit simulator was an Airbus A320 FMGS trainer with captain and first officer positions allowing to perform automatic flights. No external view was available. The simulator was composed of the following standard elements: PFD, ND (including a simplified TCAS display), MCDU, FCU, throttles, flaps, speed brakes and a simplified ECAM. ASAS capabilities have been added. An initial design of the ASAS interface was proposed in 2000 and has been constantly improved following pilot suggestions and Airbus design principles. The ASAS features consisted in: two speed modes, a speed cue on the PFD, new graphical indications on the ND, and new MCDU pages for data input. The two ASAS speed modes (selected and managed) were used for acquiring and maintaining the required spacing through speed adjustments. In the speed managed mode, the speed followed was computed by ASAS and displayed as a normal speed managed bug on the PFD (magenta triangle, Figure 2). In the speed selected mode, the speed followed was selected by the flight crew and displayed as a normal speed selected bug (cyan triangle, Figure 2). The suggested speed computed by ASAS was displayed on the PFD as a magenta dot (Figure 2). In speed selected mode, to avoid inducing too many speed changes, the suggested speed was rounded to multiple values of 5kt. As for a normal speed mode, when ASAS was engaged, the flight crew has the ability to switch from one to the other ASAS speed mode by pulling or pushing the speed knob on the FCU. No specific ASAS indication was provided on the FMA. No ASAS lateral mode was available and the resuming action (of a “heading then merge”) was performed as a normal direct-to. On the ND, the following indications were displayed (Figure 3): target aircraft information, spacing indications and, depending on situations, specific advisories (e.g. to perform the direct-to when in “heading then merge”), and caution or warning messages (e.g. when outside the tolerance margins).

Figure 2: ASAS speed indication of the PFD in speed selected (top) and speed managed (bottom) modes.
IV. Experiment Design and Setup

A. Objective

The main objective of the present air experiment was to assess the use of a speed managed mode for airborne spacing compared to a speed selected mode. The secondary objectives were to validate the automatic disengagement of airborne spacing at 2000ft and improvements of the interface, in particular a speed cue on the PFD.

B. Condition

Three conditions were considered depending on the speed mode available for airborne spacing:

- “Selected”: only the speed selected mode was available and the speed adjustments were performed manually by the flight crew through the FCU.
- “Managed”: only the speed managed speed mode was available and the speed adjustments were performed automatically by the system (ASAS).
- “Mixed”: both speed modes were available and the flight crew could switch between the two at their discretion.

For each condition, two runs were performed, to allow each participant to fly as PF and as PNF. The mixed condition requires pilots to be sufficiently trained with both speed modes. As the duration of the training was limited, it was decided to perform the runs in the same order (selected, managed, mixed). The induced training effect could not be quantified.

C. Participants and Schedule

The simulation was conducted over a period of three weeks from November 21st to December 9th 2005. It involved seven crews of two European airline pilots which participated during 1½ days each. Among the 14 participants, all Airbus rated, 1 was an experimental test pilot from Airbus, 3 were captains, 1 was senior first officer and 9 were first officers. The age ranges from 29 to 46 (mean 38), experience from 2000 to 16000 hours (mean 6200), experience with Airbus from 1000 to 8000 hours (mean 3700). Eight of the participants were newcomers not familiar with airborne spacing. For each crew, the program covered a general briefing, four training runs, six measured runs, and a general debriefing.
D. Simulated Environment

The simulated airspace was the one used in the 2004 ground experiment (derived from Paris area) and consisted in enroute arrival sectors and a terminal area (Figure 4). To use airborne spacing in the terminal area, specific trajectories have been introduced, from the two initial approach fixes (IAFs) to the final approach fix (FAF) via a merge point. The measured flights lasted approximately 40 minutes and consisted in arrivals to an airport, 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). Recordings from the 2004 ground experiment were used to simulate the ATC 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. Although all ATC instructions were recorded, a pseudo-controller was present on the frequency to confirm the target positioning made by the crew, re-issue an instruction in case it was missed or misunderstood, and answer any request from the crew (e.g. descent).

![Airspace Simplified Map](image)

**Figure 4.** Airspace (simplified map) with enroute arrival sectors (AW and AE) and terminal area (APS). Initial approach fixes were ODRAN and MOTEK, and final approach fix was FAO26. Merge points were CODYN, OKRIX and LOMAN.

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. The descent mode was let at pilots’ discretion but it should be stressed that pilots were not authorized to modify route or change altitude, unless explicitly instructed by the controller.

The flight crew had to perform successively, with a tolerance of ±5s, two spacing tasks:
- A “merge” at 90s to CODYN or OKRIX.
- A “continue heading then merge” at 90s (or 120s if the target was “heavy”) to LOMAN, until the automatic ASAS disengagement at 2000ft AAL.

For both spacing tasks, the target was itself under spacing. For the “heading then merge”, the target was either the same as for the “merge”, or an aircraft coming the other IAF. Concerning the flight task distribution, following today’s practices, it was suggested that the PNF would perform the data input in the MCDU and that the PF would control the flight parameters through the FCU. Both pilots would monitor the spacing.
V. Main Findings

The main findings are presented in three parts: human factors, human activity, effectiveness addressing performance and cost. Two phases are considered for analysis: the initial descent (from top of descent to IAF) and the approach (from IAF until 2000ft).

A. Human Factors

The feedback was globally positive and consistent with previous experiments: all pilots found airborne spacing feasible and compatible with their usual flying task, from cruise until 2000ft, with an automatic disengagement. In terms of situation awareness, by flying on standard trajectories and with the knowledge of preceding aircraft, they felt more in the loop and more able to anticipate their flight. They also perceived other benefits: reduction of communications, increased capacity due to better spacing accuracy. However, they raised the issue of fuel consumption, passenger comfort, variation of pitch or engine regime due to the speed adjustments. Some were concerned by a possible conflict between the airborne spacing speed and the landing speed profile. They were also concerned by the impact of mixed ASAS equipage, bad weather conditions (e.g. turbulences, wind) and technical failure onboard. The training of all the parties involved (pilots, controllers) to standardized procedures seemed to be a key point for many pilots.

All the pilots agreed that both speed modes should be available. They all found that the speed managed mode was the most appropriate during the initial descent. Half of them preferred the speed selected mode during final approach, to respect airline policy or to keep the control of their speed in this critical phase. However, as they could get enough confidence in the speed managed mode, they would have been ready to use it, in particular in more demanding situations (e.g. at the end of a long-haul flight).

Whatever the speed mode, the spacing task generates a moderate level of workload without affecting the pilots perceived level of performance. The assessment of pilots’ workload obtained through NASA-TLX questionnaires shows no clear effect of condition. However, according to pilots, the speed managed mode clearly reduced their workload in comparison with the speed selected mode as it suppresses the manual speed adjustments. In all conditions, the pilots felt an increasing level of workload near and on the ILS due to multiple tasks to perform (intercept of localizer, intercept of glide slope, speed reductions, flap extraction, monitoring of spacing, transfer to tower).

The usability of the interface was rated globally good. The display of the suggested speed on the PFD was found intuitive. Some pilots nevertheless reported a cluttering of the ND in some cases, and some inconsistencies between phraseology and MCDU, in particular for the activation of a spacing instruction while already under spacing. The logic of engagement and disengagement was globally satisfactory but one transition was incorrectly perceived as a mode reversion. The improved speed guidance was well appreciated as it was more stable.

B. Flight Crew Activity

The flight crew activity was assessed through two aspects: the number of speed actions (in selected condition) and the use of speed modes (in mixed condition). In line with the previous experiments, the pilots performed on average less than 1 speed action† per minute. The approach phase is slightly more demanding than the initial descent. There were however variations during the flight, with a maximum of 5 actions per minute in initial descent and 3 in approach (Figure 5). This means that, even if the spacing task was rather “quiet” most of the time, there were short periods (corresponding speed reductions of the target) more demanding. Concerning the use of the speed mode, it clearly depends on the flight phase. When the speed managed mode is used more than 95% of the time during initial descent, it is used 62%‡ during the approach phase (Figure 6). This is in line with the pilots’ comments: half of them preferred switching to speed selected mode during final approach.

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† 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).
‡ Due to a technical problem, when the approach phase was activated (on the very final part, near the runway axis), the speed bug indicated the approach speed instead of the suggested speed (the speed followed was the suggested speed). In some cases, this problem induced pilots to switch to speed selected mode. This may have contributed to increase the time under speed selected mode to a maximum of 8%.

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C. Effectiveness

The effectiveness covers two aspects: performance and cost. The performance is measured by the achieved spacing (during the maintaining period, once it has been acquired). It can be seen (Figure 7) that the spacing was well maintained within the 5 seconds tolerance margins whatever the speed mode with an average of –0.1s, about 1s standard deviation, 95% intervals of [–2.4s; 1.8s] and [–1.8s; 1.7s] (respectively in initial descent and in approach). The extremes values were observed in both flight phases when using the speed selected mode. Similar results have been obtained in other studies.\textsuperscript{3,14}

The cost aims at capturing the effect of airborne spacing on the speed profile of the subject aircraft. It is obtained by considering the additional speed changes compared to the target (subtracting the amount of target speed changes to the amount of subject aircraft speed changes). With ideal initial conditions (same speed and altitude, spacing equal to desired), a value of zero corresponds to a perfect replication of the target speed profile, a negative value to an improvement (e.g. smoothing of speed variations), and a positive value to a degradation (e.g. introduction of additional speed variations). If the speed profile is degraded, the spacing task may be more difficult to achieve for the following aircraft. Thus, when considering a chain of aircraft, the cost can also be used as an indicator of stability.

On average, about 60kt additional speed changes per flight is induced for the complete descent phase (28kt for initial descent, 32kt for approach, Figure 8). Whereas the speed mode had no impact on the average value, it has a strong impact on the standard deviation. The speed selected mode led to a large dispersion as it is closely linked to inter individual differences (pilots’ strategies and reaction times). In addition, the extreme values show that the
maximum but also the minimum cost (respectively +214kt and −20kt) for the complete descent phase were obtained with the speed selected mode. This stresses the fact that the cost is less predictable when the speed is handled by the flight crew.

As defined, the cost includes two main factors: the initial conditions (speed, altitude, spacing value) and the air system (flight crew, spacing guidance, aircraft). For instance, the cost can be impacted by a large initial spacing value that would automatically impose an acceleration. It can also be impacted by an inappropriate pilot reaction to a speed modification of the target (too late or early, too large or small speed adjustment) that could lead to an acceleration followed by a deceleration (or vice versa). An analysis of the contribution of each factor would be necessary. Model-based simulations have been performed\textsuperscript{15} that allowed an initial quantification of the contribution of the air system (the other factor was negligible as the initial conditions were almost ideal). In conditions similar to the present experiment, the air system induced a cost of about 15kt on average with extreme values of +5kt and +40kt. This suggests that, compared to the initial conditions, the air system would have a smaller impact on the cost.

Beyond, remains the issue of trade off between performance and cost. In the experiment, the spacing was maintained with a high accuracy, without taking advantage of the full range of the tolerance margins. In the speed selected mode, this could have been influenced by “align the bug” culture\textsuperscript{8}. A better use of the tolerance and possibly a larger tolerance (although necessary for final approach, the tolerance margins of ±5s are probably unnecessary for initial approach) should help reducing the cost. An initial trade-off analysis has been performed through model-based simulations\textsuperscript{15}.

![Graph](image.png)

**Figure 8.** Cost induced during initial descent (left) and approach phase (right).

\textsuperscript{8} Although this may have been less predominant than in the previous experiment. In the present experiment, the pilots mainly followed the suggested speed which used the tolerance margins and less the spacing scale which clearly highlighted any deviation from the required value. This effect has been observed during the NASA flight trials.
VI. Conclusion

A flight deck experiment was conducted on an Airbus A320 fixed-based cockpit simulator to assess the use of a speed managed mode for airborne spacing. Seven crews of two European airline pilots participated during 1½ days each. The overall feedback was globally positive and consistent with previous experiments. The availability of a speed managed mode reinforced the pilot acceptability. All pilots found airborne spacing feasible and compatible with their usual flying task, from cruise until automatic disengagement at 2000ft. They reported benefits in terms of situation awareness (knowledge of preceding aircraft, flying on standard trajectories), accuracy of achieved spacing, reduction of communications, but expressed concerns in terms of fuel consumption and passenger comfort. The speed managed mode was found as the most appropriate during the initial descent (as it reduced workload) but some pilots preferred the speed selected mode during final approach. The spacing was well maintained below the 5 seconds tolerance margins whatever the speed mode with an average of –0.1s and a 95% containment within ±2.5s. The cost induced is in the order of 60kt additional speed changes for the complete descent phase, with a maximum but also a minimum cost when using the speed selected mode. Results obtained from model-based simulations suggest that the initial conditions have a larger impact on the cost than the flight deck. This has to be further investigated. Beyond, remains the issue of trade-off between required performance (spacing accuracy) and cost induced. Model-based simulations are being conducted to further investigate this trade-off. An experiment will be conducted on an Airbus A330 full flight simulator to validate the use of speed and lateral managed modes in a more realistic environment.

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