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PROPAGATION OF AIRBORNE SPACING ERRORS IN MERGING TRAFFIC STREAMS

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Abstract

Research results from domains such as road highway traffic and military vehicle platoons conclude that string stability cannot be obtained when vehicles use only relative spacing information to maintain constant distance behind a predecessor. Air traffic studies confirm these results but such instability has not been shown for constant time delay based airborne spacing. Unlike constant distance based, constant time delay based spacing has the potential to enhance stability by anticipating changes in spacing using the preceding aircraft's history. This simulation based study analysed the merging of aircraft by constant time delay based spacing over the period of the order of an hour to observe any build up of error propagation effects. Aircraft descended from 12,000 feet to 4,000 feet, each trying to achieve ninety seconds spacing with respect to its predecessor. The spacing anticipation time for each trailing aircraft to react to the preceding aircraft's time history was varied from 0 to 20s. Without anticipation, a time spacing error was observed to propagate at about 20 knots groundspeed in a forwards direction (towards runway) growing to about -3.5s (trail aircraft too early and too close). This compression wave was avoided by increasing spacing anticipation to 10s. Values larger than 10s reversed the error and moved it upstream. A tuned scenario was repeated for 5,400 random values of initial time spacing error and top of descent with automatic and manual airborne spacing modes. Time spacing accuracy and pilot activity were measured to be within required values previously derived for a pair of aircraft but the corresponding cost in speed variation was higher.

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 [5]. It relies on the ability of the controller to task the flight crew to maintain a given spacing with respect to the preceding aircraft [1], [8] and [18]. 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 [3]. Airborne spacing assumes air-to-air surveillance (ADS-B, Automatic Dependant Surveillance – Broadcast [15]) along with cockpit automation (ASAS, Airborne Separation Assistance System).

Human-in-the-loop simulations based on Paris airspace indicate that airborne spacing sequencing and merging may produce a smoother, more expeditious and orderly flow of traffic than is achieved through conventional ATC instructions (e.g. speed and heading). Both distance and time-based airborne spacing to sequence aircraft have been studied using fast time [7], [10], [12], [18] and real-time experiments [2], [9], [13] and [14].

The experiment described in this paper forms part of a series of complementary model and human-in-the-loop based validation exercises aimed at investigating the use of spacing instructions for merging and sequencing of arrival flows [6]. The human-in-the-loop experiments (pilots and controllers) are used to assess the operational feasibility of airborne spacing, and model based experiments are used to prototype and assess system performance.

This particular set of model based experiments was designed to investigate system stability in particular how airborne spacing errors propagate along a sequence of aircraft being merged a constant spacing behind their nearest neighbour.

There has been a significant amount of research in to distance based vehicle self-separation in different domains such as highways and military formations of unmanned aerial vehicles. Seiler et al, 2002 [16] summarise these results by concluding "that 'string stability' cannot be obtained when vehicles use only relative spacing information to maintain a constant distance behind their predecessor." Slater, 2002 [17] showed using a linear aircraft model and linear controller that "controls based only on the neighbouring vehicle result in unacceptable performance, but good string behaviour can be achieved if lead vehicle state is included in the feedback law".

The difficulty with using state information about the lead aircraft of a sequence in the TMA is that the lead changes each time an aircraft lands. This paper continues to investigate nearest neighbour self-spacing and error propagation but with the less well studied constant time delay based spacing. The objective of constant time delay based spacing is for the trail aircraft to minimise longitudinal spacing error with respect to a 'ghost' of the target's past position. This means that the trail does not have to react to instantaneous changes in the current speed of the target to maintain spacing and the future state of the 'ghost' is available for anticipating control demands.

The main objective of this paper is to investigate how disturbances of time spacing error are propagated through sequences significantly longer than two aircraft, during a descent from 12,000 feet down to 4,000 feet. Particular areas of interest of this study were the behaviour of aircraft under airborne spacing while being merged (i.e. string creation) and close to landing (i.e. string termination). The motivation was to check that undesirable wave effects did not build up with time even in a short spatial string.

The paper is organised as follows: the 'remain behind' and 'merge behind' applications are described followed by a description of the simulation platform, aircraft and pilot models. The method describes the operational scenario, metrics and range of experimental variables used. Results are presented as a series of graphs, followed by discussion and conclusion.

Airborne spacing

'Merge behind' application

The constant time delay based airborne spacing 'Merge behind' application involves an air traffic controller instructing a pilot to select a neighbouring aircraft as a target on a Cockpit Display of Traffic Information (CDTI). An example of the phraseology developed [9] is:

Controller designates the target aircraft using e.g. transponder code ("XYZ, select target 4522")

Flight crew identifies target aircraft ("XYZ, target 4522 identified, 8 o'clock, 30 miles")

Controller confirms the identification ("XYZ, target 4522 correct")

Controller, when appropriate, issues the spacing instruction ("XYZ, continue present heading then merge WPT (merge waypoint name) 90 seconds behind target")

Flight crew continues on heading, then initiates direct when spacing achieved ("XYZ, merging WPT"), then adjusts speed to maintain 90 seconds

Controller, when appropriate, cancels spacing ("XYZ, cancel spacing, speed 180 knots")

Prototype CDTIs with visual spacing cues or automatic mode have been developed to support pilots in this new spacing task.

An example of the 'Merge behind' application is illustrated in Figure 1. The two aircraft, the lead (target) and the trailing aircraft, are flying straight to the same fixed merge waypoint. The solid arrows represent the current position and track angle of the aircraft, and the dashed arrows represent the desired positions of the two aircraft when the lead 'reaches' the merge waypoint. *By this point the spacing in time between aircraft must be within a defined tolerance from the desired spacing, and the aircraft should have similar speeds.* After the waypoint the problem is the same as the *in-trail following aircraft* situation, i.e. each aircraft follows the same route within a sequence maintaining the spacing between itself and the aircraft immediately in front.

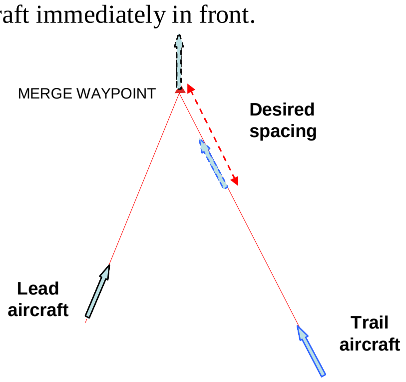

Figure 1 **Merge behind encounter**

Conceptually, for the purposes of closed-loop guidance law design, this operational goal can be extended upstream of the merge waypoint by defining and minimizing a continuous time spacing error t_{error}, at time *t*. The spacing error t_{error} is defined as the difference between the elapsed time (t- t^*) since the lead aircraft was at the same distance from the merge waypoint as the trailing aircraft is currently (t) and the desired time spacing $t_{spacing}$:

$$t_{error}(t) = t - t^* - t_{spacing} \qquad (1)$$

'Remain behind' application

The constant time delay based airborne spacing 'Remain behind' application involves an air traffic controller asking a pilot to select a neighbouring aircraft as a target on a CDTI and to remain a specified constant time delay behind it. For phraseology and more details see [5].

Constant time delay spacing control

To achieve a constant time delay spacing, the trailing aircraft tries to minimise longitudinal spacing error with respect to a 'ghost' of where the target was $t_{spacing}$ s in the past. A control law was derived to minimise $t_{error}(t)$ [7]. This control law made use of the 'future' state information about the ghost (i.e. lead history) in two ways:

- a spacing anticipation time constant to compensate for lags in the system due to mass inertia and throttle response delay.
- to reduce the number of discrete speed changes requested to the pilot.

When the spacing anticipation time constant is set to zero, the automatic guidance tries to match the current trail aircraft groundspeed with the lead groundspeed delayed by a desired time spacing in seconds. By increasing the value of the spacing anticipation, the guidance will track the current trail aircraft groundspeed (GS) with the lead groundspeed delayed as follows:

$$GS\_desired\ (t) = GS\_lead\ (t - time\_spacing + spacing\_anticipation) + Correction\_term\ (t) \quad (2)$$

Apparatus

Simulation platform

All aircraft models, spacing guidance, and atmosphere models were simulated in MATLAB and Simulink running on a Windows based PC with a Pentium IV (1.5 GigaHertz, with 1 GigaBytes RAM). Perfect airborne surveillance transmission quality of lead aircraft position and velocity to the trailing aircraft was assumed i.e. continuous update rate, no delay, and perfect accuracy.

Aircraft model

The aircraft model (Airbus 320) includes the basic equations of motion, aerodynamic model, engine model, auto-pilot, auto-throttle control system, aircraft sensors and air-data model. The aircraft model is based on point mass equations of motion but with additional realistic rotational dynamics about the centre of gravity. The model includes lateral motion of the centre of gravity and dynamic characteristics of the engines. An admissible speed envelope model based on physical limits like stall speeds and maximum airframe speeds is incorporated in the aircraft model. These limits may not be as conservative as airline normal operational limits. A detailed description of the aircraft model and its validation can be found in Fokker, 1989 [4], NLR, 2002 [11].

Human pilot model

Pilot reaction to the demands from the spacing director cues was modelled as a sum between a 'scan' reaction time and an 'action' reaction time. This led to a random model based on a normal distribution with a mean of 5s and a standard deviation of 1s, comparable with the average pilot's reaction time in real-time simulations.

Method

Operational scenario

The first aircraft descended from the Initail Approach Fix (IAF) at 12,000 feet to the Final Approach Fix (FAF) at 4,000 feet with a speed change from 230 knots to 180 knots of Calibrated airspeed (CAS). The second aircraft was initialised 90s later and an airborne spacing algorithm [7] tried to maintain this time spacing down to 4,000 feet. The aircraft were flying straight, on different trajectories, towards the merge waypoint (see Figure 2).This was repeated for 29 more aircraft over a period of about 53 minutes. Standard atmospheric conditions were used with no wind.

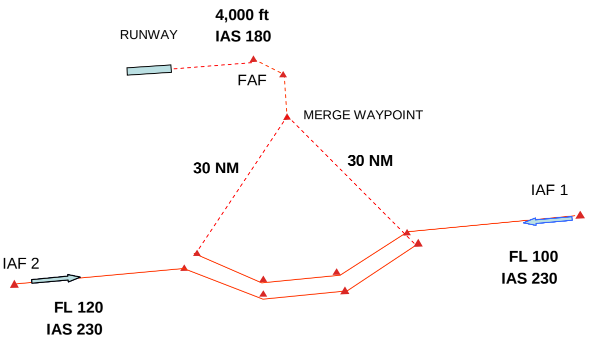

Figure 2 TMA route structure for merging two traffic streams at a waypoint in descent from IAF to FAF

Experimental variables

The following parameters were varied as indicated in table 1:

Table 1 Experimental variables

Parameters	Values
Spacing anticipation time (s)	0, 5, 10, 15, 20
Airborne spacing director mode	Automatic mode and manual mode with human pilot model
Initial time spacing error between aircraft (s)	Random between -5 (trail early) to +5 (trail late)
Top of Descent distance from FAF (NM)	Random between 38 and 42

Metrics

The following metrics were applied to each trial:

- Time spacing error between each aircraft pair for every simulation step.
- Cumulative CAS variation between each aircraft pair over all simulation steps. Cumulative CAS variation is the difference between the cumulative CAS changes of the lead and the cumulative changes in CAS demand of the trail. This is a measure of the efficiency of airborne spacing.
- Number of discrete speed actions per aircraft (manual mode only). This is a measure of the cost to a human pilot.

Only the time spacing error during the 'maintain spacing' phase was measured. This phase corresponds to a situation where the spacing is achieved within ±3s of tolerance and the spacing evolution is stabilized (closure rate between lead and trail aircraft less than 20 knots). The "maintain spacing" phase could start during the merge behind application because spacing error is already defined upstream of the merge waypoint. Measuring spacing error continuously before the merge waypoint, gives an indication of the smoothness and predictability of an aircraft's behaviour within a merging flow.

Tables 2 and 3 are airborne spacing performance requirements derived for a single pair [7]. These values are used to compare with results for sequences in this paper.

Table 2 Performance requirements for automatic mode derived from a pair of aircraft

Performance parameter	Requirement
Time spacing error (s)	|Mean| < 1.5 lower safety containment bound = -4 upper efficiency containment bound = 4
Cumulative airspeed variation (knots)	|Mean| < 10 k with a standard deviation < 10

Table 3 Performance requirements for manual mode derived from a pair of aircraft

Performance parameter	Requirement
Time spacing error (s)	|Mean| < 2.5 lower safety containment bound = -6 upper efficiency containment bound = 6
Frequency of speed adjustments (actions per minute)	|Mean| < 1 with a standard deviation < 1
Cumulative airspeed variation (knots)	|Mean| < 10 with a standard deviation < 10

Results

Figures 3 to 8 show how time spacing error varies with distance along track for each aircraft pair as a function of control law spacing anticipation time.Figures 3, 4 and 5 show how the time spacing error varies continuously between each aircraft pair.

Figures 6, 7 and 8 show how the time spacing error varies between each aircraft pair at discrete intervals determined by when an aircraft reaches level 4,000 feet. The 'Pairs of aircraft in TMA' axis corresponds to the state of the flow at the same instant, with pair 1 being at the front of the sequence. The 'Number of sequences' axis corresponds to the number of aircraft that have reached the 4,000 feet level and therefore left the sequence.

Figures 9, 10 and 11 show the results of randomly varying the initial time spacing error and top of descent using the scenario tuned with a spacing anticipation value of 10s. In total 80 trials (2,400 aircraft pairs) of the automatic mode and 100 trials (3,000 aircraft pairs) of the manual mode were performed.

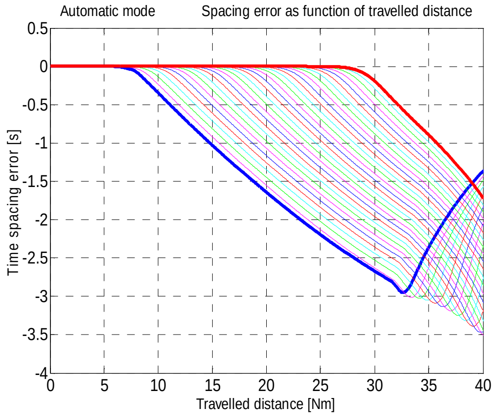

Figure 3 Continuous time spacing error versus distance, spacing anticipation = 0s, first pair (bold blue), last pair (bold red)

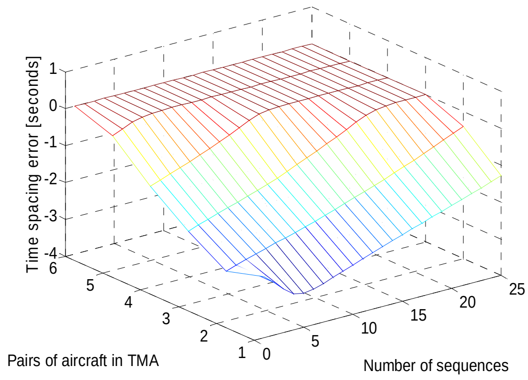

Figure 6 Discrete time spacing error between each pair in a sequence for 25 consecutive landings, spacing anticipation = 0s

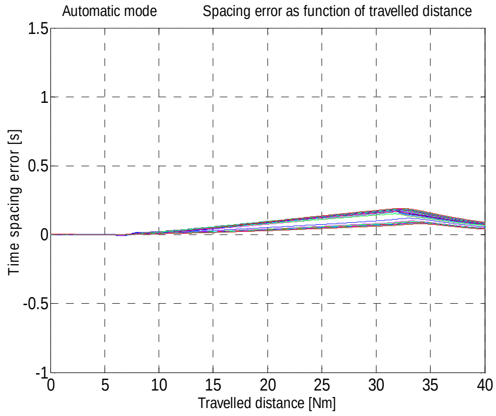

Figure 4 Continuous time spacing error versus distance, spacing anticipation = 10s, first pair (bold blue), last pair (bold red)

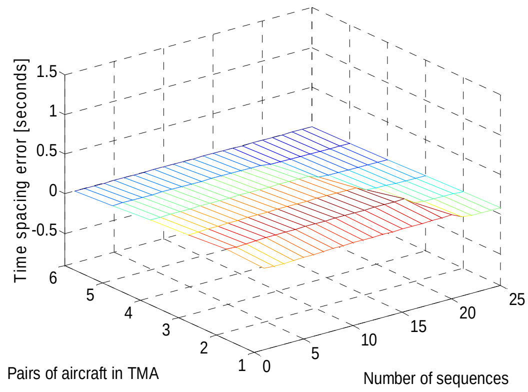

Figure 7 Discrete time spacing error between each pair in a sequence for 25 consecutive landings, spacing anticipation = 10s

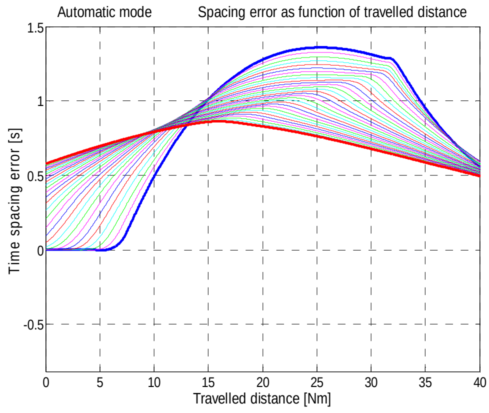

Figure 5 Continuous time spacing error versus distance, spacing anticipation = 20s, first pair (bold blue), last pair (bold red)

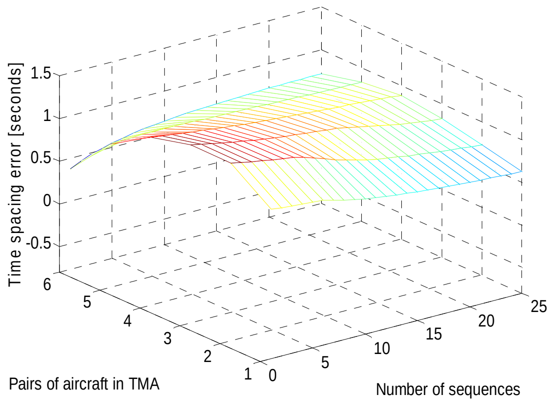

Figure 8 Discrete time spacing error between each pair in a sequence for 25 consecutive landings, spacing anticipation = 20s

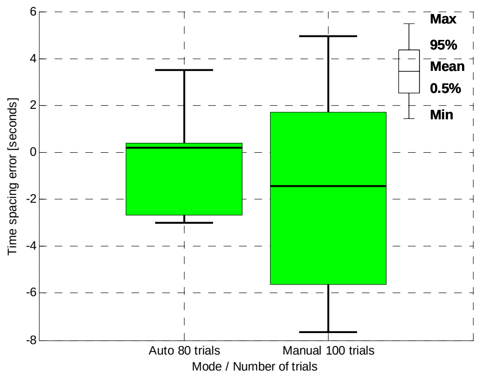

Figure 9 Time spacing accuracy

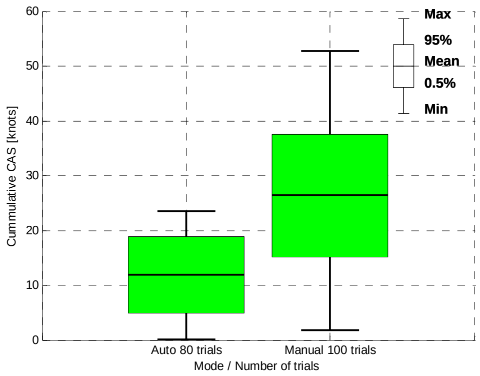

Figure 10 Cost in speed variation

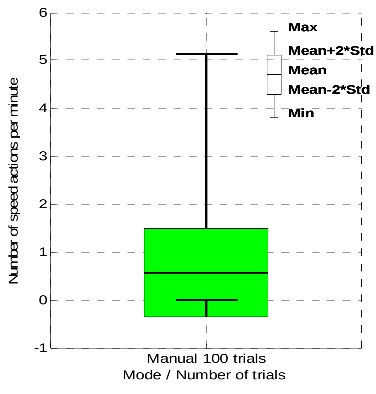

Figure 11 Pilot activity

The distribution of time spacing error is not necessarily normal, therefore the metric used is the mean time spacing error, associated lower safety containment bound (corresponding to a go-around rate < 0.5%), upper efficiency containment bound (corresponding to > 85% of values), and minimum and maximum values (Figure 9).

Figure 10 shows the cumulative CAS variation of the automatic and manual modes. The means and standard deviations are represented in the shaded areas and the extreme minimum and maximum values are also shown.

Figure 11 shows the mean number of speed actions per minute of the manual mode. The positive and negative standard deviations are represented by the shaded area and the short horizontal bars mark the minimum and maximum values. Note that the negative standard deviation from the mean is lower than zero, the minimum possible value, indicating that the distribution is not symmetrical about the mean.

Discussion

Figures 3 and 6 show that, without spacing anticipation, a time spacing error was observed to propagate at about 20 knots groundspeed in a forwards direction (towards runway) growing to about -3.5s (trail too early and too close) by the time the twelfth aircraft reached 4,000 feet.

In Figures 4 and 7, for 10s spacing anticipation, a time spacing error of less than 0.25s was obtained which appeared to be stationary with respect to the ground.

Figures 5 and 8 show that, for 20s spacing anticipation, a time spacing error was observed to propagate at about 22 knots groundspeed in a reverse direction to the flow growing to a peak of about 1.5s (trail too late and too far behind) before decaying.

The results for anticipation spacing values of 5s and 15s are not shown but fit the trend defined by the extreme cases given here.

The error propagation results show that the compression wave can be avoided by making use of the history of the preceding aircraft to compensate for lags in the system. The spacing anticipation parameter can be used to control the degree of error propagation. A value larger than 10s can reverse the error and move it upstream. This has the effect of increasing the spacing between aircraft but a balance must be found with throughput.

Figure 9 shows that the desired spacing (90s) is achieved and maintained within the required accuracy for automatic and manual modes. With automatic mode the mean is 0.25s, lower safety containment bound -3s and upper containment bound +1s. For the manual mode, the mean is -1.5s, lower safety containment bound -6s and upper efficiency containment bound +2s.

Figure 10 shows that the mean and standard deviation of cumulative CAS variation per trail aircraft is 12 (±7) knots for automatic mode and 26 (±11) knots for manual mode. The mean value for automatic mode is slightly greater than the required value derived for a pair of aircraft but the mean value for manual mode is over twice that for a pair of aircraft.

Figure 11 shows the manual mode pilot activity is about 1 speed action every two minutes i.e. within the required value of 1 (±1) actions per minute

To change spacing accuracy with the manual mode, there are several solutions:

- There is a trade off between the number of speed actions and the spacing accuracy. For this experiment, a dead-zone of ±2.5s was used in order to reduce the number of speed actions. This dead-zone was tuned for a sequence of 6 aircraft. By reducing the dead-zone to zero, the spacing error is likely to decrease.
- A value of 15s was used for the spacing anticipation parameter in manual mode (10s from automatic mode plus 5s to compensate for the average pilot latency). A statistical approach could be used to test other values, and to propose an improved calculation.

Conclusion

Spacing error propagation effects were studied when two arrival streams of aircraft were merged using constant time delay based airborne spacing. It was shown that time spacing errors can propagate along a sequence of aircraft descending from 12,000 to 4,000 feet over the period of the order of an hour. At any instant, there were about six aircraft in sequence. By making use of the lead aircraft history in the airborne spacing control law of the trail, the direction and magnitude of error propagation could be adjusted. Tuning the anticipation to 10s produced a flat peak in spacing error, with amplitude less than 0.25s and which was stationary relative to the ground.

The tuned scenario was repeated 180 times for different random initial spacing errors and top of descent points in automatic and manual airborne spacing modes. The time spacing accuracy and number of speed actions per minute (manual mode only) were found to be within requirements derived in a previous study for a pair of aircraft. The cumulative airspeed variation was found to be higher than those for a pair (in automatic mode a mean of 12 (±7) knots, instead of 10 (±10) knots and for manual mode a mean of 26 (±11) knots instead of 10 (±10) knots).

Future work could include extending requirements from a pair of aircraft to sequences of three or more aircraft. For the manual mode, tuning spacing anticipation as a function of pilot reaction time could be investigated. The current implementation of the spacing dead-zone could be re-considered in order to increase the spacing accuracy.

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Keywords

Air traffic management (ATM), airborne separation assistance system (ASAS), guidance, speed control, in-trail, airborne spacing, aircraft, cockpit display of traffic information (CDTI), pilot, constant time delay, automatic dependent surveillance broadcast (ADS-B) , vehicle string stability

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Dan Ivanescu is a research engineer for Steria in France working at the Eurocontrol experimental centre on the design and evaluation of theoretical models for airborne separation assistance systems. He received degrees in control systems from the Polytechnical Institute of Bucharest, Romania (BSc 1995) and Laboratoire d'Automatique de Grenoble, France (MSc 1997, PhD 2000), and held a post doctoral position at Compiegne university. Dan has published over 30 book chapters, journal and conference papers. In 2001 he was awarded the `Ph.D. Thesis award' from Institut National Polytechnique de Grenoble. His research interests include air traffic management and aircraft design, delay systems with applications to the design of real systems.

Chris Shaw was born in Scotland and attended school in Yorkshire, England. He studied physics (BSc, 1987) at the university of Bristol, then control systems (MSc, 1988) in conjunction with British Aerospace. At Smiths Industries Aerospace in Cheltenham, he developed avionics for the Boeing 777 and US presidential helicopter. His government research experience includes prototyping a 4D tube based navigation system at the British Royal Aerospace Establishment (RAE, 1990-2), and experimenting with airborne separation systems at NASA Ames in California's Silicon Valley (1998-9). Chris has flown in trials for NASA and RAE, and participated in standards development for RTCA. Currently he works for Eurocontrol in France evaluating future concepts for European air traffic management.

Karim Zeghal received his PhD in Computer Science from the University of Paris VI in 1994. His thesis which was conducted at ONERA (French aerospace research agency), focussed on the application of multiagent systems to air traffic control, and proposed a model of "coupled force fields" for multiple mobile co-ordination. During 1994-1996, he worked with the support of CENA (French centre for study in air traffic), to apply and evaluate the model of co-ordination for airborne conflict resolution. In 1996, he joined the Air & Space department of STERIA (software & consulting company), and since then has worked at the EUROCONTROL Experimental Centre. Since 1998, he has been leading the real-time simulations on ASAS, with a special focus on operational concepts and evaluation. Since 2002, he joined EUROCONTROL as project leader of CoSpace.

Eric Hoffman is the Scientific & Technical Manager of the Sector Safety & Productivity Research Area at the EUROCONTROL Experimental Centre. Over the past recent years, he has led a number of studies on concepts and benefits of ASAS applications in the context of several collaborative European projects. He has been involved in the writing of PO-ASAS and the ICAO ASAS Circular as well as in the definition of Package 1. Prior to joining EUROCONTROL in 1992, he worked on the use of game theory for the definition of strategic defence systems. Additionally he spent a year in the French Air Force coordinating the flight testing of a UAV. His research interests also include guidance and control, trajectory prediction and distributed simulations. Eric received his Aerospace Engineering (BS) and DEA (MS) degrees in 1987 from ENSAE (Sup'Aero), Toulouse, France and his PhD in 1991 from the Georgia Institute of Technology, Atlanta, Georgia USA. He has authored several papers and is a member of AIAA and IEEE.