Towards Performance Requirements for Airborne Spacing - a Sensitivity Analysis of Spacing Accuracy

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The objective of this air traffic management study was to analyse the trade-off between time spacing accuracy and corresponding control effort in a potential future application of airborne separation assistance systems (ASAS). The ASAS application airborne spacing sequencing and merging was simulated in fast-time. Lead aircraft speed profiles were generated using complete descent profiles from real-time experiments. For validation purposes, three metrics were derived from real-time experiments: time spacing error (accuracy), frequency of speed adjustments (control activity), and cumulative airspeed variations (control cost). Four experimental parameters were varied: automatic and manual speed control, spacing dead-zone, guidance law dynamics time constant and initial time spacing error. A trade-off between the metrics was found for a sequence of two aircraft by comparing their variation with the experimental parameters. Corresponding ‘minimum’ performance requirements for the metrics are proposed: (i) time spacing error - mean less than 1.5s with 0.5 to 85% of the values between -4 and +4s (automatic mode), and mean less than 2.5s with 0.5 to 85% of the values between -6 and +6s (manual mode), (ii) frequency of speed adjustments - mean less than 1 action per minute (manual mode) and (iii) cumulative airspeed variations - mean less than 10 knots (automatic and manual modes). These requirements form a basis for investigating sequences longer than two aircraft where chain propagation effects may lead to additional constraints.

Nomenclature

ADS-B  =  Automatic Dependent Surveillance Broadcast
ASAS   =  Airborne Separation Assistance System
ATM    =  Air Traffic Management
CAS    =  Calibrated Air Speed
CDTI   =  Cockpit Display of Traffic Information

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 [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. 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 [7]. Airborne spacing assumes air-to-air surveillance (ADS-B, Automatic Dependant Surveillance – Broadcast [20]) along with cockpit automation (ASAS, Airborne Separation Assistance System).

Human-in-the-loop simulations based on Paris airspace have demonstrated 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 [2], [8], [14], [17], [21] and real-time experiments [3], [12], [18], [19].

During trials pilots expressed the need for assistance in gauging the spacing and closure rate, and deriving the corresponding desired calibrated airspeed (CAS). A prototype cockpit tool (‘airborne spacing director’) for reducing the frequency of speed changes suggested to a pilot was designed using the prototyping tool MATLAB [10].

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A real time experiment was conducted on an Airbus A320 fixed-based cockpit simulator to investigate the use of a speed managed mode (automatic) for airborne spacing [9]. The speed managed mode was found to be the most appropriate during the initial descent (as it reduced workload) but some preferred the speed selected mode (manual aided by airborne spacing director) during final approach to respect airline recommendations or to keep the control of their speed in this critical phase. The spacing was well maintained within the 5 seconds tolerance whatever the speed mode (selected or managed) with an average of -0.1s (95% interval is [-2.4s, 1.8s] from cruise to initial approach and [-1.8s, 1.7s] from initial approach until 2000 feet). The cost induced (measured as unnecessary speed changes) was in the order of 60 knots for the complete descent phase, with a maximum and minimum cost of 214 knots and -20 knots respectively when using the speed selected mode. These results raise the issue of trade-off between required performance (spacing accuracy) and cost induced, but also suggest that the cost is less predictable when the speed is handled by the flight crew.

The objective of the present paper was to provide an assessment for a pair of aircraft of the main trade-off between spacing accuracy and the corresponding control effort (speed variation and number of speed actions in manual mode) to obtain this spacing accuracy.

II. Airborne Spacing Application

A. ‘Merge’ Application

The time-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:

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 (merge waypoint name) 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”)

An initial prototype CDTI with visual spacing cues has been developed (see Figure 1):

Figure 1: ‘Merge behind’ application on CDTI in real time experiments

The enlarged spacing scale on the left of the navigation display copes with possible different display range requirements between navigation and spacing. The suggested airspeed† on the primary flight display (see Figure 1) is proposed to the pilot for input into the autopilot. Accurate time based calculations of this nature are easily performed by computer but are more difficult for pilots especially in parallel with other tasks. An example of the

† For the purposes of this note, indicated airspeed (IAS) and calibrated airspeed (CAS) are considered to be the same.
‘Merge’ application is illustrated in Figure 2. 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 its own trajectory within a sequence maintaining the spacing between itself and the aircraft immediately in front.

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 and the desired time spacing $t_{spacing}$:

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

where $t^*$ satisfies:

$$d_{lead}(t^*) = d_{trail}(t)$$  \hspace{1cm} (2)

This time based spacing error was rewritten as an equivalent constant distance based expression. The equivalent distance based spacing error $d_{error}$ was defined as the difference between the delayed position where the lead had been $t_{spacing}$ seconds ago and the current position of the trailing aircraft.

$$d_{error}(t) = d_{lead}(t) - d_{trail}(t)$$  \hspace{1cm} (3)

B. ‘Remain’ (sequencing) Application

The time-based airborne spacing ‘Remain’ application involves an air traffic controller asking a pilot to select a neighbouring aircraft as a target on a CDTI. For phraseology and more details see [7].

III. Airborne Spacing Director Design

A. Automatic Mode (automatic guidance)

The automatic spacing guidance law aims at establishing a given time spacing along track to a lead aircraft. The guidance law receives surveillance data from the lead aircraft and feeds the desired CAS input ($CAS_{automatic}$) of the aircraft model. The desired altitude ($h_{desired}$) is fed independently, and depends on the top of descent scenario. The following spacing guidance law was derived respecting the performance requirements:
\[
\text{CAS}_{\text{automatic}} = GS \rightarrow \text{CAS}_{\text{conversions}}(GS_{\text{automatic}})
\]

where the desired CAS of the trail aircraft \(\text{CAS}_{\text{automatic}}\) is derived by converting the desired groundspeed of the trail aircraft \(GS_{\text{automatic}}\) to the equivalent CAS. The desired groundspeed of the trail aircraft is based on the groundspeed of the lead aircraft where it was \(t_{\text{spacing}}\) seconds before, \(GS_{\text{lead}}(t - t_{\text{spacing}})\), plus a corrective speed term derived from the spacing distance error \(d_{\text{error}}\) divided by a variable time value \(t_{\text{leadogo}}\).

\[
GS_{\text{traildesired}}(t) = GS_{\text{lead}}(t - t_{\text{spacing}}) + \frac{d_{\text{error}}}{t_{\text{leadogo}}},
\]

where \(t_{\text{leadogo}}\) is given by:

\[
\text{If } d_{\text{lead}} \geq 2 t_{\text{spacing}} GS_{\text{lead}} \text{ then } t_{\text{leadogo}} = \frac{d_{\text{lead}}}{GS_{\text{lead}}} - t_{\text{constant}},
\]

\[
\text{else } t_{\text{leadogo}} = t_{\text{constant}},
\]

where \(t_{\text{constant}}\) is the guidance time constant that defines the guidance dynamic. Note that this algorithm was validated in real-time experiments (see [9]).

B. Spacing Accuracy Tolerance

In order to allow nonzero spacing accuracy tolerance, the time based spacing error \(t_{\text{error}}(t)\) was modified by modelling a dead-zone around 0. This dead-zone receives \(t_{\text{error}}(t)\) as input and generates zero output within the specified region. The lower and upper limits of the dead-zone are specified as the start and end of dead-zone parameters. The output depends on the input and dead-zone:

- If the input is within the dead-zone (greater than lower limit and less than upper limit) the output is 0.
- If the input is greater than or equal to the upper limit, the output is the input minus the upper limit.
- If the input is less than or equal to the lower limit, the output is the input minus the lower limit.

This dead-zone model uses lower and upper limits of - Threshold and + Threshold around zero.

C. Filtering Suggested CAS

To cope with human in the loop constraints the desired CAS of the trailing aircraft \(\text{CAS}_{\text{automatic}}\) is passed though a filter to reduce variations and to be presented to the pilot:

\[
\text{if } |\text{CAS}_{\text{out}}(t-1) - \text{CAS}_{\text{in}}(t)| \leq \text{Filter}_{\text{threshold}} \text{ then } \text{CAS}_{\text{out}}(t) = \text{CAS}_{\text{in}}(t)
\]

\[
\text{else } \text{CAS}_{\text{out}}(t) = \text{CAS}_{\text{out}}(t-1)
\]

where \(\text{Filter}_{\text{threshold}}\) is set to 5 knots, and \(\text{CAS}_{\text{out}}\) is the filtered CAS of the trail aircraft. This algorithm meets the spacing accuracy requirements (for validation see [7] and [10]) but leads to a large number of speed adjustments. When the lead aircraft makes a large change in CAS, the trail aircraft follows the speed profile but, instead of performing the equivalent CAS, as the lead did, in one step only, it makes this change by many consecutive adjustments.
D. Manual Mode with Lead History based Prediction

During real-time simulation experiments pilots commented that reducing the number of CAS changes would reduce their workload. Therefore to reduce the manual airspeed changes by the pilot, the spacing director also makes use of the history of the target’s position and velocity. By filtering out small changes in the speed profile history of the target, a larger less frequent step change can be derived for suggestion to the ownship flight crew. The algorithm is based on an analogy with human pilot behaviour in similar conditions. Searching through the lead CAS history, the moment when the lead performed a CAS change can be detected and corresponding magnitude of change estimated. This value is thereafter taken into account to derive the suggested desired CAS.

The filter frequency of the history based algorithm was tuned using Matlab based fast-time simulations by varying the length of the interval used to search through the speed profile of the selected target. Note that this algorithm was validated in fast-time experiments (see [10]).

Guidance mode for ‘remain’

The guidance law used to maintain the in-trail spacing is similar [10] to the merging guidance, and is not described in this note.

IV. Apparatus

A. Aircraft Model

The aircraft model (Boeing 747-400) 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 (see [15] and [16]). The model includes lateral motion of the centre of gravity and dynamic characteristics of the engines [6]. A detailed description can be found in [16]. 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.

B. Wind Model

The wind model is based on that of the EASA Certification Specifications for All Weather Operations (EASA-CS-AWO) autoland certification process [4]. In this model the mean wind speed is altitude dependent, and directly associated with the wind as measured at 30 feet AGL (Above Ground Level). The mean wind speed determines the turbulence intensity, and the wind velocity increases with altitude.

Mean wind

The magnitude of the mean wind increasing with altitude is defined by the following expression:

\[ V_{mean} = V_{30} \left( \frac{h}{30} \right)^{1/2} \]

where \( V_{mean} \) is the mean wind speed (knots) measured at \( h \) metres AGL and \( V_{30} \) is the mean wind speed (knots) at 30 feet AGL.

Turbulence spectrum

The turbulence model has a Gaussian distribution, conforming to the Dryden spectrum. The turbulence provided disturbances of the aircraft airspeed and angle of attack.

C. Human Pilot Model

Pilot reaction to the above demand from the spacing director, was modelled as the sum of a ‘scan’ reaction time and an ‘action’ reaction time. This model led to a normal distribution with an average of 8s and a standard deviation of 2s. This value is comparable with the average pilot’s reaction time in real-time simulations.
V. Method

A. Simulation Platform

The airborne spacing ‘remain’ and merge’ applications were simulated in fast-time using aircraft, pilot and wind models implemented with MATLAB/Simulink. 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.

B. Operational Scenario

The scenario used in real-time experiments [9] and replicated in Matlab was as follows: the lead aircraft 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. The corresponding lead aircraft profile generated by high-fidelity aircraft simulator based real-time experiment was recorded and used in fast-time simulations (Figure 4).

The lead aircraft followed its own descent profile and a trail aircraft of the same type (Boeing 747-400 with initial mass 271 tonnes) adjusted its own speed to acquire and maintain desired time spacing behind the lead. The two aircraft were flying straight along different merging trajectories to the same fixed merge waypoint. Once the lead reached the waypoint each aircraft follows its own trajectory within the sequence, trail aircraft maintaining the spacing between itself and the lead, with both aircraft descending to 5,000 feet.

The same entry conditions as in real-time experiment were simulated (CAS: 270 knots and FL 260 - Lead, CAS 290 knots and FL 250 - Trail). All scenarios were conducted assuming an ideal datalink between aircraft, to be consistent with real-time experiment conditions.
C. Metrics

The following metrics derived from real-time experiment [9] were used to evaluate the results:

- **Accuracy metric**: time spacing error during the “maintain spacing” phase (seconds). 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 (see equation 1). The advantage of measuring spacing error continuously before the merge waypoint, is that it gives an indication of the smoothness and predictability of an aircraft’s behaviour within a merging flow. In order to cope with a distribution of time spacing error which is not necessarily normal, 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 5: Accuracy metric illustration](image5)

- **Activity metric**: in fast time simulations this metric corresponds to the number of speed adjustments per minute performed by the pilot of the trail aircraft to acquire and maintain spacing. The metric is the mean number of speed actions per minute, associated with its standard deviation, minimum and maximum values (Figure 6). This metric is not used for the automatic mode because in this case demanded speed is varying continuously in time.

![Figure 6: Activity metric illustration](image6)

- **Cost metric**: cumulative CAS speed variation. The metric assess the impact of the spacing instructions on the flight efficiency, in measuring the CAS speed variations along the flight. The metric is computed in two steps: (1) compute CAS speed variations for each run (including lead), (2) compare the performed speed
variations to the lead speed variations (Figure 4) i.e. the difference between trail aircraft cumulative demanded CAS and lead aircraft cumulated CAS (knots). Same type of presentation was used as for the activity metric.

D. Experimental Parameters
The following parameters were varied as indicated in table below:

Table 1: experimental parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airborne spacing director mode</td>
<td>Automatic mode and manual mode with human in the loop pilot model</td>
</tr>
<tr>
<td>Guidance law dynamics time constant</td>
<td>Slow guidance (time constant = 180s)</td>
</tr>
<tr>
<td></td>
<td>Standard guidance (time constant = 120s)</td>
</tr>
<tr>
<td></td>
<td>Fast guidance (time constant = 60s).</td>
</tr>
<tr>
<td>Spacing dead zone threshold</td>
<td>0s, ±1s, ±2.5s, ±5s, ±7.5s</td>
</tr>
<tr>
<td>Initial time spacing error between aircraft</td>
<td>Random between -3s (trail early) to +3s (trail late)</td>
</tr>
<tr>
<td>Pilot random reaction time</td>
<td>Normal distribution with a mean of 8s and a standard deviation of 2s.</td>
</tr>
</tbody>
</table>

VI. Results

A. Number of Runs
In automatic mode, for each spacing dead zone threshold level, 30 runs were performed as follows: 10 runs (corresponding to 10 different initial spacing errors) x 3 (for each guidance dynamic) = 30 runs.
In manual mode for each spacing dead zone threshold level, 1,500 runs were performed, as follows: 10 runs (corresponding to 10 different initial spacing errors) x 3 (for each guidance dynamic) x 50 (random pilot reaction time) = 1,500 runs.

B. Accuracy Results
For each run, the mean, the maximum and minimum values, the lower and upper containment bounds of time spacing error were computed and recorded. Figure 7 and Figure 8 summarise the results for the automatic and the manual mode.
For each spacing accuracy tolerance level an overall corresponding spacing error was plotted as follows:
• Each mean represents the average of the 30 mean spacing errors (in automatic mode) / 1,500 means (manual).
• Maximum value is largest value over the 30 maximum spacing errors (automatic) / 1,500 maximums (manual).
• Minimum value is smallest value over the 30 minimum spacing errors (automatic) / 1,500 minimums (manual).
• Lower containment bound is smallest value over the 30 lower containment bounds (automatic) / 1,500 (manual).
• Upper containment bound is largest value over the 30 upper containment bounds (automatic) / 1,500 (manual).

Figure 7: Spacing error as function of spacing dead zone threshold – overall results for automatic mode
The manual mode results in a greater spacing error (Figure 8) than the automatic mode (Figure 7). This is not surprising since the manual mode is based on the automatic mode with the addition of an average 8s delay and a filter for removing small adjustments. Also the effect may be amplified by averaging over slow, medium and fast guidance law dynamics time constants.

C. Activity Results

For each run in manual mode, mean, standard deviation, maximum and minimum values of speed actions per minute were computed and recorded. Figure 9 summarizes the results. For each spacing accuracy tolerance level an overall corresponding number of speed actions per minute was plotted as follows:

- Mean represents the average of the 1,500 means.
- Maximum value is the largest value over the 1,500 maximum values.
- Minimum value is the smallest value over the 1,500 minimum values.
- Standard deviation is the average of the 1,500 recorded standard deviations.

For the lead profile under test, the mean number of speed actions decreases with spacing accuracy tolerance up to a spacing accuracy tolerance of 5s. The maximum number of speed actions for a spacing accuracy tolerance of 7.5s seems to increase. More data and more spacing accuracy tolerance levels are needed for greater spacing accuracy tolerances to investigate this effect.
D. Cost Results
For each run the mean, standard deviation, maximum and minimum values of cumulative CAS speed variations were computed and recorded. Figure 10 summarizes the results for both manual and automatic modes.

![Figure 10: Cumulative CAS variation as function of spacing accuracy tolerance: overall results (automatic and manual modes)](image)

The cumulative speed variation decreases significantly with increasing spacing accuracy tolerance until a spacing accuracy tolerance of 5s. As with the activity results, cost increases when spacing accuracy tolerance is 7.5s.

E. Minimum Performance Requirements
A trade-off between the metrics was found by comparing their variation with the experimental parameters. A spacing accuracy tolerance level of 2.5s gave the lowest control activity and cost for the minimum acceptable spacing error. Corresponding minimum performance requirements for each of the metrics are derived in Table 2. Although the spacing error distributions tended to be asymmetric, simple symmetric bounds were derived from the highest positive or negative value. Note: maximum and minimum values for all the results correspond to the extreme values from each of the three guidance laws dynamics time constants (slow, medium, fast).

<table>
<thead>
<tr>
<th>Requirement type</th>
<th>Performance parameter</th>
<th>Automatic mode</th>
<th>Manual mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>Time spacing error</td>
<td>[Mean] &lt; 1.5s</td>
<td>[Mean] &lt; 2.5s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>lower safety containment bound = -4s</td>
<td>lower safety containment bound = -6s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>upper efficiency containment bound = 4s</td>
<td>upper efficiency containment bound = 6s</td>
</tr>
<tr>
<td>Control activity</td>
<td>Frequency of speed adjustments</td>
<td>Not applicable</td>
<td>[Mean] &lt; 1 action per minute, with a standard deviation &lt; 1 action per minute</td>
</tr>
<tr>
<td>Control cost</td>
<td>Cumulative airspeed variation</td>
<td>[Mean] &lt; 10 knots with a standard deviation &lt; 10 knots</td>
<td></td>
</tr>
</tbody>
</table>

Note that the accuracy requirement assumes a measurement of time spacing at current position whereas some complementary studies by NASA [12] assume a measurement of time spacing predicted at the runway threshold.

VII. Conclusion
The trade-off between time spacing accuracy and corresponding control effort in a potential future ASAS application was investigated. The ASAS application airborne spacing sequencing and merging was simulated in fast-time. Lead aircraft speed profiles were generated using complete descent profiles from real-time experiments. For validation purposes, three metrics were derived from real-time experiments: time spacing error (accuracy), frequency of speed adjustments (control activity), and cumulative airspeed variations (control cost). Four experimental parameters were varied: automatic and manual speed control, spacing dead-zone, guidance law dynamics time constant and initial time spacing error. A trade-off between the metrics was found for a sequence of two aircraft by comparing their variation with the experimental parameters. Corresponding ‘minimum’ performance requirements for each of the metrics are proposed: (i) time spacing error - mean less than 1.5s with 0.5 to 85% of the...
values between -4 and +4s (automatic mode), and mean less than 2.5s with 0.5 to 85% of the values between -6 and
+6s (manual mode), (ii) frequency of speed adjustments - mean less than 1 action per minute (manual mode) and
(iii) cumulative airspeed variations - mean less than 10 knots (automatic and manual modes). These requirements
form a basis for investigating sequences longer than two aircraft where chain propagation effects may lead to
additional constraints.

The above initial set of minimum performance requirements will be refined and improved by considering a large
number of lead aircraft airspace profiles and by adding more trail aircraft of mixed types in the sequence. In
particular the degree to which disturbances of spacing error are propagated and amplified through sequences longer
than two aircraft needs to be quantified and incorporated in the minimum performance requirements. Compounding
effects of: strong turbulent winds and airborne surveillance transmission quality such could also be investigated.

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