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# Pilot Support for Distance-Based In-Trail Following Tasks

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## PILOT SUPPORT FOR DISTANCE-BASED IN-TRAIL FOLLOWING TASKS

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Transferring the spacing task from the air traffic controller to the pilot can benefit efficiency and capacity. To separate a chain of aircraft, time-based rather than distance-based principles are preferred as they result in better performance in case of gradual reducing speeds in arrival streams. The present-day air traffic management systems, however, operate mainly on a spatial rather than a temporal basis, and air traffic controllers monitor the distance between trailing aircraft to determine if separation requirements are satisfied. If the disadvantages of distance-based spacing can be dealt with, the implications of introducing distance-based procedures for the current controller and pilot working environment would be much smaller than compared to time-based procedures. This paper presents the *spacing reduction concept* as a solution for the principal disadvantage of distance-based in-trail following, the slow-down effect. Displays and procedures were tested in a pilot-in-the-loop experiment. It is shown that distance-based spacing procedures can produce a stable chain of up to five aircraft, with very low pilot workload.

### Introduction

Sequencing aircraft on an arrival route requires the air traffic controller to provide each aircraft steering commands, including speed, altitude and heading directions. Controllers attempt to have aircraft follow similar speed profiles along the arrival. When limits for separation are (to be) violated, speed clearances are issued to counteract the violation. In doing so, the controller transforms the ‘global’ mental picture of the approach sequence into a set of ‘local’ commands for one particular aircraft, a task that results in considerable workload. Transferring the spacing task from the controller to the pilot, i.e., *in-trail self-spacing*, would relieve controllers from this task, to the potential benefit of efficiency, capacity, and safety (Hoffman et al. 1999, Abeloos et al, 2001).

Pioneering work showed that spacing can be either *time-based* or *distance-based* (Sorensen & Goka, 1983, Williams, 1983). Generally, time-based spacing is preferable over distance-based spacing. A ‘constant distance’ criterion results in a slow-down in the speed-profile of a chain of aircraft because it requires trailing aircraft to fly the same ground speed as the leading aircraft. This is referred to as the *slow-down effect*. Time-based procedures would require the time distance between aircraft to be kept constant throughout the arrival. Subsequent lower speeds would not result in slow-down effects because the time requirement imposes subsequent lower spacings. These procedures, however, differ considerably from the way controllers and pilots currently operate. Current day radar systems and procedures operate under *spatial* representations of the air-traffic situation. Pilots share these problems during time-based self-spacing procedures, as the main sources of traffic-related information in the cockpit, like the Cockpit Display of Traffic Information (CDTI), also provide spatial situation presentations. Time-based procedures require new displays and tools to help pilots and controllers in handling time-based procedures (Lee et al, 2003).

Distance-based self-spacing procedures require far less modifications of procedures and systems. This paper describes how these procedures can be defined without the slow-down effect to occur. The pilot interface was developed simultaneously with the procedure (Pritchett & Yankoski, 2003). The results of an experiment are presented.

### Spacing Reduction Procedure

With the ‘constant distance’ method the pilot task is to maintain a certain distance behind another aircraft, the *spacing requirement*. The aircraft that is being followed is called the target aircraft or *target*, the aircraft following target is called the own aircraft, or *own*. The spacing between aircraft is defined along the track. The difference between the required spacing and the actual spacing is the *spacing error*.

A requirement of self-spacing procedures is that every aircraft in a chain must follow the same ground speed profile. ‘Basic’ distance-based spacing does not automatically yield the same speed profile of the target aircraft like time-based methods do. It can be adapted, however, to bring about the same behavior. The crux of the matter lies in the fact that a *fixed* spacing requirement forces trailing aircraft to fly the same speed as the very first aircraft in the chain. But when the spacing requirement is allowed to *vary*, in a structural and procedurally well-described manner, along the approach, the slow down effect can be eliminated. This is shown in Figure 1.

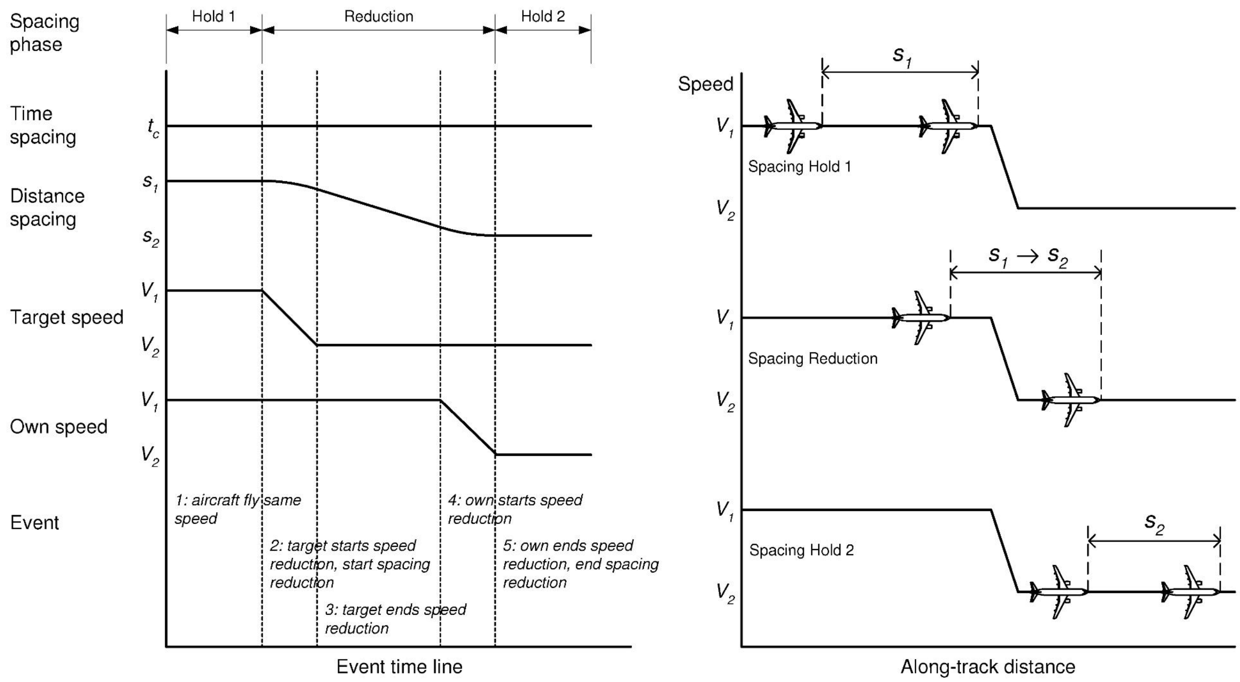


**Figure 1.** *Spacing development caused by a speed reduction of target from $V_1$ to $V_2$, with a constant time spacing $t_c$.*

The very moment at which the spacing requirement should change, is when *target starts its reduction in speed* (event 2). The change in spacing requirement should be discrete rather than continuous, and should be $s_2$. This $s_2$ belongs to the speed that target is heading at, $V_2$ in Figure 1. Right after the spacing requirement has been changed, *no action by own* is initially necessary. Only after the spacing has reduced from $s_1$ to $s_2$, own is to reduce speed to $V_2$. During the spacing reduction own is to *remain its current speed* $V_1$. The speed reduction to $V_2$ (event 4) is to take place some time before the spacing has reduced completely (event 5), because during the deceleration from $V_1$ to $V_2$ the spacing will still reduce a little. One can see that although the *speed profile* of own and target do not match exactly, the spacing requirement is met. The phase in which a speed reduction of the target aircraft initiates a spacing reduction, until the own aircraft meets the spacing requirement, is referred to as the *spacing reduction* phase. The phase during which the spacing is constant is referred to as the *spacing hold* phase. These phases can also be identified in Figure 1.

*Chains*

The present study will consider a chain of aircraft flying using the spacing reduction procedure. A leading aircraft receives speed clearances from the controller, the trailing aircraft operate under self-spacing procedures. Each trailing aircraft executes the self-spacing task with respect to its predecessor in the chain. All aircraft in the chain fly the same trajectory. The speed profile that is flown by the first aircraft in the chain is the *nominal speed profile* of a chain. Since self-spacing is best performed when aircraft follow the same speed profile, good self-spacing behavior should result in trailing aircraft flying speeds close to the nominal speed profile.

*Controller Tasks*

The task for the controller is to issue speed clearances to the very first aircraft in the chain. By doing this the controller defines the nominal speed profile for the chain that this aircraft is leading. A trailing aircraft should now be issued spacing clearances at the very moments that the target of this aircraft reduces speed.

*Pilot Tasks*

Two tasks exist for the pilot, dependent on the spacing phase. First, in the case of spacing hold, the pilot is to maintain a constant distance behind the target aircraft. Basically the pilot needs to adjust his speed so that the spacing does not change. Therefore own's *ground speed* has to be the same as target's ground speed. Spacing errors should be counteracted by changes in speed. The second task is executed when the pilot enters the spacing reduction phase. When the spacing requirement changes, the procedure requires the pilot to maintain the current speed $V_1$ until speed has to be reduced to meet the spacing requirement. After a change in spacing requirement, the spacing error and the closure rate both instantly increase. The pilot is expected, however, to *take no action* to counteract these ‘errors’. Instead the pilot should be aware that the spacing error will decrease *by itself*, since the target aircraft has reduced speed. Only when the spacing requirement is met the pilot is to take action by reducing speed. An experiment will evaluate whether this procedure is acceptable.

## Display Design

It is assumed that aircraft are equipped with ADS-B. The ADS-B message contains state information of the target aircraft, such as indicated airspeed, ground speed, track and position. This information together with the state of own makes it possible to calculate for example relative speed and distance information. The navigation display (ND) that stands at the basis of the experiment is a Boeing 747-400 ND, Figure 2. A design objective was to keep additional self-spacing systems as straightforward as possible. No automation and only simple algorithms are used.

### *Self-Spacing Symbols*

Self-spacing augmentations included the target state information (speed, altitude), relative information (current distance), trend information (closure rate), intent information (target $V_{cmd}$) and predictive information (spacing capture marker, speed reduction counter). Also the spacing requirement with the allowed error margin was depicted on the display (spacing marker).

### *Traffic Symbols*

The display design used TCAS-like information for all traffic and the target, where an indicated airspeed indication was added to every traffic symbol. This enables pilots to assess what speeds can be expected, thus making an estimation of the nominal speed profile. Knowledge of target’s current speed and the nominal profile, which is flown by the first aircraft in the chain, is expected to yield better performance.

### *Spacing Marker and Allowed Error Margin*

A *spacing marker* indicated the position along-track where own should be. To rule out exact error tracking, a spacing requirement *area* or *spacing error margin* is presented to the pilot instead of the exact spacing requirement. The allowed error was 5% of the requirement. It is hypothesized that if pilots are allowed to have some spacing error, not every speed change by the target aircraft is followed. In this way speed errors made by preceding aircraft are expected to be “filtered out”, improving chain stability.

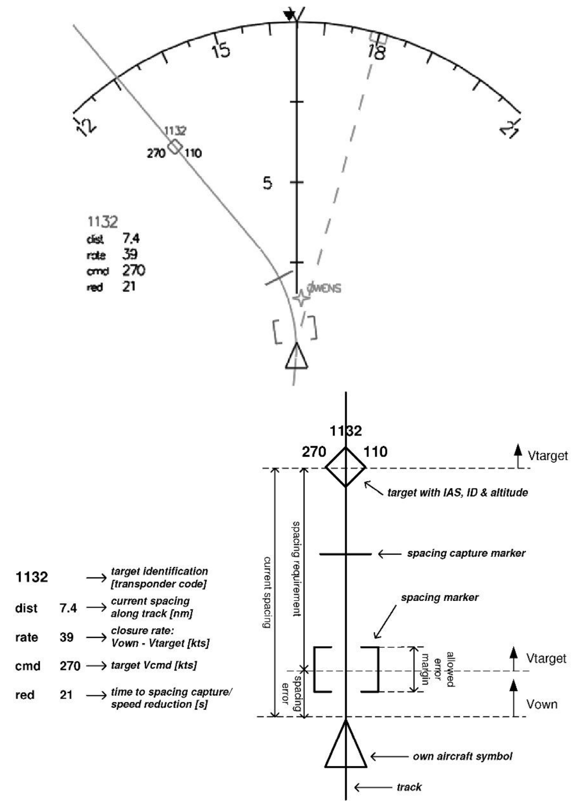


**Figure 2** The Boeing 747-400 Navigation Display, augmented with self-spacing symbology.

### *Spacing Capture Marker*

The *spacing capture marker* (SCM) can assist pilots during spacing reduction. Here the spacing error reduces since target is flying at a lower speed then own. At some point in the future the error will be zero and the spacing requirement will be met. The SCM marks the location along-track where the spacing requirement will be met, and calculates the time to get to this location. It takes into account the time needed to decelerate to the target’s speed and achieve a zero closure rate. The SCM uses a linear deceleration model that predicts the very moment at which the pilot should reduce speed (event 4 in Figure 1). When the marker is reached, pilots can reduce and select a speed that matches the ground speed of the target.

## Experiment

*Subjects and Instructions to Subjects.* Twenty professional airline pilots participated in the experiment. The first four pilots each did twelve experiment runs, where the remaining sixteen pilots did sixteen runs. Pilots were introduced to the general concept of self-spacing, and more specifically to the principles of the procedure developed here. They were instructed to execute the spacing reduction phase by maintaining their speed. During spacing hold, pilots were instructed to use the spacing error margin in case of deviant behavior of their targets.

*Independent variables and experiment design.* Three independent variables were tested.

Two procedures were defined. First, the *controller's initiative* procedure, where pilots received spacing instructions directly from the controller. The spacing instructions were tied to the sections that defined the arrival and the nominal speed profile, through waypoints. The second procedure is the *pilot's initiative* procedure, where it is the pilot's task to determine and select the correct spacing requirement in case of a speed reduction of the target aircraft. A table with the correct spacings for several speeds was shown on the arrival chart.

Four different displays were used. They incorporated all features introduced above. To assess the usability of the SCM and $V_{cmd}$ indication, these features were not always present in the display. This results in four display configurations.

Four chain positions, namely positions 2 to 5, were used. The aircraft flying at position 1 was pre-recorded and followed a perfect nominal speed profile. Every run was recorded and played back: a pilot would be following a target aircraft that was actually flown by a previous experiment pilot.

The three independent variables yield 32 experiment conditions. These would require 32 pilots, who each fly 32 runs. This amount of runs would require too much time, and the amount of combinations and therefore pilots is cut in half. Pilots still fly each combination of 'procedure' and 'display' but only half of the possible combinations of 'procedure and display' and 'position'. The remaining sixteen combinations included a different set of positions for each pilot, while still all four positions would be flown four times by each pilot.

*Arrival scenarios.* Nine arrival scenarios were defined, where each scenario *arrival route* shared the same underlying structure (Figure 3). Each route would be rotated, mirrored and given an altitude offset yielding a different scenario for each run.

In section 2 a disturbance is introduced in the scenario. In section 2A the speed of 300 IAS and a nominal altitude of 12000ft, together with a time spacing of 81 seconds dictates a spacing of 8.0 nm. When aircraft entered section 2B pilots had to descend 1000ft. While still flying at 300 IAS, the lower altitude causes the true airspeed, and hence the ground speed, to drop a few knots. Trailing aircraft, still flying 1000ft higher and trying to maintain a low closure rate, would be forced to slow down a little.

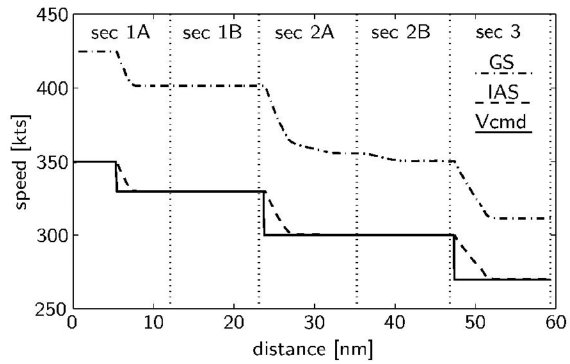


**Figure 3.** *Nominal speed profile where speed reductions are tied to the sections of the arrival route.*

*Apparatus.* The experiment was conducted in a fixed base simulator. This simulator included two 18" LCD screens on which a Primary Flight Display, Navigation Display and virtual Mode Control Panel (MCP) were shown. The autopilot was engaged during the entire run. Pilots could select autopilot speed and altitude targets via the MCP. The experiment leader acted as air traffic controller.

*Aircraft and weather model.* A non-linear B747 200 model was used. An ISA standard atmosphere was used and no wind was present.

*Dependent measures.* Since the nominal arrival would only require three speed reductions, the *number and size of speed changes* during the runs is the first measure. The second measure is the error of the *ground speed trace* of a run compared to the nominal speed profile. The error is measured over *time* since the experiment tries to separate the aircraft with a constant time-spacing equivalent. The third measure is spacing performance, i.e., the time that a pilot remains in spacing hold and the average spacing error. Workload was assessed using NASA TLX.

*Hypotheses.* It is hypothesized that it is possible to bring about constant-time-like self-spacing behavior using a constant-distance procedure in a stepped speed profile, canceling any slow-down effects. It is expected that intent information like target $V_{cmd}$ and in particular the SCM will increase performance and reduces workload. Finally it is hypothesized that pilots will be able to cancel out “chain-effects”. A chain-effect is defined by the passing on and amplification towards the back of the chain of “deviant” behavior of aircraft at the front of a chain. It will be assessed by determining how the three dependent measures speed changes, speed error and spacing error of aircraft at the back of the chain is effected by deviant behavior for the same three measures by aircraft in the front of the chain.

## Results and Discussion

*Number of speed changes*

Where the nominal speed profile only required three speed reductions the average number of speed changes was slightly more than 6. It was not affected by the procedure or the display, it slightly increased for positions further back in the chain, but this effect was not significant. This indicates that pilots were quite able to ‘filter out’ any unnecessary speed changes of aircraft flying in front of them.

A significant effect on the number of speed changes is found for the *section* in which the aircraft was flying (F=49.746, $p$<0.01). The number of speed changes in section 2 was almost twice the number in sections one and three. In section 2 the altitude dropped 1000ft when aircraft entered section 2B. When the *target* aircraft entered section 2B, the altitude drop causes the ground speed to reduce a little. This had to be compensated by *own*, still flying in section 2A, requiring some small speed reductions.

Overall, pilots understood the difference in tasks between the spacing hold and reduction phases. During spacing reduction pilots were to remain their current speed until the spacing requirement was met. Therefore the number of speed changes is lower as compared to the spacing hold phase. The average of about 6 speed changes are almost all accounted for during the spacing hold phase, which lasted about 70 % of the total runtime. Thus the comparison of the total amount of speed changes during spacing hold and reduction should be done with care.

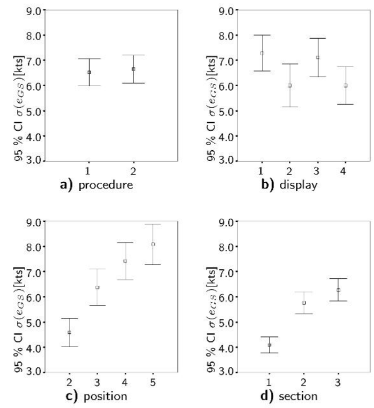


**Figure 4.** *Speed error with respect to nominal.*

*Speed Error*

Figure 4 shows the (standard deviation of) the ground speed error $e_{GS}$, where the ground speed of every run is compared to the *nominal speed profile*, see Figure 3. The procedure does not impose effects on the speed error. Performance significantly improved for displays with the SCM (2 and 4) (F=11.950, $p$<0.01).

The effect of the chain position is also significant (F=19.038, $p$<0.01), resulting in a growing speed error for positions further back in the chain. In sections 2 and 3 the speed error is larger then in section 1. This is caused by a slow-down effect in section 2, where the average speed decreases for positions further back in the chain. This coincides with findings for the speed changes in section 2, discussed above. The slow-down is *compensated for*, however, in section 3, where speed error grows more positive for positions further back in the chain.

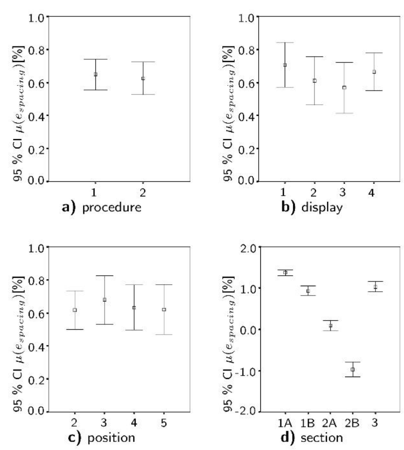


**Figure 5.** *Spacing error with respect to nominal.*

*Spacing Performance*

The spacing error with respect to the *nominal spacing profile*, i.e., tied to the arrival structure, is studied. By analyzing spacing performance with respect to the nominal spacing profile the spacing performance is assessed from a controller's perspective. Figure 5 reveals no effects of the experiment conditions on the average spacing error. However, over the *sections* the error varied much. In section 2 pilots started flying 'too-close'. Apparently the slow-down effect is compromised by pilots letting the spacing error become more negative instead of trying to fly a zero closure rate and a zero spacing error. This was substantiated by analysis of the closure rate for small spacing errors; in section 2 the average closure rate for small spacing errors is two times higher then in sections 1 and 3 (de Groot, 2004).

*Chain Effects*

Some chain effects are found for the speed error but these effects are not very strong. This means that high speed errors of aircraft flying at the front of the chain did not result in much higher speed errors at the back of the chain. No chain effects are present for the spacing error either, i.e., large spacing errors of aircraft flying at the front of the chain are not passed through towards the back of the chain.

*Workload*

The workload of the task was rated very low. No effects were found of the procedures. Displays with the SCM reduced workload, ($F=3.5934$, $p=0.059$). Borderline significance was found for the position in chain ($F=2.358$, $p=0.072$), indicating that the workload was a little higher at the back of the chain.

*Subjective Comments*

Pilots rated the procedure as providing enough information to assist them in the self-spacing task. They preferred the controller's initiative procedure, as they believe the controller has a better overview of the situation and therefore should remain in control of determining and issuing spacing requirements. Also time pressure is rated lower compared to the pilot's initiative procedure. Pilots noted that the latter could become a very efficient procedure if they would be allowed to follow their own vertical trajectory, with only spacing requirements at certain positions along the arrival. Finally, pilots commented that spacing requirements could be tied to waypoints instead of arrival sections or target speeds.

*Displays*

Generally the displays were rated as providing an appropriate level of information to the pilot. Ratings for the various display features reveal that the distance to the target aircraft and the closure rate were very helpful. Pilots commented that the spacing marker is required but should not be placed on the track because it requires a small display range. Instead they would prefer a spacing indication in the form of a bar that does not depend on the ND range.

The target $V_{cmd}$ indication was considered superfluous since the nominal speed profile was clear and pilots did not expect the target aircraft to select off-nominal speeds. However, in off-nominal situations they indicated that $V_{cmd}$ could be useful.

The SCM was considered very helpful, as it was reported to take away time pressure during spacing reduction. Instead of having to scan the display continuously, the SCM instantly indicates if action (speed reduction) is already required. Many pilots reported an intensive use of the speed bug attached to the target aircraft symbol. They used the speed bugs on other traffic flying down the arrival to assess what speeds are to be expected, thus creating a mental picture of the nominal speed profile.

## Conclusions

The spacing reduction concept can rule out slow-down effects with distance-based spacing in approaches where speeds gradually reduce. The selection of spacing requirement by the pilot instead of the controller does not bring about more off-nominal speed and spacing behavior. Pilots commented that a procedure where speed and spacing requirements are published on arrival charts would create a workable situation. However, they noted that the controller should remain responsible and intervene in cases of off-nominal behavior of target.

No strong chain effects were found. The allowance of spacing error introduced a dampening effect because it allowed pilots more time to assess, and act to, the actions of the target aircraft. The knowledge of the nominal speed profile, provided by speed tags on traffic symbols, also retained pilots from following off-nominal behavior of target aircraft. Pilots rated the workload of the self-spacing task as very low and they believed that introducing the task into the arrival phase of the flight is possible.

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