# TJHSST Senior Research Project
# Advanced Speed Guidance for Merging and Sequencing Techniques
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**Abstract**

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# 1 Introduction

For several years now, aviation experts have been working to design procedures and technologies that will be placed aboard aircraft to help controllers with merging streams of traffic inbound to the same airport and keeping those aircraft properly spaced as they complete the approach and landing. Those technologies include software that computes a suitable speed to fly and presents that information to the pilot. However, one of the problems researchers are currently running into is that too many speed recommendations are being sent to the pilot. With too many speed commands, a pilot can be overwhelmed and may not be able to devote his/her attention to the proper places. The purpose of this project is to use various methods and algorithms to reduce the number of speed command while maintaining proper spacing

# 2 Background

Merging and sequencing techniques take advantage of Automatic Dependent Surveillance-Broudcast (ADS-B) technology that enables aircraft to send trajectory data directly to another aircraft. When engaged, ADS-B allows aircraft to seamlessly communicate and exchange data with one another without requiring the pilot's direct attention. This advancement in technology becomes particularly useful when aircraft are following one another. With ADS-B, an aircraft can receive the trajectory data (position, velocity, heading, etc.) from the target aircraft (the lead aircraft) and use this data to calculate a recommendation for a proper following distance between the aircraft. The speed changes that are required to get to where the aircraft should be are recommended to the pilot. Because ADS-B updates very frequently, merging and sequencing technologies that are on board aircraft can use the data coming from ADS-B to continually update the aircraft's trajectory based on the target aircraft.

# 3 Procedures

As previously mentioned, experts have been working on algorithms and procedures that will be used on aircrafts to keep aircraft properly spaced as they complete the approach and landing. While experts have not reached a consensus on what algorithms should included in the software, an overall procedure for the use of the algorithms has already been defined.

The overall goal of the algorithms is to give ownship recommendations for a speed to fly so that proper spacing will be maintained between the ownship and target aircraft. The algorithms use trajectory data from the target aircraft to calculate the current spacing value, that is, a measurement of how far ownship is behind the target aircraft, and compares that to the desired spacing value. The desired spacing value is a spacing distance that is declared by the Air Traffic Controller that is monitoring the airspace. After comparing the current spacing value to the desired spacing value, a spacing value is calculated that indicates how far ownship is from the desired spacing value. In order to maintain the desired spacing value, the spacing value must be corrected. The speed to fly that will elimate the spacing value, and thus obtain the required spacing value, is estimated and sent to the pilot as a recommendation. While this is the core of the procedure, there are other functions and algorithms which are used in unison with those listed above. These include filters, quantisers, and the improved algorithm.

### 3.1 Calculation of the Spacing Value

The desired spacing value is a measurement of how far behind the target aircraft's current position an aircraft should be. This spacing value reflects the optimal flying distance between aircrafts, based on the profile of each aircraft, that is considered to be safe. For distance-based spacing, the spacing value increases as the speed of the aircraft increases. With time-based spacing, the spacing value represents a constant time delay behind the target aircraft. A major benefit to time-based spacing is that the distance between the aircraft naturally compresses and expands as the speed of the aircraft increases.

### 3.2 "Remain Behind"

The idea of "Remain Behind" applications is that an aircraft remains behind a target aircraft at a desired spacing value. The flight crew adjusts the speed of the aircraft to acquire, if neccessary, and maintain the desired spacing value. The goal of the algorithm in this case is to give the flight crew a speed recommendations for how to obtain the desired spacing value.

### 3.3 "Merge Behind"

"Merge Behind" applications occur when two aircraft are flying along trajectories that plan to merge together. During the merging phase, the flight crew adjusts the speed of the aircraft so that the aircraft will be properly spaced behind the target aircraft when the merge is complete. The goal of the algorithm is to estimate how close the aircraft will be to the target aircraft when the merge is complete and give the flight crew a speed recommendation that will yield proper spacing upon the completion of the merge. After the merge point, the aircraft automatically transitions to the "Remain Behind" phase.

## 4 Calculation of The Spacing Value

### 4.1 Distance-Based Spacing for "Remain Behind"

For "Remain Behind" applications, ownship attempts to directly follow the path of a target aircraft. With distance-based spacing, the Along Track Distance (ATD) between ownship and the target aircraft is computed and used to calculate the proper spacing value. The ATD is not the direct distance between the aircraft, but rather the distance along the path to be flown.

If there are no turns between ownship and the target trajectory, the ATD is simply the distance from the target aircraft and ownship's projection onto the target trajectory as shown in Figure 2. However, if there are turns in the target's trajectory then they must be taken into account when computing the ATD. If there are one or more waypoints between ownship and the target (e.g. 2) then

- ATD = dist(ownship, start of turn1) + dist(start of turn1, end of turn1) + dist(end of turn1, start of turn2) + dist(start of turn2, end of turn2), dist(end of turn2, target)

As with all of the spacing algorithms, the spacing value at any point in time is calculated by taking the difference between the required spacing, x, and the actual spacing. For distance-based spacing, the current spacing is ATD(ownship, target aircraft), so the spacing value is x - ATD(ownship, target aircraft).

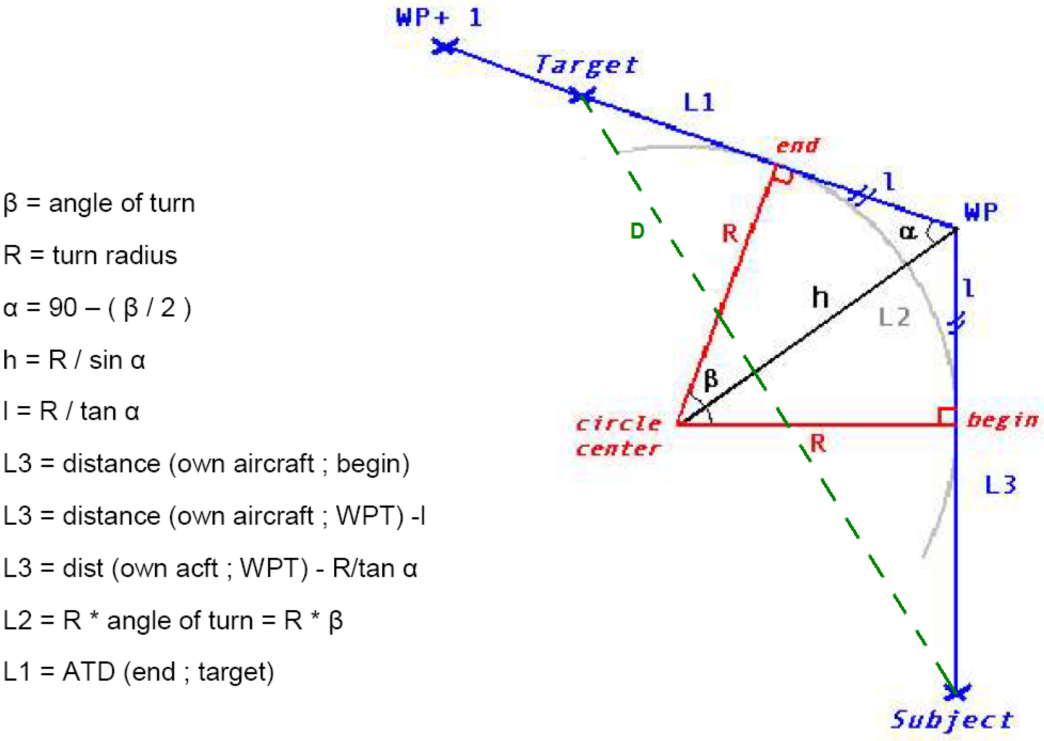


Figure 1: The ATD is L1 + L2 + L3, the distance along the path to fly, not D [3]

### 4.2 Time-Based Spacing for "Remain Behind"

In "Remain Behind" applications, the objective of time-based spacing is to follow the target with a constant time delay. In other words, ownship should be where the target aircraft was x seconds ago. To calculate this spacing, the target aircraft's position must be recorded. The positions of the target aircraft are recorded in a table that will be used to look up where the target aircraft was x seconds ago. To limit the size of the table, data is only saved for x seconds (desired spacing value) so that there are never more data points than needed. The position of the target aircraft x seconds ago is compared to ownship's current position, and the ATD is calculated. The ATD is then converted to time units by dividing the ATD by ownship's ground speed, giving the equation for time-based spacing as:

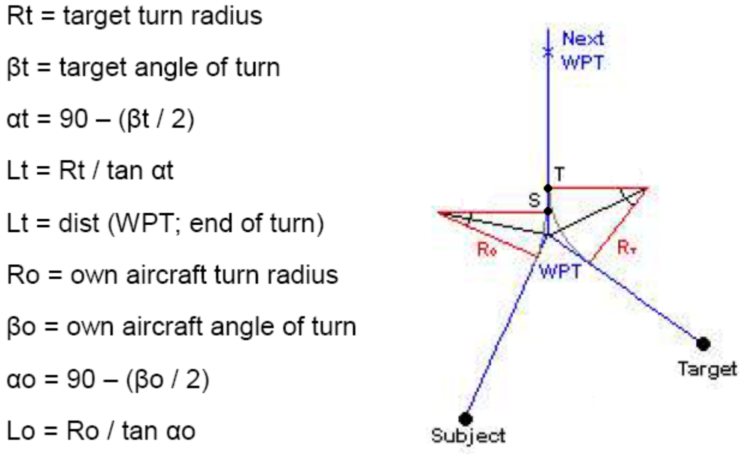
- Time-based Spacing $= x + \dfrac{ATD(ownPos(t), targetPos(t-x))}{ownGS(t)}$

In order to compute this spacing, the trajectory data of the target aircraft shall be recorded in a table. By saving the history data, the data from $t - required\_spacing$ seconds ago may be easily accessed and used to compute the spacing value. If data from $t - required\_spacing$ is not available, that is, if $t < required\_spacing$, then the the current position of the aircraft is compared to the position of the lead aircraft at the earliest available time.

## 4.3 Distance-Based Spacing for "Merge Behind"

The spacing value for merge applications is the projected spacing distance that will exist between the two aircraft when the target aircraft reaches the merge point. Trying to estimate the positions of both aircraft when the merge is complete is normally very unstable; the capability to calculate a proper spacing value is limited by the accuracy of the expected flight plan of ownship and target aircrafts. This is because the aircraft do not merge at the same point, so the merges for each aircraft are considered complete at different times. However, if the spacing calculation takes the distance to the first common point of the two aircraft after the merge into account, the spacing value becomes much more stable. The spacing value is derived by calculating the difference in the ATD of each aircraft to the first common point after the merge.

## 4.4 Time-Based Spacing for "Merge Behind"



Rt = target turn radius

βt = target angle of turn

$\alpha t = 90 - (\beta t / 2)$

$Lt = Rt / \tan \alpha t$

Lt = dist (WPT; end of turn)

Ro = own aircraft turn radius

βo = own aircraft angle of turn

$\alpha o = 90 - (\beta o / 2)$

$Lo = Ro / \tan \alpha o$

Figure 2: The spacing value is calculated by using the first common point in the trajectory, T, as opposed to the point where the merge is complete, S. [3]

As with distance-based calculation, trying to estimate the time spacing between both aircraft after the merge point based on their relative ground speeds would lead to a very unstable value of spacing. To ensure the stability of the spacing value when passing from merge to remain behind, calculations should be based on the position of the target aircraft (t-x) seconds ago, x being the desired spacing value. As with remain behind applications, the current spacing value is calculated based on the target data x seconds ago:

- Time-Based Spacing $= x + \dfrac{ATD(own\_pos(t), FCP) - ATD(target\_pos(t-x), FCP)}{OGS}$

Where ATD is the along track distance and FCP is the first common point of the two aircraft in the trajectory.

# 5 Suggested Speed Calculation

## 5.1 Basic Calculation

The suggested speed is a recommendation made to the flight crew in order to maintain proper spacing. Using the spacing value and time constraints, as previously defined, the suggested speed corrensponds to the following ground speed:

- Distance-Based Spacing: $\text{GS} = TargetGS + \frac{Spacing\_value}{Time\_Constraint}$
- Time-Based Spacing: $\text{GS} = TargetGS(t - x) + OGS * \frac{Spacing\_value}{Time\_Constraint}$

## 5.2 Improved Suggested Speed Calculation

When there is a large change in the Indicated Air Speed (IAS) for the target, ownship will attempt to follow the desired speed profile but instead of making one large speed change as the target aircraft did, ownship will make many consecutive adjustments. Small, consecutive speed commands are recommended to the pilot when there is no improved algorithm. The goal of the improved algorithm is to reduce the number of speeds recommendations that are sent to the pilot by giving the pilot one large speed command in place of multiple small commands. However, this must be done while maintaining the proper spacing between aircrafts. This is demonstrated in Figure 3. The red line is the target aircraft, the blue line represents the speed recommendations calculated for ownship, and the green line represents what ownship flies like with the improved algorithm.

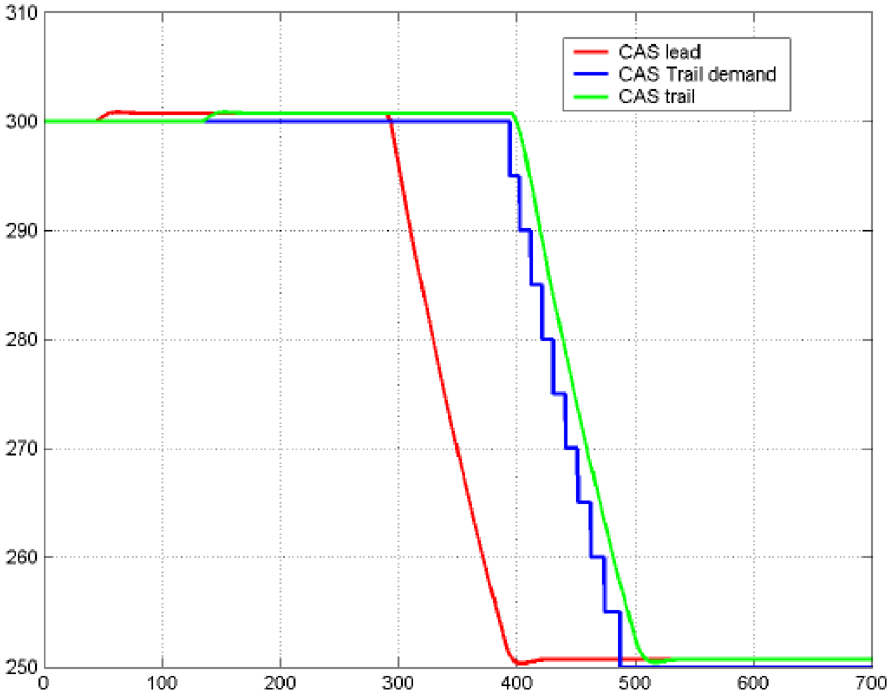


Figure 3: Comparison of the improved algorithm and the regular spacing algorithms[3]

The improved algorithm is neccessary to avoid small consecutive adjustments such as these. By searching through the target IAS history, the moment when the lead aircraft begin making a large IAS change can be detected and the corresponding magnitude of change can be estimated. The goal of the improved algorithm is to give one large speed command instead of many consecutive speed commands. To achieve this goal, the improved algorithm was executed according to the process below, as defined in [3].

### 5.2.1 Algorithm Process

1. Compute the basic filtered IAS by means of "Remain Behind" or "Merge Behind" algorithms.

2. Estimate the IAS of the target aircraft based on its groundspeed and barametric altitude.

   To conserve memory, the IAS of the target aircraft should be recorded during a period covering at least the time corresponding to the required spacing.

3. Detect the moment in the past at which the target changed its IAS

   The derivative of the target estimated IAS is computed and should be recorded during a period equal to the period during which the target estimated IAS is recorded.

   $$Target\_estimated\_IAS\_derivative(t) = \frac{Target\_estimated\_IAS(t) - Target\_estimated\_IAS(t - \Delta t)}{\Delta t}$$

   It is considered that there is a change in the target estimated IAS when the magnitude of the derivative at [t - Required Spacing] is greater than a threshold value. A threshold IAS_derivative_threshold is defined within the range of 0.1 knots/second to 0.5 knots per second.

   IF $Target\_estimated\_IAS\_derivative\,(|t - required\_spacing\_time)| > IAS\_derivative\_threshold$
      THEN a change in the target IAS is considered to be detected
   ELSE IF $|Target\_estimated\_IAS\_derivative\,(t - required\_spacing\_time)| \leq IAS\_derivative\_threshold$
      THEN no change in the target IAS is detected

4. Estimate the magnitude and duration of the detected target IAS change

   After an initial change is detected in the IAS (step 3), the difference between consecutive discrete IAS values is computed. These values are calculated on a constant search interval starting at $t - required_{s}pacing_{t}ime$. While these differences are above a given threshold, consecutive differences are cumulated to obtain the total magnitude of change (*change_estimated_magnitude*) and the corresponding duration of the change (*change_estimated_duration*).

   The search continues until one of the following occurs:

   (a) The difference between two consecutive discrete IAS is below the threshold.
   (b) When the search reaches the most recently recorded data point. In other words, when there is no more data to search through.

5. Compute the improved suggested speed

   Once the *change_estimated_magnitude* and *change_estimated_duration* have been calculated, the change detection should be frozen for the next *change_estimated_duration* seconds.

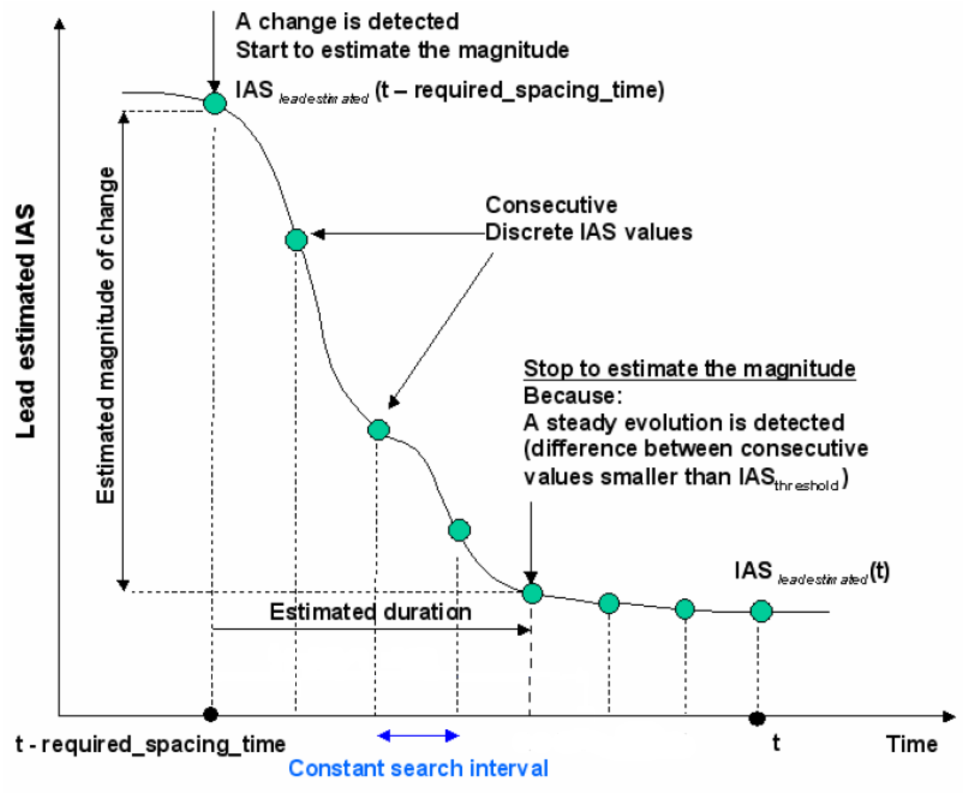


Figure 4: Algorithm principle of the improved speed algorithm[3]

During the freeze time, the Improved_suggested_speed is the sum of the *change_estimated_magnitude* and the suggested speed to fly from either "Merge Behind" or "Remain Behind" applications.

6. Rounding of the suggested speed

   The Improved_suggested_speed, as calculated above, is rounded to the closest multiple of a rounding threshold (e.g. 5 kt) to obtain a speed which will be sent to the pilot as a recommendation.

### 5.2.2 Effects of the Improved Algorithm

When running the improved algorithm, the number of commands sent to the pilot by the merging and spacing algorithms was cut in half. This feat was accomplished all the while maintaining acceptable spacing values, and is a significant improvement from the simple "Merge Behind" and "Remain Behind" applications.

## 5.3 Filtering of the Suggested Speed

If there are slight deviations in the path of the target aircraft, these fluctuations show up in error corrections made to maintain proper spacing. For instance, if the target aircraft was moving in a sinsoidual manner, the tail aircraft will follow the same path. To limit the osciallations, the suggested speed goes through a filter. The goal of this filter is to prevent continuously varying speed suggestion from being sent to the pilot as a result of the algorithm. Instead, only the commands which result in a significant speed change should be sent to the flight crew. To accomplish this, the filter checks if the change in speed from the current speed to the calculated speed is greater than a filter threshold. If the change is less than the threshold, the change in speed is not considered to be significant enough to be suggested to the flight crew. After passing through the filter, the speed is rounded (using a rounding threshold) before being displayed to the pilot.

The filter calculations are performed as follows:

-
  ```
  IF $|current\_speed - suggested\_speed| > filter\_threshold$
      THEN $filtered\_speed = suggested\_speed$
  ELSE $filtered\_speed = current\_speed$
  ```

The rounding calculations are performed as follows:

- two numbers, “integer” and “remainder”, can be computed so that:
  $filtered\_Speed = integer * Rounding\_Threshold + remainder$

-
  ```
  IF $remainder > Rounding\_Threshold/2$
      THEN $suggestedspeed = (integer + 1) * Rounding\_Threshold$
  ELSE $suggested\_speed = integer * Rounding\_Threshold$
  ```
- We define the rounding threshold as the nearest multiple to which we will round. The pseudocode above represents the rounding calculations.

## 6 System Functionality

These algorithms were tested in a cockpit simulator in MITRE/CAASD’s ATM lab. Talk about bigwig.

## 7 Future Research

If there are multiple aircrafts on the same path, according to the current algorithm, each one follows the one in front of it. This leads to more and more oscillations in flight path as the aircrafts get further and further away from the leader. This is because each aircraft inherits all of the spacing errors of the aircrafts in front of it. A new proposal being created to try to make each aircraft space itself solely on the lead aircraft. The spacing value would, of course, be larger. One possible adjustment to the spacing value would be to make the spacing 1.1 times larger per aircraft. In this case, the third aircraft from the lead would be spaced 3.3 times the normal spacing from the lead aircraft. The only major problem with this is that it assumes that each aircraft is following the correct speed recommendation. The reason this is a problem is because each aircraft only spaces itself properly with respect to the lead aircraft and does not space itself properly from the aircraft(s) in front of it. Ideally, this plan would work because each aircraft would always maintain proper spacing with respect to the lead aircraft so no spacing conflicts would ever arise between consecutive aircraft. Realistically, however, if an aircraft were to get too far behind the lead aircraft and the aircraft behind it were to get too close to the lead aircraft then the spacing value between the two consecutive aircraft could be potentially dangerous.

Creating a time decay heuristic based on the distance from either waypoints or final destination. Make the time decay smaller as the waypoint or final destination gets closer.

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