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MODELING OF THE AIRCRAFT IN-TRAIL-FOLLOWING TASK DURING PROFILE DESCENT*

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ABSTRACT

The FAA and NASA are jointly developing Cockpit Display of Traffic Information (CDTI) system concepts which enable the pilot to observe the surrounding air traffic pattern. The impact of such a system is far reaching in terms of improved safety, pilot and controller workload, and aircraft fuel efficiency. One direct payoff is the ability to distribute the ATC workload to the pilot in such tasks as merging and spacing. In this paper, the CDTI application of spacing approach aircraft in the terminal area is addressed. At both Langley and Ames Research Centers, in-trail-following/CDTI experiments were performed using realistic cockpit simulators and profile descent approach scenarios. Based on collected experimental simulator data, pilot models were developed which include state estimation, decision making and flight control aspects. These models were coupled with models of aircraft and CDTI equipment to study the dynamic phenomena and stability of strings of aircraft along various approach patterns.

INTRODUCTION

Both the use of more automation and more involvement of the pilot in the air traffic control process are well understood to be future needs for providing greater terminal area capacity. In hearings conducted in June 1977 by the U.S. House of Representatives Subcommittee on Transportation, Aviation and Weather it was concluded [1] that NASA should make extensive use of its Terminal Configured Vehicle (TCV) and other cockpit simulators to assist the FAA in:

(1) examining the capabilities and limitations of cockpit displays of traffic information (CDTI);

(2) exploring distributive management concepts for air traffic control; and

(3) examining human factor problems related to distributive management concepts.

Since that time, a program has been organized which will tie together FAA ATC (ground-based) simulators and NASA aircraft and associated cockpit simulators into a joint research project [2] to explore applications of the CDTI system.

One application of particular interest is the use of the CDTI display by the pilot for non-vectored clearances relative to other traffic. Under this category are functions such as control into a traffic merge point, and queuing, or spacing, along a route.

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In order to derive the control requirements for such functions, it is first necessary to understand the dynamics of merging and trailing aircraft.

Several questions arise associated with this CDTI-based terminal area traffic tactical control concept. These include:

(1) What are the basic dynamic phenomena associated with independently controlled strings of aircraft?

(2) What conditions would produce instability in the string?

(3) What information does each pilot need (from the CDTI and elsewhere) to merge his aircraft adequately into the string and then to maintain appropriate spacing?

(4) What are the effects of measurement and display errors, wind shears, aircraft mixes, spacing constraints, and merge trajectories on the dynamics and control performance of the system?

(5) What advantages does this concept have compared to the ground-based control?

This study begins to address these questions from a systems point of view.

In this first year's effort, focus was placed on analysis of the dynamics of already formed strings of aircraft. To aid in this analysis, use was made of data from NASA cockpit simulator studies of in-trail following. The experimental data were used to confirm analytical predictions and to uncover new phenomena for the spacing task.

BACKGROUND

System Overview

The flight system (i.e. the pilot/aircraft/CDTI combination interacting with other aircraft and ATC) is assumed to be entering the terminal area and proceeding along an established approach to landing. A sketch of such a scenario is depicted in Fig. 1. The flight systems can be further described by the block

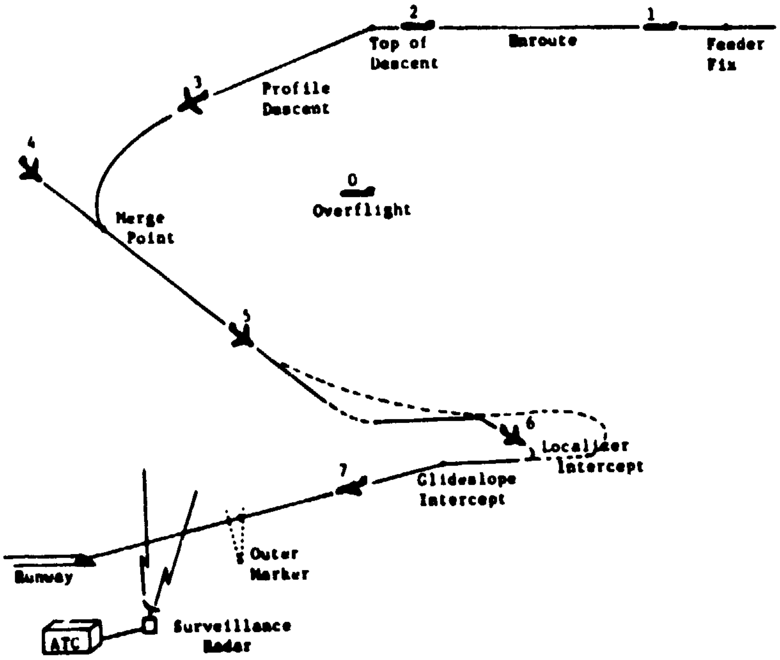

Figure 1. Sketch of Approaching Aircraft in a Terminal Area Scenario.

diagram shown in Fig. 2. With regard to the ten blocks of Fig. 2, the following assumptions were made for this initial effort:

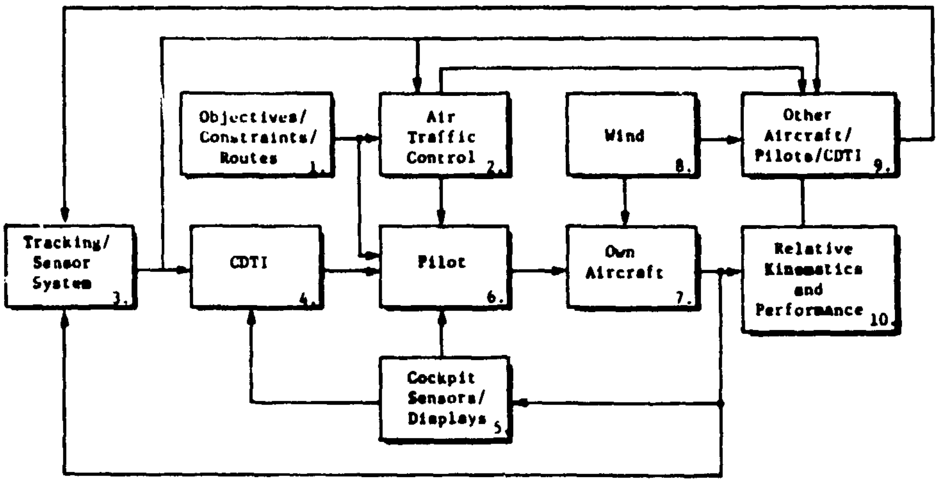

Figure 2. Block Diagram of a Flight System with CDTI Equipment.

1. Lead aircraft were given specified descent profiles for the approach task. Profile descents into Denver Stapleton International Airport were examined.
2. Air Traffic Control was used to issue the initial sequencing and separation commands (e.g., "Close and maintain 60 sec separation behing UA Flight 305").
3. No specific tracking system was assumed. Target aircraft were displayed as symbols which took discrete movements every four sec.
4. The CDTI display symbology was based on formats chosen for the NASA cockpit simulators. [3, 4, 5]
5. Other cockpit displays were chose standard for the simulated aircraft.
6. Part of the modeling objective was to characterize the pilot using the CDTI in a following situation to sufficient detail so that the overall string dynamics could be accurately emulated. Thus, only the longitudinal control was particularly studied.
7. Modeling of own aircraft longitudinal dynamics was relatively simple.
8. No wind model was used.
9. Other aircraft trajectories were stored from previous simulations.
10. The relative longitudinal dynamics of each aircraft was measured as projected on the desired horizontal flight path.

Previous Vehicle String Studies

There has been considerable previous investigation of traffic flow and control problems of ground vehicles in strings [6-8]. Probably L.A. Pipes' work of the early 1950's [6] was the first attempt utilizing the methods of operations research. He derived a mathematical model for strings of automobiles (which was a basic model used by later researchers), and he studied dynamic behavior of a string of vehicles initially at rest or after a sudden stop of the leading vehicle. Haight [5], contributed a great deal to the understanding of traffic flow by assuming a stochastic environment and using queuing theory. However, because his approach was macroscopic in nature, such problems as to how to control individual vehicles or how the stability of the string of vehicles is affected were not resolved.

Athans and others [9-10] solved the optimal control problem of a string of vehicles via the well known LQG (linear, quadratic and Gaussian) method. Athans and Porter [10] applied these techniques to the problem of controlling aircraft in the near terminal area under somewhat restrictive assumptions. The LQG approach is mathematically interesting and concise; however, it is very difficult to realize in light of CDTI applications.

Another approach to the metering and spacing problem was that taken by Tobias [11]. He obtained a general scheduling algorithm to generate time slots at each way point for each aircraft traveling along the air route. However, because his simulation did not provide dynamic interactions between adjacent aircraft, it cannot be utilized to study string stability.

Based on a review of the above work and other pilot modeling efforts [12-14], it was determined that a fresh start was needed to understand the dynamic phenomena and stability aspects of a string of decelerating, descending aircraft in a terminal area. This required analyses of different possible separation criteria and the development of longitudinal flight system models.

SEPARATION CRITERIA

Finding a suitable longitudinal distance separation criterion is especially important when the pilot independently executes the spacing task with the aid of a CDTI system. The separation criteria must satisfy three qualifications: safety/efficiency, executability, and computability/displayability. There could be numerous criteria which satisfy these requirements based on either distance, ground speed, or time. Four possible criteria expressed mathematically are:

(1) constant distance (CD)

$$\Delta d = d_i - d_{i+1} = \text{constant} ,$$

(2) constant time follower (CTF);

$$\Delta d = d_i - d_{i+1} = T_F V_i \quad (T_F = \text{constant}) ,$$

(3) constant time predictor (CTP);

$$\Delta d = d_i - d_{i+1} = T_P V_{i+1} \quad (T_P = \text{constant}),$$

(4) constant time delay (CTD);

$$d_i(t) - d_{i+1}(t-T_D) = 0 \quad (T_D = \text{constant}) .$$

Here, Δd is the separation, d_i and d_{i+1} are longitudinal distances of the ith and (i+1)th aircraft from a common reference point, and V_i and V_{i+1} are the corresponding ground speeds.

Differentiating the separation distance criteria yields the ideal speed profile to maintain the separation. This neglects pilot and aircraft caused delays. For example, in the case of the constant distance criterion, the separation equation is given by:

$$d_i(t) - d_{i+1}(t) = \text{constant} \qquad (1)$$

Differentiating this equation yields

$$V_{i+1}(t) = V_i(t) \; . \qquad (2)$$

Equation (2) implies that in order to maintain a constant separation distance, the following aircraft speed must be identical to that of the lead aircraft. Table 1 summarizes the ideal speed profile corresponding to each of the five separation criteria listed above. The table also shows the effect of each criterion repeated for the ith time (as in a string) with respect to the first aircraft speed.

Table 1. Separation Criteria and Ideal Velocity Profile

Separation Criteria		Ideal Velocity Profile	i^{th} Vehicle
Constant Distance (CD)	$d_i - d_{i+1} =$ constant	$v_{i+1}(t) = v_i(t)$ $v_{i+1}(s) = v_i(s)$*	$v_i(s) = v_1(s)$
Constant Time Follower (CTF)	$d_i - d_{i+1} = T_F\, v_i$, T_F = constant	$v_{i+1}(t) = v_i(t) - T_F\, \dot{v}_i(t)$ $v_{i+1}(s) = (1 - T_F s)\, v_i(s)$	$v_i(s) = (1 - T_F s)^{i-1} v_1(s)$
Constant Time Predictor (CTP)	$d_i - d_{i+1} = T_p\, v_{i+1}$, T_p = constant	$\dot{v}_{i+1}(t) = -\frac{1}{T_p} v_{i+1}(t) + \frac{1}{T_p} v_i(t)$ $v_{i+1}(s) = \frac{1}{T_p s+1} v_i(s)$	$v_i(s) = \left(\frac{1}{T_p s+1}\right)^{i-1} v_1(s)$
Combination Constant Time Predictor-Follower (CTFP)	$d_i - d_{i+1} = T_F\, v_i + T_p v_{i+1}$ T_F, T_p = constants	$\dot{v}_{i+1}(t) = -\frac{1}{T_p} v_{i+1} + \frac{1}{T_p} [v_i - T_F\, \dot{v}_i]$ $v_{i+1}(s) = \frac{1-T_F s}{T_p s+1}\; v_i(s)$	$v_i(s) = \left(\frac{1 - T_F s}{T_p s+1}\right)^{i-1} v_1(s)$
Constant Time Delay (CTD)	$d_{i+1}(t) - d_i(t-T_D) = 0$, T_D = constant	$v_{i+1}(t) = v_i(t-T_D)$ $v_{i+1}(s) = e^{-T_D s}\, v_i(s)$	$v_i(s) = e^{-(i-1)T_D s} v_1(s)$

* s = Laplace Operator

IN-TRAIL FOLLOWING EXPERIMENT RESULTS

Results from experiments conducted at NASA Langley Research Center, using their TCV cockpit simulator, were analyzed. The nominal approach path followed by the lead aircraft was along the profile descent leading to Denver Stapleton runway 35R depicted in Fig. 3. The trailing aircraft was situated to begin at the KEANN waypoint. The nominal separation criterion for these experiments was

$$\Delta d = \max\,[V_o T,\ 3\ \text{nmi.}] \qquad (3)$$

where Δd is the nominal separation, Vo is the own aircraft ground speed, and T is a time constant of 60 sec. This criterion is a combination of the constant time predictor (CTP) and the constant distance (CD) of Table 1, with crossover being at own ground speed of 180 kt.

Experiment Design

For Experiment No. 1, the lead aircraft was placed 7 nmi. in front of the trailing aircraft. This represented a positive initial separation error of 1.7 nmi. for own, when own had an initial ground speed of 340 kt. Own pilot's first task was to close the separation error to 5.3 nmi. After this capture phase, the task was to hold the separation according to Eq. (3) and to maintain the aircraft reasonably close to the nominal profile depicted in Fig. 3.

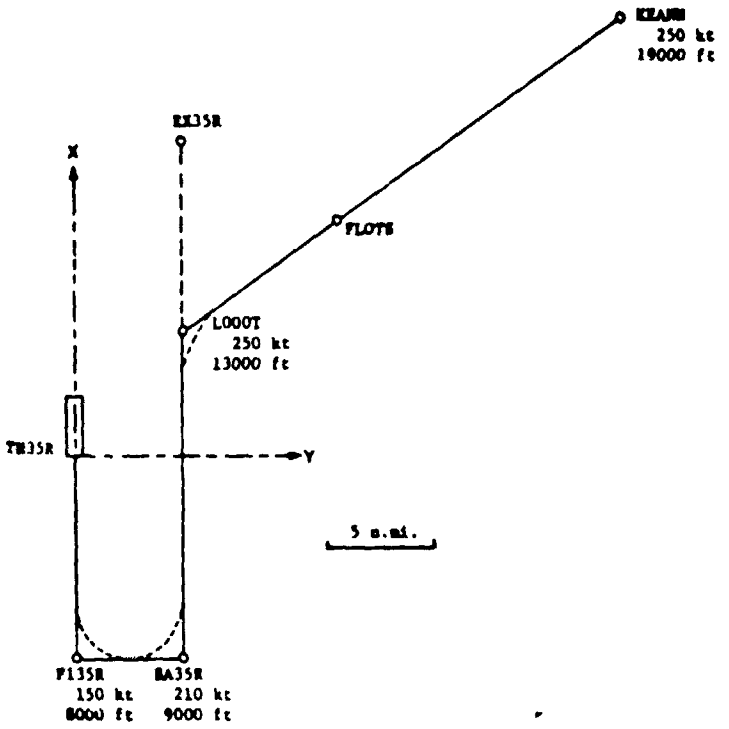

Figure 3. Nominal Approach to Denver Runway 35R

Eight runs, consisting of a single following aircraft trailing nominal leads, were selected for analysis in Experiment No. 1. Longitudinal separation was measured by first projecting the lead aircraft position onto the future position of the following aircraft.

For Experiment No. 2 ("the daisy chain experiment"), eight successive trailing aircraft were initialized at the KEANN waypoint when the immediately preceding aircraft passed 5.3 nmi. (60 sec) ahead of this point. The lead aircraft of this nine-aircraft string followed a nominal profile descent along the path of Fig. 3. There were no initial separation errors in Experiment No. 2. The Eq. (3) separation criterion was again used.

An example of the six key variables that were recorded from each of the experiments are depicted in Fig. 4. These variables are the own and lead aircraft ground speeds, the actual and nominal relative separations between own and the lead aircraft, and own aircraft's throttle and spoiler settings. These data were used to construct two different pilot models characterizing the results of Experiment Nos. 1 and 2.

Pilot Models

In examining Experiment No. 1 data, a great deal of variation in pilot strategy and actions was seen from run to run, even through the same pilot could be following the same lead aircraft with identical initial conditions. Thus, the models developed had to contain features which allowed for changes in pilot decision and control from run to run. The approach taken for developing the combination pilot/aircraft/CDTI flight system model for in-trail following was direct. Given a set of input/output time sequences from the experiments, the model was designed as a functional set of equations and logic with variable parameters which would provide similar input/output sequences.

Fig. 5 depicts a first-level block diagram of the flight system model developed here, which is referred to as Model No. 1. Aircraft control dynamics are represented by a first order lag between the commanded and actual accelerations. The actual acceleration is integrated twice to obtain own aircraft ground speed and distance traveled.

The CDTI display is modeled to generate the separation error $\tilde{\delta} r_M$. The recorded target ground speed V_T is integrated to obtain the target distance traveled, r_T. The distance traveled by the flight system model, r_M, is subtracted from r_T to produce the model separation distance r_{act}. The model ground speed, V_M is multiplied [illegible] sec (which is limited to 3 nmi. from below) to compute the model's nominal separation distance r_{Nom}. The model separation r_{act} is subtracted from r_{Nom} to obtain the model separation distance error $\tilde{\delta} r_M$. The pilot sees a quantized value of $\tilde{\delta} r_M$ on the CDTI display. All modeled values are initialized to those

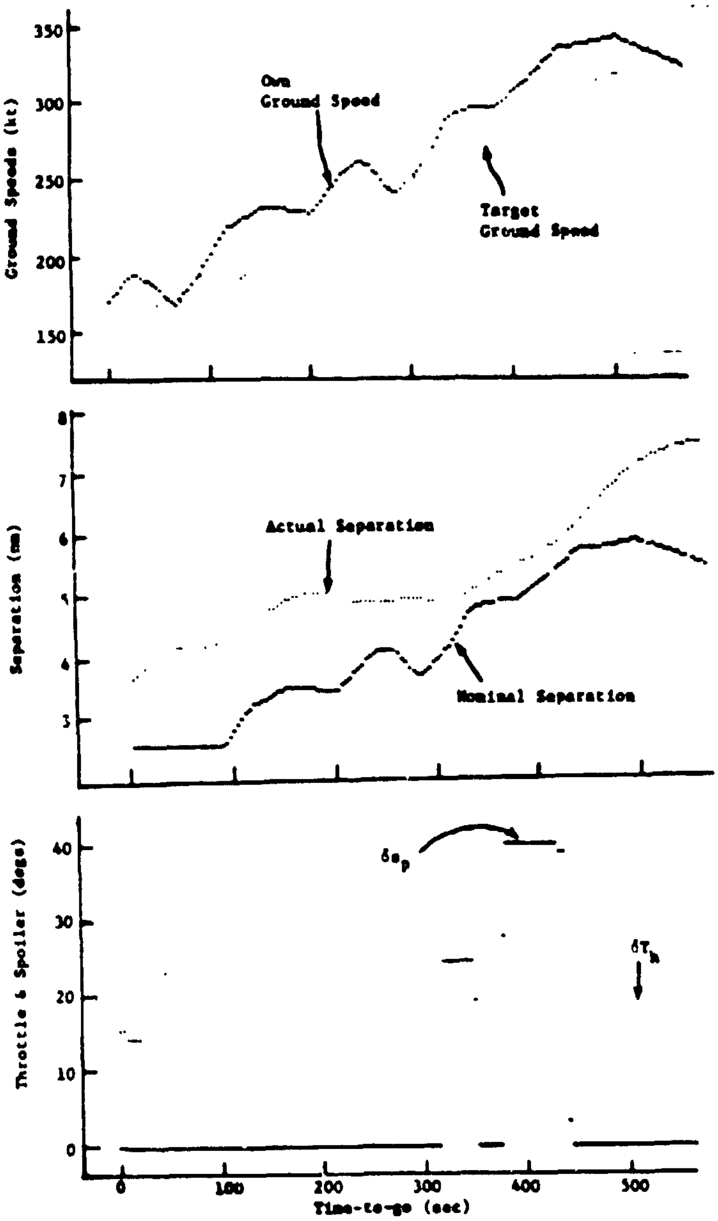

Figure 4. Example of Data Recorded From Experiment and Used to Develop System Model.

recorded during an experimental run. The model separation error is input to a second order tracking filter to approximate the pilot's estimate of the error and its rate ($\Delta\hat{r}$, $\Delta\hat{v}$).

Fig. 6 shows further details of the CDTI/pilot model implementation. A tentative regulator acceleration command is obtained by using a constant gain regulator law based on output from the pilot estimator. That is,

$$a_{M1} = G_p(\Delta\hat{r} + \Delta r_{Ref}) + G_v\Delta\hat{v}. \qquad (4)$$

The regulator law controls the separation error to a bias, Δr_{Ref}. This bias is a function of the map scale and it was introduced based on an observation that pilots tend to stand off at the initial part of the approach and then tend to close in later.

The resulting regulator acceleration is averaged over a 10 sec time interval. If the average value exceeds the current commanded value by a threshold amount θ_a, then the average value $\bar{a}$ is used for the command. This logic simulates the fact that the pilot tends to not change the throttle setting unless the error or command builds up beyond a certain point. Also, he changes the throttle position to a new point which is then held. The acceleration command a_T contains two components: The one, a_{Th} is for the throttle, and the other, a_{sp} is for the spoiler. The acceleration command due to the spoiler provides one discrete deceleration pulse when the separation estimate is closer than the threshold value.

Authority and velocity limiting at the various phases of the approach are introduced to simulate additional observed pilot behavior. For example, the pilot never accelerated above 340 kt nor did he decelerate below 130 kt. regardless of the separation error.

Fig. 7 shows typical time plots of the results of using this flight system model compared to experimental results. The top plot in Fig. 7 compares three ground speeds - recorded target, recorded own, and model predicted own (V_M in Fig. 5). The second plot compares three separation distances between own and target - recorded, model derived (r_{act} in Fig. 5), and nominal model (r_{Nom} in Fig. 5). To produce these results, the model depicted in Figs. 5 and 6 was given identical initial conditions (separation, ground speed) as that of the actual run, and it was driven by the recorded target ground speed V_T.

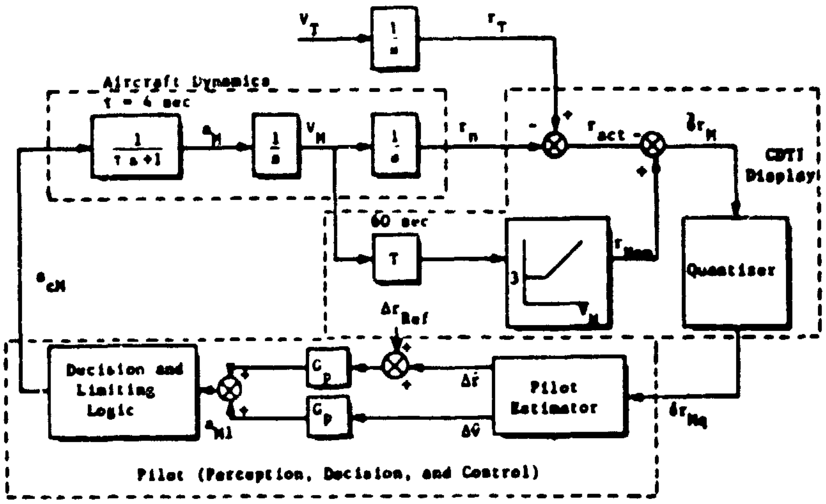

Figure 5.

First Level Block Diagram of In-Trail Following Flight System Model.

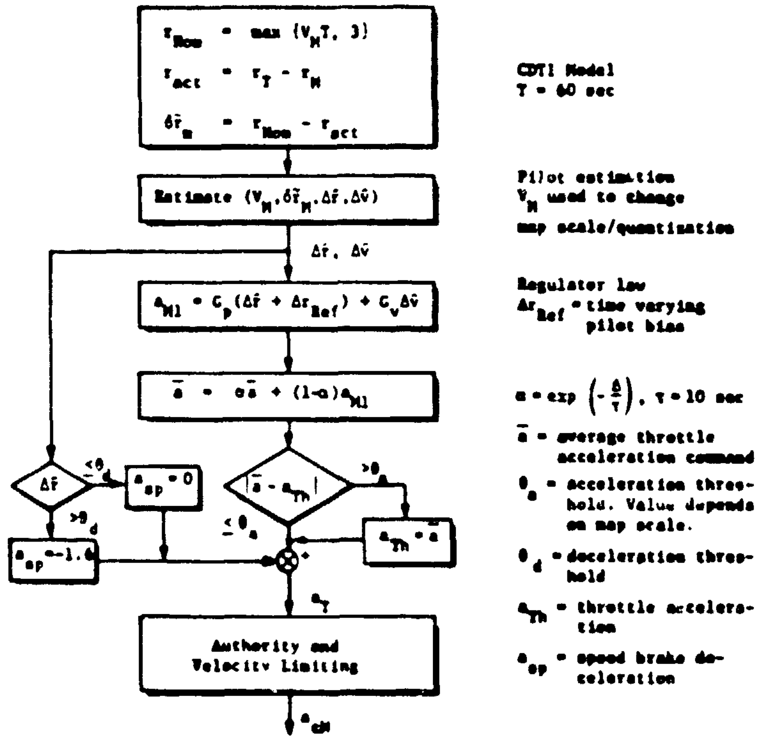

Figure 6.

Second Level Block Diagram of CDTI and Pilot Acceleration Command Generation.

The goodness by which the flight system model matched the performance of the actual experiments varied somewhat from run to run. Over the eight runs, the model predicted ground speed had a mean error of -5.1 kt and an rms error of ±15.3 kt when compared to the recorded ground speed of the following aircraft. Part of the error is due to the fact that the recorded ground speed excursions were greater than predicted by the model. The frequency spectrum of the excursions in the model and actual data were seen to agree well. This indicates that control gain and acceleration command thresholds are good representations of the pilots' control tactics.

In analyzing the Experiment No. 2 data, some observations were made that demonstrated a different following behavior than in Experiment No. 1. To obtain these differences, the flight system Model No. 1 was modified in four ways. Observations and model modifications were as follows:

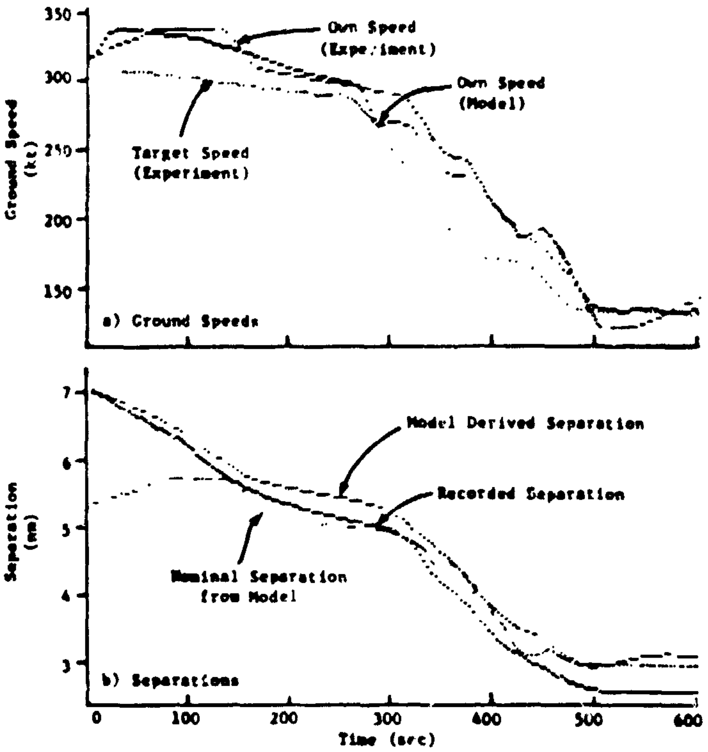

Figure 7.

Comparison of Actual and Model Derived Speeds and Separations.

(1) The initial deceleration of own aircraft was limited to a smaller value than in Experiment No. 1

(2) Own aircraft had a different ground speed undershoot limit when it was decelerating than the 10 kt used for Model No. 1.

(3) The model separation bias Δr_{Ref} was changed to different levels during a run depending on own's ground speed.

(4) The acceleration threshold θ_a shown in Fig. 6 was made smaller to reflect that the pilot's acceleration commands had smaller changes more often. This reflects better tracking accuracy and smaller separation excursions experienced in Experiment No. 2.

The result of these changes is referred to as Model No. 2. The difference between recorded and Model No. 2 ground speeds had a mean error of -0.5 kt and an rms value of ±10.6 kt which is a 30% improvement over the fit provided by Model No. 1.

With a large enough data base, the parameters that are contained within the two models could be treated as stochastic variables; they could then be picked randomly from run to run while exercising the model. However, it is emphasized that our purpose here is not to identify the perfect model but rather to capture the essence of the performance of the pilot/aircraft/CDTI combination in the in-trail following task.

String Dynamic Simulations

The flight system Model Nos. 1 and 2 were used to simulate the longitudinal dynamics of a string of nine aircraft. The lead aircraft in this simulated string followed a sequence of constant decelerations at discrete time points to produce a profile similar to the nominal approach. Initial spacing errors were small.

Fig. 8 shows the simulated results for the first, fifth, and ninth aircraft using Model No. 2. The first plot depicts the following aircraft spacing error, the second plot compares the ground speeds as functions of range-to-go. The interesting point to note from these plots is that each successive aircraft slows

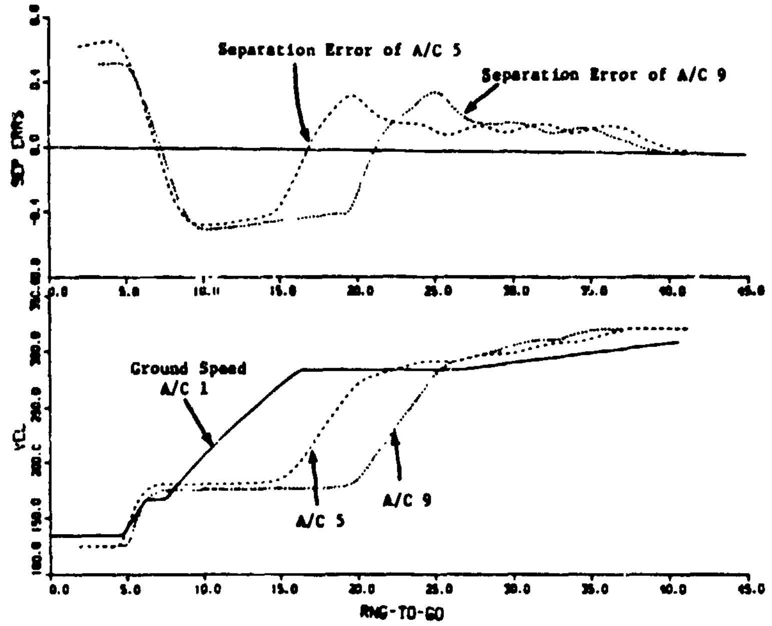

Figure 8.

Comparison of Profiles for Aircraft Nos. 1,5, and 9. Model No. 2.

down at an earlier range-to-go. The slow-down effect was seen on both Experiment No. 2 results and the two simulated strings of nine aircraft using Model Nos. 1 and 2.

The slow-down effect was not caused by the 60 sec time lag inherent in the CTP separation criterion. To prove this conclusion, a simple autopilot was designed (to replace the pilot model) to null out the separation and speed errors. The nominal separation distance was set to the constant time predictor criterion of 60 V_o (i.e., the criterion did not switch at 180 kt.).

The autopilot model was also used to simulate a string of nine aircraft as before. The results of this simulation were then compared to those of the string simulation using Model Nos. 1 and 2 and the actual results from Experiment No. 2. Fig. 9 compares results for the ninth aircraft in each of these four cases. The top plot shows the separation errors, and the bottom plot compares the predicted and actual ground speeds.

Conclusions

From the previous results, the following conclusions can be made:

(1) Both Model Nos. 1 and 2 Experiment No. 2 aircraft have slower ground speeds than the ideal autopilot model, and so they take longer to arrive at the outer marker. (This amounted to an increase in flight time of about 13%.) Thus, the CTP criterion is not responsible for the slow-down.

(2) The differences in separation errors and ground speeds predicted by the Model Nos. 1 and 2 and the ideal autopilot model indicate the addition of in-trail errors caused by the pilots' decisions and actions. The pilot introduces errors because of many items: (a) the switch in the separation criterion and the tendency to hold a greater than indicated separation, (b) inattention to tracking caused by the competitive task of steering to the nominal profile and other tasks associated with landing, and (c) the hunting nature observed in the pilots' acceleration inputs. This latter fact is probably due to the pilot not having a good ground speed reference to use to null the separation error.

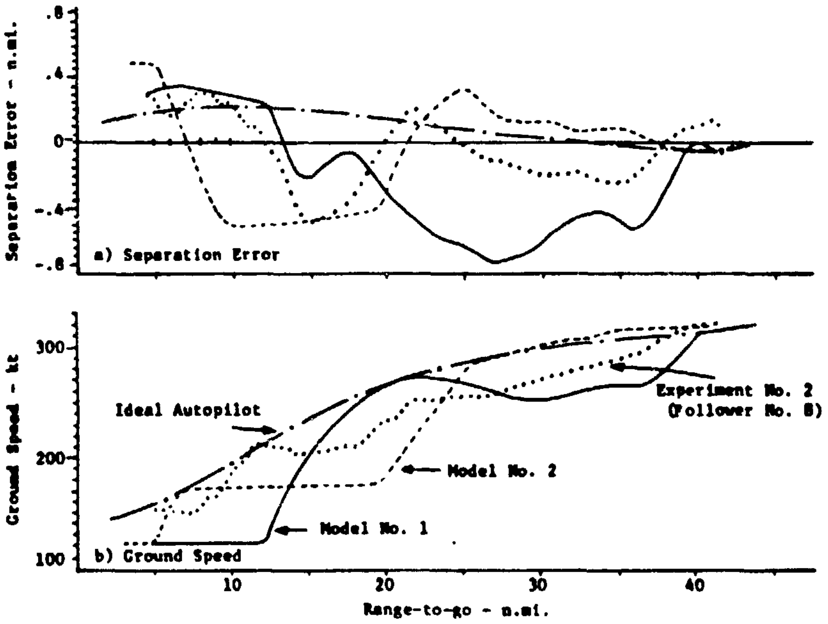

Figure 9.

Comparison of Last Aircraft Profiles in Nine-Aircraft String.

(3) Both in separation error and ground speed, the ninth pilots' results from Experiment No. 2 fall between the results predicted by Model Nos. 1 and 2. This is good verification of the models' adequacy in predicting flight system dynamic performance in a string when using the separation criterion expressed by Eq. (3).

(4) Despite the differences seen between the experimental-based models and the autopilot model, the separation errors are acceptable and within 15% of the value specified by Eq. (3). Also, there is no gradual buildup or oscillation of these errors. Thus, we can conclude that the pilot does not induce instability into the string for this aircraft/CDTI configuration.

ADDITIONAL WORK

The above results are preliminary and somewhat ideal. Currently, we are analyzing another set of in-trail following task experimental results based on using the NASA Ames 747 cockpit simulator [15]. This experiment is different from the previously discussed Langley experiments in that (a) the simulated flight begins during the final portion of cruise, (b) the initial separation errors are varied, (c) the vertical control task to follow the desired profile descent is not as automatic as for the TCV simulator, and (d) the lead aircraft have altitude and speed errors in their descent profiles.

There are several more items that should be investigated regarding the in-trail following task. These include the effects of (a) mixed types of aircraft, (b) different separation criteria, (c) winds, (d) some aircraft not being CDTI equipped, and (e) the CDTI sensor and display errors. Beyond this, the stability and dynamic phenomena associated with merging several aircraft into a common string requires a combination of analytical and experimental study. Finally, the dynamic aspects of pilot/air traffic controller interaction for terminal area merging and spacing using CDTI concepts will require investigation.

REFERENCES

1. Anon., "Future Needs and Opportunities in the Air Traffic Control Systems," Report prepared by the Subcommittee on Transportation, Aviation, and Weather, of the Committee on Science and Technology, U.S. House of Representatives, Ninety-fifth Congress, November 1977.

2. Anon., "Joint NASA/FAA Program: Cockpit Display of Traffic Information (CDTI)," Program plan, FAA/NASA, Washington, D.C., February 1980.

3. Sorensen, J.A., and Goka, T., "Analysis of In-Trail Following Dynamics of CDTI-Equipped Aircraft," Report No. 81-9 , Analytical Mechanics Assoc. Inc., Mountain View, CA, June 1981.

4. Kelly, J.R., "Preliminary Evaluation of Time and Distance Spacing Cues Using a Cockpit Displayed Target," NASA TM 81794, August 1980.

5. Palmer, E.A., et al, "Perception of Horizontal Aircraft Separation on a Cockpit Display of Traffic Information," Human Factors, Vol. 22, No. 5., October 1980.

6. Pipes, L.A., "An Operational Analysis of Traffic Dynamics," Jour. of Applied Physics, Vol. 24, No. 3, March 1953.

7. Haight, F.A., Mathematical Theories of Traffic Flow, Academic Press, New York, NY, 1963.

8. Bekey, G.A., "Control Theoretic Models of Human Drivers in Car Following," Human Factors, Vol. 19, No. 4, 1977.

9. Levine, W.S., and Athans, M., "On The Optimum Error Regulation of a String of Moving Vehicles," IEEE Trans. on Automatic Control, Vol. AC-11, No. 3, 1966.

10. Athans, M., and Porter, L.W., "An Approach to Semi-Automated Optimal Scheduling and Handling Strategies for Air Traffic Control," Proceedings of the Joint Automatic Control Conf., St. Louis, 1971

11. Tobias, L., "Automated Aircraft Scheduling Methods in the Near Terminal Area," J. of Aircraft, Vol. 9. No. 8, August 1972.

11. McRuer, D.T., et al, "A Theory of Human Error," Tech. Report No. 1156-1, Systems Technology, Inc., Hawthorne, CA, May 1980.

12. Baron, S., and Levison, W.H., "The Optimal Control Model - Status and Future Directions, IEEE Decision and Control Conf., 1980.

14. Cavelli, D., "Discrete-Tune Pilot Model," Proc. of the 16th Annual Conf. on Manual Control, Cambridge, MA, May 1980.

15. Chappell, S.L., and Palmer, E.A., "In-Trail Following During Profile Descretes with a Cockpit Display of Traffic Information," Aviation Psychology Conf., Columbus, OH, May 1981.