MIXING 4D-EQUIPPED AND UNEQUIPPED AIRCRAFT IN THE TERMINAL AREA

L. Tobias, H. Erzberger, and H. Q. Lee
NASA Ames Research Center
Moffett Field, CA 94035

and

P. J. O'Brien
FAA Technical Center
Atlantic City, NJ

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INTRODUCTION

On-board 4D guidance systems, which can predict and control the touchdown time of an aircraft to an accuracy of a few seconds throughout the descent, have been developed and demonstrated in several flight test programs. However, in addition to refinements of the on board system, two important issues still need to be considered. First, in order to make effective use of these on-board systems, it is necessary to understand and develop the interactions of the airborne and air traffic control (ATC) system in the proposed advanced environment. Unless the total system is understood, the advanced on-board system may prove unusable from an ATC standpoint. Second, in planning for a future system in which all aircraft are 4D equipped, it is necessary to confront the transition situation in which some percentage of traffic must still be handled by conventional means. In terms of 4D, this means that some traffic must still be given radar vectors and speed clearances (that is, be spaced by conventional distance separation techniques), while the 4D-equipped aircraft need to be issued time assignments. How to reconcile these apparent differences and develop an efficient ATC operation is the subject of this paper.

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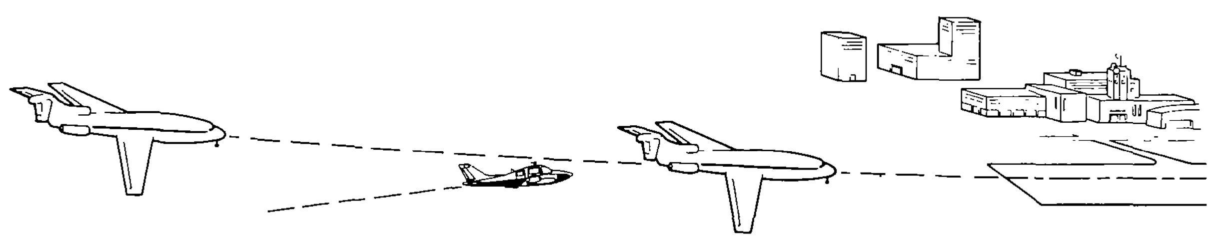


OBJECTIVES

The objectives of this study are to develop efficient algorithms and operational procedures for time scheduling a mix of 4D-equipped and unequipped aircraft in the terminal area, and, using the NASA Ames real-time air traffic control (ATC) simulation facility, to evaluate the system operation under various mix conditions.

- DEVELOP CANDIDATE OPERATIONAL PROCEDURES AND TIME-SCHEDULING ALGORITHMS FOR CONTROLLING A MIX OF 4D-EQUIPPED AND UNEQUIPPED AIRCRAFT IN THE TERMINAL AREA
- EVALUATE THE SYSTEM OPERATION UNDER VARIOUS MIX CONDITIONS

OPERATIONAL PROCEDURES

The basic operational procedure is as follows: the ATC computer generates time assignments for all aircraft as they enter the greater terminal area. For the 4D-equipped aircraft, the controller assigns the aircraft a route and a touchdown time. The 4D-equipped aircraft generates and flies the 4D route. The controller was instructed not to alter this assigned time unless necessary for safety reasons. The unequipped aircraft must still be controlled by radar vectors. However, the controllers can use the position of the 4D aircraft to achieve the time assignments for the unequipped aircraft.

ATC COMPUTER GENERATES TIME ASSIGNMENTS

- 4D EQUIPPED:
  - CONTROLLER ASSIGNS TOUCHDOWN TIME
  - AIRCRAFT GENERATES AND FLIES 4D ROUTE
  - ASSIGNED TIME NOT ALTERED
- UNEQUIPPED:
  - CONTROLLER ISSUES RADAR VECTORS
  - CONTROLLER USES 4D AIRCRAFT POSITIONS TO ACHIEVE TIMES FOR UNEQUIPPED

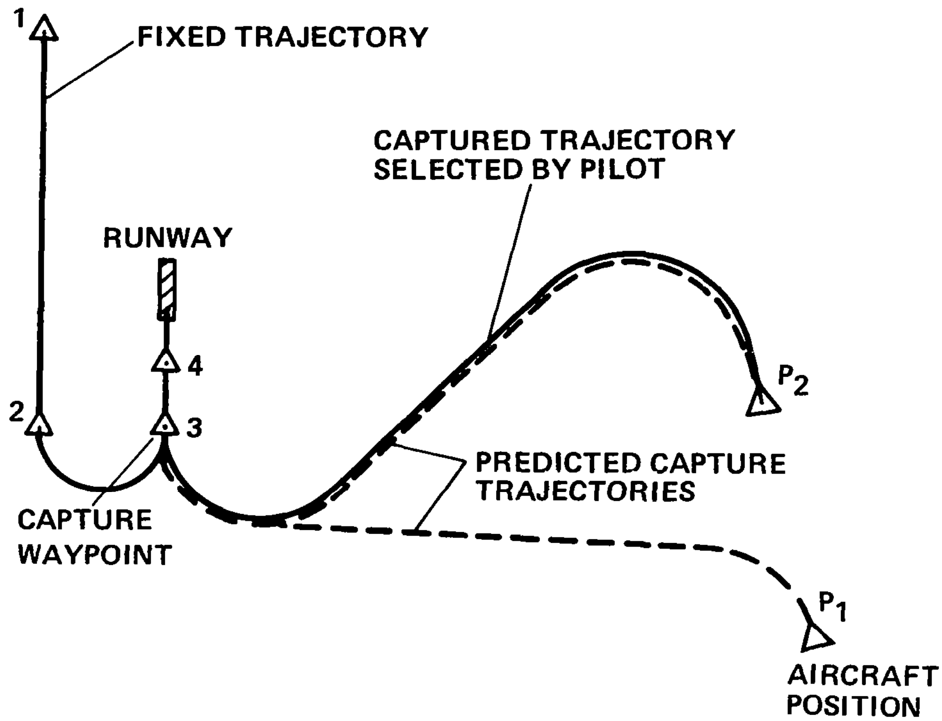
ON-BOARD SYSTEM

A complete on-board 4D guidance system is a complex entity involving interaction between numerous guidance, control, and navigation subsystems in an aircraft. The integrated collection of these subsystems augmented with special algorithms to provide fuel-efficient time control essentially constitutes the 4D flight management system of an equipped aircraft. The basic steps in the trajectory synthesis are shown below. For a number of years, NASA has designed and flight tested research systems incorporating various types of time control methods for both STOL and conventional aircraft. These tests have demonstrated the ability to predict and control arrival time accurately under varied operational conditions, achieving arrival time accuracies of ±10 sec.

- AIRCRAFT SYNTHESIZES TRAJECTORY
  1. HORIZONTAL PROFILE: TURNS AND STRAIGHT LINES
  2. VERTICAL PROFILE: LEVEL FLIGHT AND CONSTANT DESCENT ANGLE SEGMENTS
  3. AIRSPEED PROFILE: CONSTANT CAS AND DECELERATION SEGMENTS
- ARRIVAL TIME ACCURACIES OF ±10 sec ACHIEVABLE
- CONTROLLER CAN VECTOR AIRCRAFT; THEN ASSIGN NEW TIME VIA CAPTURE

CAPTURE TRAJECTORIES

A 4D-equipped aircraft which has been vectored off its 4D route can be assigned a revised time and a waypoint to capture the 4D route. This figure shows two aircraft positions P_1 and P_2. A capture trajectory is shown by a dotted line from position P_1 to the capture waypoint 3. If the touchdown time associated with this trajectory is too early, the aircraft continues to fly according to its last vector clearance until it reaches position P_2, where the pilot captures the 4D route via the trajectory shown.



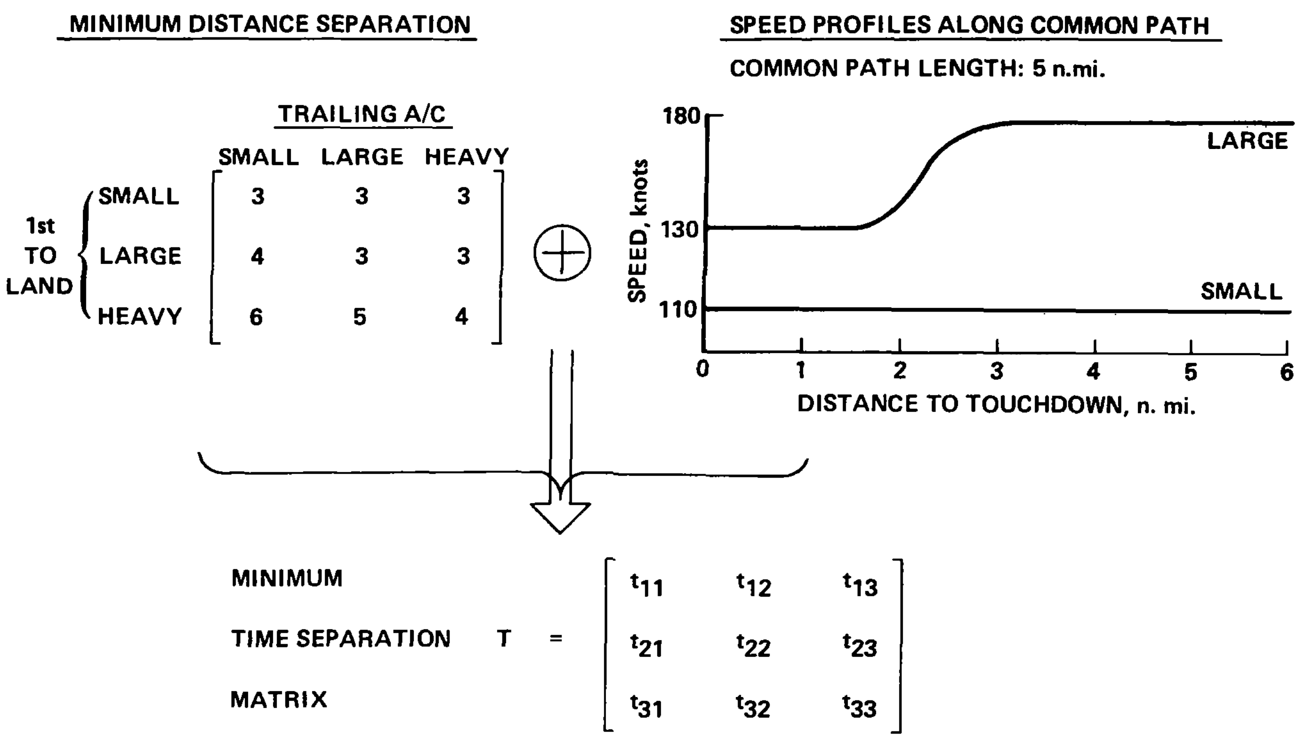
TIME-SCHEDULING ALGORITHMS

The 4D-equipped aircraft have the capability of meeting a touchdown-time assignment to an accuracy of a few seconds. It is now desired to use this capability to formulate efficient operational procedures for the time scheduling of all aircraft in the terminal area. This will be developed in three parts: (1) determine the minimum time separation conditions given the minimum distance separations; (2) determine the interarrival time separations for two consecutive aircraft to be used in aircraft scheduling; and (3) develop a scheduling algorithm for assigning landing times.

- **TRANSLATION OF DISTANCE SEPARATIONS TO TIME**
- **TIME SEPARATIONS AT TOUCHDOWN**
- **INTERACTIVE SCHEDULING ALGORITHMS**

TRANSLATION OF DISTANCE SEPARATIONS TO TIME

The minimum separation distance rules depend on aircraft weight category and are summarized in this figure. These distances can be converted to minimum separation times using speed profile data. The result is the matrix T, where each element is the minimum separation time at touchdown so that at no time when aircraft are along a common path is the separation distance rule violated.



TIME SEPARATIONS AT TOUCHDOWN

It is assumed that, if two consecutive aircraft are 4D-equipped, the interarrival times given by T can be used for scheduling purposes. However, unequipped aircraft will need additional time buffers to prevent separation distance violations. If the probability density function of an unequipped aircraft meeting an assigned time via controller vectoring is known (this can be determined in the specific experimental context), then time buffers can be determined to keep the probability of separation distance violation below a desired level. These time buffers result in a revised time separation matrix T' described below.

BUFFERS ADDED TO PREVENT MINIMUM SEPARATION VIOLATIONS

FOR TWO CONSECUTIVE AIRCRAFT AT TOUCHDOWN:

IF BOTH EQUIPPED, $T' = (t'_{ij}) = (t_{ij} + \delta_a)$

IF ONE EQUIPPED, $T'' = (t''_{ij}) = (t_{ij} + \delta_b)$

IF BOTH UNEQUIPPED, $T''' = (t'''_{ij}) = (t_{ij} + \delta_c)$

WHERE $0 \leqslant \delta_a < \delta_b < \delta_c$

INTERACTIVE SCHEDULING ALGORITHMS

The previous discussion established the time separation matrix at touchdown shown as a function of weight category, and whether or not aircraft are 4D equipped. It is assumed that the feeder fix time for each aircraft is known. Based on this time and on the desired time to traverse the route, a desired touchdown time for each aircraft can be determined. This information can be used to generate an initial time schedule, as described in reference 1. However, in addition to setting up an initial schedule, algorithms are required to revise the schedule. Missed approaches need to be accommodated. Also, the controllers may need to change the aircraft arrival rate. It may be that they also are required to block out specific time periods from the computer schedule to accommodate a missed approach or a priority landing. These are important aspects of the complete scheduling problem.

WITH TIME SEPARATION CONSTRAINTS CAN NOW GENERATE SCHEDULE

- ESTABLISH TOUCHDOWN ORDER
- PROVIDE FOR REVISIONS
  - CHANGE ARRIVAL RATE
  - MISSED APPROACHES
  - EMERGENCIES

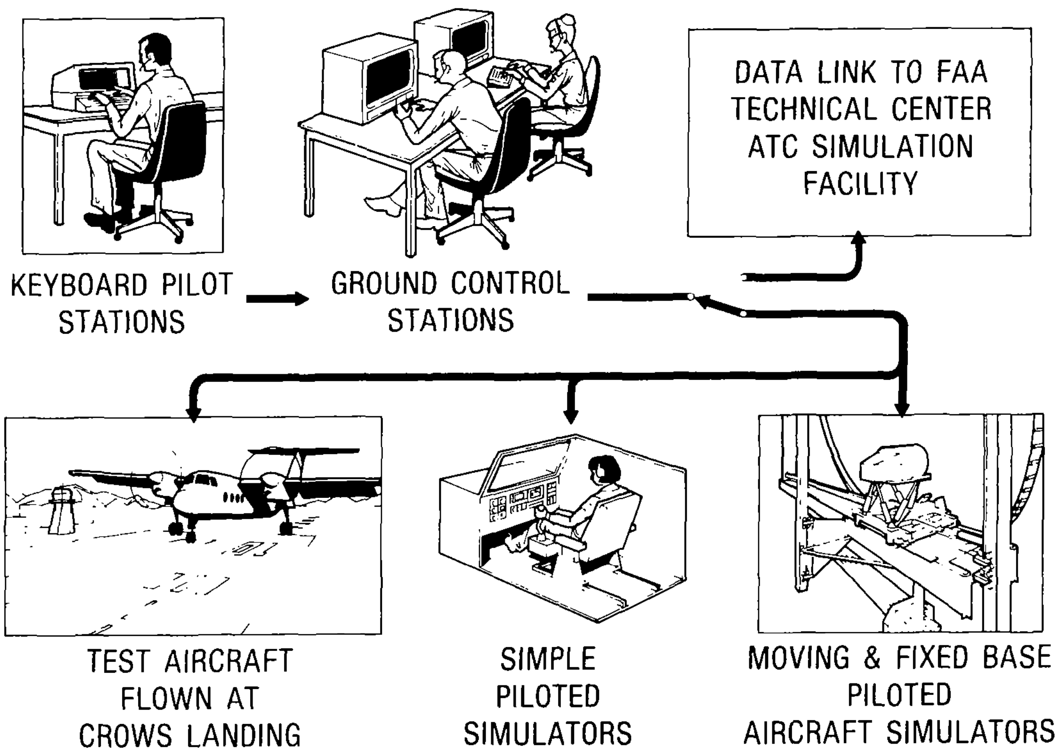
EVALUATION OF SYSTEM OPERATION UNDER VARIOUS MIX CONDITIONS

The candidate operational procedures and time schedule algorithms previously described were used in a real-time ATC simulation study of operations under various mix conditions.

- SIMULATION FACILITY
- SCENARIO AND TEST CONDITIONS
- RESULTS

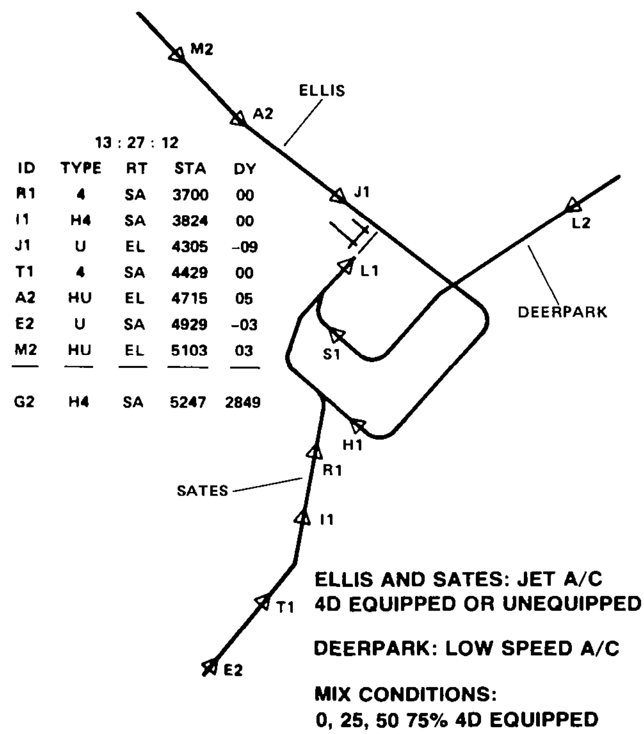
SIMULATION FACILITY

The simulation was conducted using the NASA Ames ATC Simulation Facility shown in this figure. It includes two air traffic controller positions, each having its own color computer graphics display. In this study, one was designated arrival control and the other, final control. The controllers each communicate with one or two keyboard pilots. Each keyboard pilot can control up to 10 computer-generated aircraft simultaneously. The clearance vocabulary includes standard heading, speed, and altitude clearances as well as special clearances for 4D-equipped aircraft. This figure also depicts piloted simulators. Previous studies have utilized one or two piloted simulators which were connected by voice and data link to the ATC Simulation Facility; however, in this study, no piloted simulator was used.



APPROACH CONTROLLER DISPLAY

The route structure and runway configuration investigated are shown in this figure. Two routes, Ellis, from the north, and Sates, from the south, are high-altitude routes flown by large or heavy jet transport-type aircraft. Aircraft on these routes fly profile descent procedures, but may or may not be 4D equipped. Hence, there is a mix of 4D-equipped and unequipped aircraft of the same speed class along the same route. In addition, low-speed aircraft were considered which flew the Deerpark route from the east, but shared a 5 n. mi. common path length and used the same runway as the jet traffic. The Deerpark traffic was unequipped, and always constituted 25% of the traffic mix. To assist the controller in integrating the 4D-equipped and unequipped traffic, a flight data table (FDT) was provided to the left of the route structure. The information supplied includes aircraft type, route, scheduled touchdown time, and anticipated delay. The main test variable was the mix of traffic. Three mix cases were run: 25, 50, and 75% 4D equipped.



EXPERIMENT CONDITIONS

In this study, a saturated arrival traffic flow was used. It is assumed that instrument flight rule (IFR) conditions prevail, and that all aircraft use runway 4R; furthermore, no departures, winds, or navigation errors are simulated. For purposes of this study, it was assumed that all aircraft depart the feeder fix at their scheduled departure times. Magnitude departure errors that can be tolerated as well as the means to provide ground computer assists to nullify departure errors are main issues addressed by current research.

- **SATURATED ARRIVAL TRAFFIC FLOW**
- **NO WINDS, NO NAVIGATION ERRORS**
- **ALL AIRCRAFT DEPART AT SCHEDULED TIMES**

CONTROLLER EVALUATIONS

Three research air traffic controllers from the FAA Technical Center participated in this study. Controllers were asked to compare operations under the traffic mix conditions. The 25% equipped case was rated the condition with the heaviest workload. The main difficulty seemed to be that the controllers were establishing distance spacing of most of the traffic, and they felt that by not altering the flight path of the 4D-equipped aircraft, they were occasionally losing some slot time. They were, however, quite pleased with the 50% 4D-equipped case, which allowed for easy handling of the unequipped aircraft. The 75% 4D-equipped case was rated most orderly by all the controllers, but when this many aircraft were 4D-equipped (the only unequipped aircraft were the Deerpark arrivals, which always constituted 25% of the traffic sample), there was "basically nothing to do." The controllers were asked if there was any difficulty in handling the mix of speed classes, the slow traffic on Deerpark and the jet traffic on Ellis and Sates. They indicated that spacing behind the low-speed aircraft was sometimes a problem, since they had to allow for a large initial separation along the common path length. The controllers indicated that the time order information displayed on the flight data table was useful; however, the touchdown time and delay information was not used.

- COMPARISON OF MIX CONDITIONS
- CONTROLLING THE MIX
- USE OF DISPLAYED TIME DATA

AVERAGE NUMBER OF CLEARANCES

This figure provides the average number of clearances/aircraft. It can be seen that as more aircraft are 4D equipped, the average number of clearances per aircraft decreases. This is fairly obvious in the experiment context described, since 4D-equipped aircraft were not vectored. They were assigned a touchdown time which was not altered in most cases.

% EQUIPPED	AVERAGE NUMBER OF CLEARANCES/AIRCRAFT
0	5.2
25	4.5
50	2.7
75	2.4

EFFECT OF 4D ON LOW-SPEED TRAFFIC

The previous figure shows the decrease in the average number of controller clearances as a greater percentage of aircraft are 4D equipped. A major concern is: does the average number of clearances for the unequipped aircraft increase as the percentage of equipped aircraft increases? The answer to that question is provided in the figure below, which gives the average number of clearance/aircraft for the Deerpark route only. Recall that the Deerpark traffic was always 25% of the traffic sample, and that all Deerpark is unequipped aircraft. This figure indicates that the average number of clearances given to the Deerpark unequipped aircraft is the same, independent of the mix condition. Also shown is the average time in the system (in minutes) for the Deerpark traffic, which is also seen to be independent of the mix condition.

LOW-SPEED (DEER PARK) TRAFFIC IS 25% OF ALL TRAFFIC IN EACH TEST CONDITION

MIX	AVG. TIME IN SYSTEM, min:sec	AVG. # OF CLEARANCES PER AIRCRAFT
0	19:16	6.9
25	18:56	6.5
50	19:05	6.2
75	19:05	6.4

LOSS OF 4D SCHEDULING

There was a desire to examine how traffic handling is disrupted if a breakdown of the 4D scheduling computer occurs. To investigate this, during a 75% 4D-equipped run, the FDT was removed from the screen so that the controllers no longer had a display of schedule times and order for aircraft in their sector. Furthermore, all feeder-fix departures from then on would not have any 4D time assignment, and would have to be vectored. The map display which showed aircraft positions was not removed. Initially, there was no change. The 4D-equipped aircraft already in the control sector could still be left alone since they would continue to follow their previously assigned 4D route. This is in contrast to a totally ground-based 4D system in which the ground system generates clearances for every aircraft; when that type of system fails, all aircraft are affected in a short time. The only difficulty experienced with the system tested was that after the failure occurred, controllers continued to allow traffic to depart the feeder fixes at the higher arrival rate for the 75% equipped case, rather than to adjust to the baseline vector arrival rate. If the flow-rate adjustment for new feeder-fix departures is made when the failure occurs, then it seems clear that the use of the on-board 4D system provides a safe transition to the standard vector mode.

OBJECTIVE:	DETERMINE EFFECTS OF ATC COMPUTER OUTAGE
ACTION:	DURING A 75% 4D RUN, FLIGHT DATA TABLE REMOVED
OBSERVATION:	NO INITIAL CHANGE (BUSY PERIOD). SOME PROBLEMS WITH HIGH ARRIVAL RATE OF NEW ARRIVALS
CONCLUSIONS:	ONBOARD 4D PROVIDES SAFE TRANSITION TO VECTOR MODE. NEED TO ESTABLISH AS PART OF PROCEDURE AN IMMEDIATE CHANGE OF FLOW RATE FOR NEW DEPARTURES

CONCLUSIONS

Algorithms were developed to obtain an initial time schedule and to provide for revisions for a mix of 4D-equipped and unequipped aircraft in the terminal area. These algorithms were used to develop a candidate set of operational procedures for mixing 4D-equipped and unequipped jet aircraft along the same route, and for mixing different speed classes along merging routes. A basic rule established was not to alter the 4D equipped aircraft once they were assigned a landing time. This procedure resulted in the controllers learning to use the 4D aircraft positions to effectively vector the unequipped aircraft to their assigned landing slot. However, procedures were also demonstrated to vector the equipped aircraft and to reassign touchdown times. In addition, it was shown that a loss of the ground based 4D system results in a smooth transition to vector operations. Controller evaluations indicated that the 25%-equipped case was the most difficult to handle. Nevertheless, quantitative data actually showed a decrease in the number of controller clearances with respect to the 0% 4D-equipped case. Controllers felt that the procedure of not altering the 4D-equipped aircraft when so few were equipped was workable, but that it was a more complex task. Nevertheless, fuel was saved even in this case, compared to 0% 4D-equipped aircraft. The controller workload as measured by the average number of clearances per aircraft decreased as the percentage of 4D-equipped aircraft increased. Moreover, this average decrease was not accomplished at the expense of the unequipped aircraft. The number of clearances for the unequipped aircraft as well as the time delays was independent of mix condition.

- DEVELOPED SCHEDULING ALGORITHMS AND OPERATIONAL PROCEDURES
- ALL MIX CONDITIONS EFFECTIVELY CONTROLLED
- REDUCED CLEARANCES AS PERCENTAGE 4D INCREASED
- UNEQUIPPED NOT PENALIZED BY 4D

REFERENCE

1. Tobias, L.: Time Scheduling of a Mix of 4D Equipped and Unequipped Aircraft, NASA TM-84327, 1983.