Analysis of Sequencing and Scheduling Methods for Arrival Traffic

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SUMMARY

The air traffic control subsystem that performs scheduling is discussed. The function of the scheduling algorithms is to plan automatically the most efficient landing order and to assign optimally spaced landing times to all arrivals. Several important scheduling algorithms are described and the statistical performance of the scheduling algorithms is examined. Scheduling brings order to an arrival sequence for aircraft. First-come-first-served scheduling (FCFS) establishes a fair order, based on estimated times of arrival, and determines proper separations. Because of the randomness of the traffic, gaps will remain in the scheduled sequence of aircraft. These gaps are filled, or partially filled, by time-advancing the leading aircraft after a gap while still preserving the FCFS order. Tightly scheduled groups of aircraft remain with a mix of heavy and large aircraft. Separation requirements differ for different types of aircraft trailing each other. Advantage is taken of this fact through mild reordering of the traffic, thus shortening the groups and reducing average delays. Actual delays for different samples with the same statistical parameters vary widely, especially for heavy traffic.

ABBREVIATIONS

ARTCC   Air Route Traffic Control Center (also called Center)

ATC   air traffic control

CPS   constrained position-shift optimization scheduling method

ERM   en route metering

ETA   estimated time of arrival at the runway (no interference from other aircraft)

FAA   Federal Aviation Administration

FCFS   first-come-first-served scheduling method

N   traffic density = demand = number of aircraft/hr wanting to land

STA   scheduled time of arrival at the runway (includes required delays)

TA   time-advance optimization scheduling method

TMA   Traffic Management Advisor

INTRODUCTION

An automated system for air traffic control (ATC) may be divided into three principal subsystems whose functions involve sensing, planning, and controlling. The subject of this report is the planning subsystem that performs scheduling. The function of the scheduling algorithms is to plan automatically the most efficient landing order and to assign optimally spaced landing times to all arrivals. Several important scheduling algorithms are first described, and the statistical performance of the scheduling algorithms is then examined.

The most straightforward scheduling method assigns the landing order on a first-come first-served basis (FCFS). In this method, after aircraft enter the Air Route Traffic Control center (ARTCC), they are scheduled in the order in which they are predicted to land, using a nominal path, flight plan, preferred descent speeds, and altitude profiles. The FCFS scheduler adds appropriate delay times to insure proper spacing, which depends on the weight classes of the aircraft.

FCFS scheduling can be compared with present technology. An operational scheduling system used at some ARTCCs is called En Route Metering (ERM). ERM generates rough approximations for the estimated times of arrival (ETAs) and bases the FCFS ordered scheduled times of arrival (STAs) on those ETAs. The main use of ERM is to provide a specified flow rate from the Center to the TRACON. It does not perform optimization of schedules, nor does it provide advisories to achieve accurate arrival times. Also, the order assigned by the current scheduler is often not followed; rather, it is used primarily to indicate landing-slot availability to which the controller may assign any aircraft. Current scheduling and metering does not use spacing depending on the weight classes of aircraft; instead, it uses the same time-interval between all types of aircraft. However, the time-interval can be changed by the operator to produce a specified landing rate.

An effective method of reducing the average delay time without changing the order of the aircraft is called time-advance (TA). In this his method, the beneficial effect of occasionally speeding up an aircraft during periods of heavy traffic in order to reduce gaps that naturally occur in FCFS schedules is recognized. It is called time-advance herein and in reference 1 and is called the negative delay effect in references 2 and 3.

The spacing requirements mentioned earlier offer the opportunity to optimize the landing sequence, thereby improving on the FCFS and TA methods by minimizing the average delay per aircraft. A sequencing and scheduling optimizing method called constrained position shift (CPS) was developed several years ago by Dear (ref. 4). The CPS method assumes that an initial landing order has been determined by FCFS and that all aircraft are tightly packed, that is, that they have minimum time-separations. By rearranging the landing order, while not shifting any aircraft from its original position in the sequence by more than a few places, the total time between the first aircraft and the last aircraft can often be reduced. Though CPS is conceptually straightforward, its implementation in a real-time algorithm is more complex because of bunching and of gaps in the arrival sequence. The gaps are due to the randomness of the arrival times of aircraft in the terminal area. CPS must, therefore, be applied to individual groups of aircraft as we have done here, or the algorithm's performance index must be rewritten from that given in appendix A, so that it minimizes the sum of the scheduled flight times instead.

Another method of optimization, the branch-and-bound technique, was used in an ATC advisory system called COMPAS (ref. 5). Both optimization methods, CPS and branch-and-bound attempt to sequence incoming aircraft in such a manner as to minimize the total delay for all aircraft, and for both methods various restrictions apply in order to obtain feasible solutions.

Three of these methods of scheduling, FCFS, TA, and CPS have been implemented in a Traffic Management Advisor (TMA) Station, which is part of an automated system for the management of arrival traffic (ref. 1). The scheduler in this system permits the selective use of any of these scheduling schemes, and it contains other features that are important for the human interaction with the automated scheduler.

The purpose of this report is to statistically evaluate the scheduling methods that are implemented in the TMA. This is done using a large number of realistic traffic samples to determine their overall effect on aircraft delays. Additionally, the analysis is used to show the effects of other variables on delays such as traffic distributions, lengths of traffic samples, and winds. Also, analysis of the results for an optimal single-position-shift CPS, which cannot be implemented in an operational ATC system, permits the design of a heuristic CPS that can be implemented.

First, we discuss three scheduling algorithms, FCFS, TA, and CPS, wherein each successive algorithm improves on the preceding one by further reducing the average delay for all aircraft. Then, we build a model of incoming traffic to a hub airport for the purpose of evaluating the scheduling algorithms. Finally, we generate a sufficiently large number of randomly chosen traffic samples to obtain the statistical characteristics of the scheduling algorithm as a function of mix of aircraft and traffic density. The primary criterion of performance is average delay per aircraft. In addition, we will examine a few individual traffic samples, to determine where scheduling algorithms may be simplified or improved.

An exact solution of the constrained position-shift problem is presented in appendix A, which was written by Jeffrey C. Jackson (School of Computer Science, Carnegie-Mellon University, Pittsburgh, PA). The combined FCFS and time-advance algorithm is given in appendix B.

SCHEDULING ALGORITHMS

In order to schedule aircraft for landing at an airport in an efficient manner one has to know the separation requirements for different types of aircraft. We will therefore discuss these requirements before going to the actual scheduling algorithms.

Separation Requirements

Separation requirements are an essential input for all types of scheduling algorithms. As stated earlier, we are dealing with two types of aircraft, heavy and large. For each type, the Federal Aviation Administration (FAA) specifies a separation distance at landing that is dependent on the sequence heavy-heavy, heavy-large, large-large, large-heavy. The minimum separation matrix is shown below (separation distances are in nautical miles).

| | Second to land | |
First	Large	Heavy
Large	3	3
to land Heavy	5	4

The time-separations are based on FAA specified separation distances on final approach, and on the speed profile of each aircraft weight class (ref. 6). The time-separations for no wind are shown below (times in seconds).

| | Second to land | |
First	Large	Heavy
Large	78	78
to land Heavy	125	104

Under headwind conditions, when the trailing aircraft flies at constant airspeed independent of the wind, its ground speed is reduced by the speed of the wind. Thus for a specific separation in miles, under headwind conditions, the time-separation matrix will have larger required separations. When the headwind is 20 knots, we obtain approximately the following values (the exact values depend on the assumed indicated airspeed profile). Again, the time-separations are given in seconds.

| | Second to land | |
First	Large	Heavy
Large	91	91
to land Heavy	145	122

Modified First-Come First-Served Algorithm

The simple FCFS algorithm determines the aircraft landing sequence based on the order of its estimated time of arrival (ETA) at the runway, computed by the Center at the time the arrivals cross the Center's boundary.

The modified FCFS algorithm recognizes two scheduling horizons: an initial scheduling horizon and a final scheduling horizon. The initial scheduling horizon is a spatial horizon, which is the position at which each aircraft enters the Center's space. The final scheduling horizon, called the freeze horizon is defined by a specific time-to-landing, given no interference from other aircraft. Once an aircraft has penetrated the freeze horizon, its STA remains unchanged, being independent of ETAs of other aircraft subsequently entering into the scheduling interval.

The scheduling algorithm receives the data for each new aircraft as it passes the initial spatial scheduling horizon: present time at which the aircraft crosses the initial scheduling horizon, ETA, aircraft weight class, and aircraft identification. If the (temporal) freeze horizon is a shorter time-interval than the shortest estimated flight time from the Center boundary to landing, the scheduling algorithm establishes the landing sequence in order of the computed ETA, which is called the FCFS order, and computes the associated scheduled time of arrival (STA) at the runway. If the freeze horizon is a larger

time-interval than the shortest estimated flight time from the Center boundary to landing, the situation is more complicated, as will be discussed next.

For aircraft that enter the scheduling horizon, the STAs are computed as follows. If no other previously scheduled aircraft's ETA is later than that of the newcomer's ETA, then the STAs of the earlier scheduled aircraft are not disturbed, and the newcomer is assigned a time equal to its ETA or the time that ensures the minimum time-separation required for the types of aircraft that are following each other, whichever is larger. If a new arrival's ETA falls ahead of the time slots reserved for previously scheduled aircraft, and if none of the already scheduled aircraft had its schedule frozen, then the new arrival is inserted ahead of these aircraft in the order of the ETA and at the proper spacing from the next earlier aircraft. All aircraft following the new arrival are re-spaced with the proper spacing. If frozen scheduled aircraft have STAs later than the new arrival's ETA, we first check if a sufficiently large gap exists such that the new aircraft can be scheduled ahead of the frozen aircraft without changing any other aircraft's position. If proper separation cannot be maintained, the new aircraft is scheduled in front of the first aircraft whose schedule has not yet been frozen, and the non-frozen aircraft behind the newcomer are rescheduled. (If frozen aircraft are present, this is not strictly an FCFS scheduling, even though we call it that in this report.)

Aircraft arriving at the boundary of the initial scheduling horizon appear unevenly spaced. Therefore the FCFS algorithm creates groups of tightly scheduled airplanes with large gaps between individual groups. With the FCFS algorithm, the first aircraft in a group requires no delay whereas succeeding aircraft, on the average, require increasingly larger delays.

Time-Advance Method

The TA method, which was called the negative delay effect in reference 2, operates on the first aircraft of each group, and does not change the existing order (e.g., FCFS). The first aircraft in a group is speeded up to arrive sooner than its nominal ETA, and all aircraft in the group following it will have their delays decreased by the same amount of time. This also reduces or closes the initial intergroup gap. Since speedup is costly, the first aircraft is speeded up only when at least the immediately following aircraft requires a delay, which is shortened because of the speedup of the first aircraft. In this statistical evaluation, we do not have a program that calculates maximum, minimum, and nominal ETAs from aircraft, navigation, and weather data. In the absence of actual minimum ETA data, we chose a maximum time-advance of 1 min for all aircraft. In an implemented scheduling system, the time-advance for each leading aircraft in a group can be based on a fraction of the calculated values of the available time-advance.

When the (temporal) freeze horizon has a smaller value than the time of the shortest flightpath, FCFS and TA applied to the incoming traffic result in the same overall aircraft order. This is not so when the freeze horizon has a larger value than the time for the shortest flightpath. A more detailed description of the combined FCFS and TA algorithm is given in appendix B.

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Constrained Position-Shift Method

Optimal CPS– As previously mentioned, the CPS method reorders the existing FCFS order by taking advantage of different separation requirements for different aircraft classes. Reordering makes sense only within a group. It is theoretically most effective when the groups are long (heavy traffic). Two aircraft are considered for reordering by a single position, provided that they arrive at the airport from different directions. This prevents possible overtakes within a sector. An optimal single-position-shift algorithm was developed by Jackson (unpublished) and is described in appendix A. A necessary restriction is that none of the aircraft in the group can be given a time-advance of more than 1 min. As the algorithm is written, this restriction can only be tested after the algorithm has proposed position switches. Various non-optimal methods of removing the violations to the restrictions make the overall algorithm non-optimal. Because of computational constraints on the scheduling algorithms operating in real-time, and because of the physical constraints of time-advancing aircraft, the use of larger position shifts is not practical. Similar to the TA method, in a more complete simulation, one could use a time-advance equal to a percentage of the available time-advance for the given aircraft.

Heuristic CPS– The optimal CPS is based on the dynamic programming principle, and the solution of all position shifts is found only at the end of each group of aircraft. In an actual system, we have a scheduling window with a time-interval often much shorter than that of a group of aircraft, especially for heavy traffic, when CPS would be useful. As discussed in the results section, optimal CPS switches aircraft positions in such a way as to group heavy aircraft when possible. The following groupings are considered for the heuristic CPS, where "H" means heavy and "L" means large aircraft. Groups of size 5 which contain LHL: LHLHH -> LLHHH, HHLHL -> HHHLL, LHLHL -> LHHLL, and one HL or LH switch suffices. The sequence HHLHH is not switched. In addition, two longer patterns are considered if a sufficient number of aircraft are in the scheduling window: a pattern of size 6, LHLLHL -> LLHHLL, which requires one HL and one LH switch, and a pattern of size 7, which also requires one LH and one HL switch: LHLHLHL -> LLHHHLL. Two additional patterns, those that require a two-position shift of a heavy aircraft, are also checked for: LHLLHH -> LLLHHH and HHLLHL -> HHHLLL. This makes it possible that under certain conditions the heuristic CPS may work better than the single-position-shift optimal CPS.

For all these patterns, the earliest aircraft can be below the freeze horizon, since it is never involved in a switch; nevertheless, it determines which pairs of aircraft are switched. One additional pattern is searched for at the end of each group of aircraft LHL gap L or H -> LLH gap L or H. This increases the length of the gap. Before switching, the old order of aircraft types and STAs is preserved. After the new STAs have been calculated, using the minimum time-separation matrix shown previously, we check to verify that all delays STA[j] - ETA[j] are less than −1 min (time-advance of less than 1 min). If this is not the case, the old unswitched values are restored. This automatically takes care of larger gaps in the original aircraft sequence. The longer patterns are checked by using the original sequence of aircraft types, and the possible changes from matching a shorter pattern are changed to the longer pattern, provided they meet the delay criteria. As desired, attempted rescheduling over a large gap will cause the delay criteria to fail. No performance criterion needs to be calculated, since each switch guarantees some reduction in average aircraft delay of the traffic sample.

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TRAFFIC MODEL

Toward an Accurate Traffic Model

To evaluate the scheduling algorithms for a particular situation, one needs an accurate traffic model. Such a model might be based on scheduled airline arrivals for specific days of the week, including planned routes and aircraft types. Such lists are available at ARTCCs and are presently used by the traffic managers to predict peak traffic times. However, these lists are not accurate enough to predict aircraft arrivals at the Center boundary, because, as will be explained next, scheduled traffic must be considerably modified before it crosses the Center boundary.

All traffic samples discussed herein are based on arrivals at Denver Center. Scheduled traffic at Denver for a particular date and time-interval is illustrated in figures 1 and 2. It can be seen from these figures that the incoming traffic was heavily concentrated in the 30-min period from 7:45 A.M. to 8:15 A.M. (local time), and that almost all traffic was from the NE and SE. In fact, there were 56 aircraft scheduled in a 33-min time interval. Such peaks do not get completely flattened out by the natural statistical blurring owing to random delays in takeoffs, errors caused by winds, and flight technical factors, but the flattening process is aided by deliberate changes, such as ground holding and increases in in-trail spacing. To get a more precise model of the traffic, one would have to collect data for many days on aircraft crossing the Center boundary, along with aircraft type and planned route. Such data are difficult to obtain. Therefore, we are using a somewhat less detailed model, which is based on gross traffic statistics.

Traffic Model for Studying Scheduler Effect

The purpose of this work is to describe a statistically accurate traffic model typical of peak hours at Denver, which was used to investigate different scheduling algorithms. When many traffic samples are analyzed, the model provides a good insight into traffic problems resulting from the random nature of traffic arriving at the Center boundaries, even though the traffic scheduled by the airlines may be almost identical for many days. The aircraft arrival rates, in-trail distances, and their statistical variations are realistic for each jet route. These arrival rates may be changed, depending on what time of day is simulated. Also, traffic from one direction can be made heavier than that from the other direction. Moreover, the model assumes that the incoming traffic on different jet routes is not coordinated for conflict avoidance at the various route junctions or at touchdown. Coordination and conflict resolution have to be accomplished in the Center sectors (with the help of the scheduler) and finally in the TRACON area.

Jet traffic arrives in Denver Center's northwest arrival sectors along four routes, and in the northeast arrival sectors along three routes (fig. 3). The northwest traffic is handed to the TRACON through the Drako feeder gate, and the northeast traffic through the Keann feeder gate. Incoming traffic from the lower half-plane is not simulated, since it is landing on a separate runway during VFR operation.

One of the traffic directions usually carries high-density traffic and the other direction usually carries low-density traffic. In our simulation, the high-density direction carries about 70% of the traffic. Any other ratio of high-density-to-low-density traffic can be chosen. For this simulation, on the average, each of the four routes in the Drako area carries 25% of the NW traffic, and each of the three routes in the

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Keann area carries one third of the NE traffic. Also, on the average, of all aircraft arriving, 30% of all traffic is heavy jets, 70% is large jets. Presently we are dealing only with two types of aircraft, heavy and large. At Denver, small aircraft usually land on a different runway. These assumptions will sometimes be varied to observe the effects on the delay statistics.

Actual route-traversal times within the Center boundary are shown in the following table. These times vary considerably and make it difficult to develop a schedule that remains fixed in time, one that a controller can use. Hence, the times for each route were approximately equalized (the "total" columns in the table), which is equivalent in a real system to extending the shorter routes, J170, J10, and J157 into the adjacent Centers. The total route-traversal times are not arbitrarily made equal, since in a real system route-traversal times vary as a function of aircraft types and winds, and the scheduler must be able to handle routes of various lengths. This simulation is limited to constant route-traversal times for each route, independent of the type of aircraft, thus avoiding the study of possible conflicts on the same route, when a faster aircraft may pass a slower one.

| Jet route No. | Route traversal times | | |
	Within Center boundaries, min	Total, min	
J163	42.30	42.30	Through Drako
J 56	45.45	45.45	
J170	28.50	45.00	
J24	47.78	47.78	
J114	41.43	41.43	Through Keann
J10	25.10	45.00	
J157	34.11	45.00	

Given the chosen statistical traffic parameters, such as the landing rate and the sample time-interval, the start times and routes for exactly M aircraft are generated uniformly for the time-interval specified, where M = (landing rate × time interval), and is rounded to an integer. The aircraft arrival rate for each route is chosen based on the traffic load at Denver. Since time en route varies between 42.3 and 47.78 min for different routes, the nominal landing times have been rearranged so that the rectangular distribution for each route centers on one-half of the time-interval. This results in an overall nonuniform distribution for start and landing times, where only the first and last few minutes are affected. The uniform distributions of start times for individual routes sometimes violate the minimum separation standard of 3 min on each route. Hence, the times at which the aircraft cross the original Center boundary for each route are modified iteratively, starting from the earliest aircraft, by shifting each aircraft that violates the specified minimum in-trail spacing time-interval to a later time until all aircraft meet the specified in-trail spacing. This often generates several equally spaced aircraft, especially in heavy traffic, which duplicates real traffic situations. Also, this modification sometimes makes the traffic sample longer than the specified interval, especially when large in-trail spacing time-intervals are specified. Again, this is thought to be realistic, since a scheduling time-interval for a fixed number of aircraft must get stretched out, as the example in figures 1 and 2 showed.

To study the sensitivity of calculated delays as a function of the distribution of aircraft in the specified time-interval, we also provide the choice of a triangular distribution of aircraft for each jet route.

RESULTS

First, individual traffic samples will be discussed to give a clear picture of the generation of traffic samples and their statistical character, as well as to demonstrate the effect that scheduling has on delays. Second, statistical results will be discussed in terms of cumulative probability distributions.

Time Diagrams of Traffic Samples and Associated Delays

In this section we present a variety of traffic samples. Since traffic samples in tabular form are hard to grasp, a graphical presentation has been developed. The graphical presentation of the sample affords a quick way of understanding the interrelations of the various time-ordered lists and of grasping causes of delays, as well as suggesting some remedies. Using an example, we will first describe the time diagram in detail and then present various traffic samples, limiting the discussion to major points. Figures 4(a) and 4(b) show a theoretical traffic sample at Denver (arrival rate of 25 aircraft/hr from the NE and NW). Given a set of parameters, such as arrival rate (demand), sample time-interval, percent of total traffic on each route, minimum in-trail spacing, and freeze horizon, each random-number generator seed defines one traffic sample. Knowing this seed, one can examine in detail unusual traffic sequences detected during the statistical runs.

In all the traffic samples shown, two thirds of the traffic is through Drako and one third through Keann. The mix of large-to-heavy aircraft is 70% to 30%. The traffic sample time-intervals are 1.5 hr, with no traffic before or after. The minimum in-trail spacing in the Center is 3 min, which often results in several aircraft on a route exactly 3 min apart.

The closely spaced top horizontal lines in figures 4(a) and 4(b) are time lines for each jet route. They are from top to bottom, J157, J10, J114, J24, J170, J56, and J163 (see fig. 3). The dots on each horizontal time line show when an aircraft is crossing the Center boundary on a given jet route. The time-scale for these time-lines is given above the lines. The time-scale for the ETAs and STAs has been shifted by a constant amount (40 min) to make the figure more compact. This scale is shown below the graph.

Each downward slanting line is called a scheduling line for one aircraft. The vertical top portion of each scheduling line begins at the appropriate jet route time-line and ends at an imaginary horizontal line, the Center boundary arrival-time-line. A slanted straight line connects the vertical line's lower end to the ETA. This time represents the time the aircraft would arrive at the runway, if there was no interference from any other aircraft or from unknown navigation errors and environmental conditions. The sequence of all ETAs determines the FCFS order to be preserved (at least approximately) for fair scheduling.

Any two lines that cross between the Center boundary arrival time and the ETA belong to two aircraft on different routes, where the aircraft on the shorter route is arriving later at the boundary, but whose ETA is earlier than that of the other aircraft.

The horizontal component of the line between ETA and FCFS STA in figure 4(a) or the ETA and FCFS + TA STA in figure 4(b) represent the scheduled delay to meet separation requirements. If the scheduling line is vertical, no delay is required for the particular aircraft. The more delay the greater the slant of the line. If none of the lines intersect, as in figure 4(a), the FCFS order has been preserved, which is the case when the scheduling horizon is selected below the time for the shortest route. The average delay per aircraft in minutes is shown for each scheduling method; for example, under FCFS the average delay is 0.88 min, and further schedule optimization reduces the average delay.

In figure 4(b), for the same arrival data, the scheduling freeze horizon was deliberately chosen larger than the time it takes to fly most routes (45 min), hence, lines between ETAs and (FCFS + TA) STA sometimes intersect, showing that the FCFS order has been altered. Since FCFS and TA are not separable in their effects (the FCFS order is not preserved), only the joint schedule is shown (i.e., FCFS + TA). Scheduling around frozen aircraft often has the effect of increasing the total delay for the traffic sample when compared with strict FCFS scheduling, as demonstrated by comparing the average delays in figures 4(a) and 4(b), where the FCFS + TA average delay increased from 0.18 to 0.52 min. (In a few samples of the several thousand analyzed, this trend was reversed in cases when changing the FCFS order mimics an intelligent CPS.)

The straight line between FCFS time and TA time in figure 4(a) shows the effect of time-advance. An aircraft that had zero FCFS delay is a candidate for time-advance, provided that it is the leader of a group of at least two aircraft. The aircraft is speeded up by 1 min or until the gap to the preceding aircraft is reduced to the minimum allowable, whichever is the smaller time-advance. Commercial jet aircraft have only limited capability of speeding up in the descent phase, and a maximum of 1-min time-advance is thought to be typical. The leading aircraft incurs a fuel cost flying above its preferred speed. All other aircraft in the group that are not speeded up beyond their ETA will benefit by having their FCFS delay reduced by the amount of time-advance of the leading aircraft. For time-advance, none of the aircraft scheduling lines cross, and the previous order is preserved.

The final portion of the aircraft scheduling line shows the absence or presence of CPS. Since we allow only a single position shift, only adjacent lines cross (see figs. 4(a) and 4(b)). Only the scheduling lines for aircraft going through Keann have a dot on the FCFS + TA line to indicate whether we consider position switching for two aircraft from the same direction NE (Keann) or NW (Drako), with a resulting overtake condition, which would add to controller workload. Notice that in this example, for each constrained position shift, one aircraft arrives from the NW, the other from NE. Thus, possible overtakes are prevented.

The short vertical lines underneath each aircraft time line indicate the type of aircraft, a longer line for heavy aircraft and a shorter line for large aircraft. Where the traffic is tightly bunched, it can be noted that the separations differ, depending on the successions of types of aircraft discussed earlier.

The total number of time-advance commands to aircraft goes up for smaller numbers of aircraft per hour, because the groups of aircraft for a 1.5-hr traffic sample become shorter and more numerous, and

each leading aircraft of a group must be time-advanced. This is illustrated for four traffic samples in figures 5(a) to 5(d). The traffic samples are chosen for light traffic (25 aircraft/hr) and heavy traffic (40 aircraft/hr), one sample each with relatively low average delay and the other sample with exceptionally large delay. Figure 5 shows what causes relatively small and large delays. We have small average delays when the ETAs are uniformly spread over the time-interval considered and are without large gaps, and we have large average delays when the opposite is true. We can see that for low-density traffic or well-spread traffic, TA should not be used, since delay is small already, and the cost in time-advance for the modest delay reduction is high, 12.16 min in figure 5(a) and 14.49 min in figure 5(c). There are many short groups, and many aircraft would have to fly faster than their preferred speed profiles. On the other hand, the cost in time-advance for heavy or bunched traffic is relatively small, 2.55 min in figure 5(b) and 2.22 min in figure 5(d), since only three aircraft needed to be speeded up in both cases. Figures 5(b) and 5(c) also show the modest improvement that can be achieved when CPS is added to TA optimization. For figures 5(a) and 5(d), CPS found no position shift that gave reduced delays. It is difficult to determine a break-even point for TA versus no TA, since both time and fuel are involved either as savings or as cost for all aircraft whose schedules are affected.

Figures 6(a) and 6(b) show a traffic sample in which CPS is applied with and without permitting overtakes. In this example, two additional heavy aircraft could be grouped together with overtakes permitted, resulting in a reduction of the average delay per aircraft from 2.87 min to 2.72 min.

It was shown in the Scheduling Algorithm section that a 20-knot headwind upon landing increases the required time-separations. A traffic sample illustrates this in figure 7, for FCFS only, for both both no wind and for a 20-knot headwind. In this example, for an identical sequence of ETAs, the average delay for FCFS scheduling is increased from 2.31 to 4.05 min. Therefore, winds can play a major role in causing delays.

Figure 8 shows parts of the traffic-sample diagrams having to do with CPS only. CPS tries to reduce the length of a group of aircraft, which reduces the average delay of all aircraft. The cost of such delay reduction is the fuel cost for those aircraft that have to be time-advanced beyond their ETA. Therefore, CPS shows the most benefit in reduced average delay when the position switching is done early in a large group, thus reducing the time delay for all following aircraft in that group. Switching at the end of a group is of little benefit in reducing the average time delay (top example of fig. 8), but controllers prefer to place a heavy aircraft at the end of a group. The remainder of figure 8 shows how CPS groups the heavy aircraft together by either time-advancing or by delaying the heavy aircraft. In this manner, groups of two, three, or four heavies are formed. Figure 8 shows only the reduction in delay: the group becomes shorter. The cost of such position switching depends on data not shown here; namely, whether the aircraft that are switched toward an earlier arrival time simply have their delay reduced, or if they have to speed up to arrive earlier than their desired time of arrival.

The optimal CPS algorithm assumes that a tightly scheduled group of aircraft can be reordered such that it is again tightly scheduled with no more than the minimum required gaps. After calculating the new order of aircraft, we find that sometimes the delay of some aircraft in the group decreases so that they have a negative delay of less than 1 min. In such cases, two alternative choices were made to meet the restriction (see the captions of figs. 9(a) and 9(b)). Either choice satisfies the restrictions at only a small loss of optimality when many samples are considered. Comparing the total delays for all aircraft in the sample of figures 9(a) and 9(b) with those of 9(d) and 9(e), we see that there is no clear choice of

method for meeting the maximum negative-delay restriction. To build this restriction into the algorithm directly would unnecessarily increase its complexity. This is not warranted, since the algorithm, as it stands, is not useful for an operational system, which has a finite scheduling window. Another minor improvement to the optimal CPS algorithm was made by deleting position switches only after an unacceptable negative delay was detected in a group of aircraft, and by retaining the earlier switches. The optimal algorithm was mainly used to get an upper bound on the performance of an heuristic algorithm, which has been derived from the insights gained by observing the performance of the optimal algorithm. In figures 9(a)-9(f), various equivalent sections of traffic have been marked by double-headed arrows of equal lengths. The arrow in figure 9(a) shows that although different switches have been made by the heuristic and the optimal algorithms, the section containing the same aircraft is only slightly longer for the optimal algorithm. The arrows in figure 9(b) show that the optimal CPS unnecessarily lengthened the sequence by one slot. Figure 9(b) still has the overall shortest delay, owing to many earlier switches in the same group of aircraft. The arrows in figure 9(c) show that for the same algorithm, the two unnecessary switches in a group of aircraft increased the delay for six of the nine aircraft, but the overall delay for all aircraft is only 8.5 min longer.

Analysis of Traffic Including Both Modes of Optimization

In interpreting the following data, we must remember that the model we are using for traffic-sample generation assumes that there is a rectangular probability distribution for arrival times at the Center boundary and that there is no traffic outside the interval under consideration, except where the 3-min minimum spacing requirements forced us to push some traffic beyond the maximum time. Almost certainly, the actual arrival-time distributions at the Center boundary are not completely rectangular, which would further modify the cumulative distributions. This means that the data given in this report are meant to show trends rather than precise values. The curves shown in figures 10-15 are approximations of the cumulative probability of the average time-delay per aircraft for a random traffic sample being equal to or less than the value given on the abscissa, with traffic density (demand in aircraft per hour) as parameter, where the average time delay per aircraft for a random traffic sample is defined as the sum of the individual aircraft delays divided by the number of aircraft in the sample. All cumulative distributions are based on 2500 traffic samples each, and data points are shown individually as dots to give an indication of the statistical noise in the data. We present the cumulative distributions rather than parameters such as expected value and standard deviation, since the distributions are neither Gaussian nor any other common distribution.

Figure 10 shows the cumulative probability distributions for the average delay per aircraft in a given traffic sample, with the parameter N, the traffic density or demand in number of aircraft per hour. The traffic mix (traffic from NW and NE) and the aircraft mix (heavies vs large) have been chosen such that it should show the greatest benefit for CPS optimization, namely both 50%/50%. Figure 11 shows data similar to those in figure 10, but for the traffic and aircraft mix chosen for most of this simulation, which is described in the Traffic Model section. As an example, if we study the N = 45 curves in figure 11, the benefits of TA and TA + CPS can be readily seen. For FCFS scheduling, an average delay of 8 min or less is realized for 46% of the traffic samples. With the addition of TA, the same average delay per aircraft or less is realized for 58% of all traffic samples. With the further addition of CPS, this delay, or less, occurs 64% of the time. In the remaining cumulative distribution figures, the groups of curves

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representing FCFS, FCFS + TA, and FCFS + TA + CPS are not always labeled separately, since they are always in the same order.

By looking at the complete cumulative distribution curves, the TA curves are moved to the left of the FCFS curves by somewhat less than 1 min, as was expected since that was the assumed maximum time-advance for each aircraft. In actual traffic, the allowable time-advance for a given aircraft depends on the type of aircraft, the aircraft state, and the proposed path. This may be somewhat more than 1 min on the average. In both figures 10 and 11, comparing the reduction of the average time-delay when CPS is added, we notice that CPS is more effective for greater traffic densities, which is fortunate. This is so, because longer groups occur in heavy traffic, and long groups can be optimized more effectively than short ones. However, compared with TA, the benefit of CPS is relatively small. Even in the best case, the delay reduction is less than 0.5 min per aircraft. In this simulation, CPS was calculated only once for each traffic sample by dividing it into groups of aircraft and applying CPS to each separate group. In an actual system, the STA calculations would have to be started for each aircraft as it arrives at the Center boundary and finished as it passes the freeze horizon. Since the present CPS algorithm is an example of the dynamic programming principle, the algorithm determines the final sequence only after the last aircraft of each group has passed the Center boundary. Making earlier decisions on position switching will cause some loss in performance.

In figure 12 we combine data from figures 10 and 11 to compare different aircraft mixes for the same traffic density. The larger number of heavies in the 50% heavy 50% large aircraft mix curves require more separation and therefore have more delay. However, CPS is more effective in this case, since more switching opportunities exist. Since the slopes of the CPS curves are steeper than those of the TA curves, CPS is also statistically more effective for samples with a higher average delay for a given traffic density.

So far all CPS data have been shown for the case in which overtakes are not permitted. That is, position-shifting for two aircraft was not considered unless one aircraft was traveling through the Keann waypoint, and the other through the Drako waypoint (see fig. 3) As shown in figure 13(a), when this restriction is removed, the reduction in average delay CPS versus no CPS has almost doubled. The cost is a higher workload for the air traffic controller. Figure 13(b) shows similar data for the heuristic CPS as compared with the optimal. As can be seen, the heuristic CPS has only a minor loss in performance compared to the optimal.

The effectiveness of the heuristic CPS depends on the size of the scheduling window. As shown in table 1 and in the inset in figure 13(b), the larger the window, the closer the performance of the heuristic CPS approximates that of the optimal single-position-switch CPS. The mean values shown as dots on the inset of figure 13(b) are above the 0.5 cumulative probability point, since the tails of the probability distributions are skewed toward large delays. For the large window sizes and a 0.5 traffic mix, the heuristic CPS even performs slightly better than the optimal single-position-shift CPS. This happens because it checks for two extra patterns, which shift one heavy aircraft either forward or backward by two spaces, and because those patterns are more frequent for the 50/50 traffic mix.

So far all cumulative probability curves shown were for 1.5-hr samples. Figure 14 gives the reduction of average delay when the length of the traffic sample is reduced. In figure 14, where we have used the same parameters as in figure 10 for 40 aircraft/hr, we can see that the reduction in sample

time-interval by a factor of 3 reduced the average delay by a factor of more than 2. However, we notice that the benefit of CPS for short samples is much smaller. The effect of longer and shorter sample time-intervals on delays will be investigated later in more detail for FCFS only.

Figure 15 shows the effect of specifying a freeze horizon above the minimum flight time from the Center boundary to landing, in an effort to make a frozen schedule available early to the air traffic controllers. The FCFS curves have been omitted to prevent curves from overlapping. As can be seen, there is a relatively high cost involved in scheduling new arrivals around already frozen aircraft slots. For the high-density traffic, the cost is almost as high as the gain from TA, and it is somewhat smaller for the lower-rate traffic (demand of 30 aircraft/hr).

Further Traffic Analysis FCFS Only

In the preceding Results subsection we have shown what optimal scheduling can accomplish under various conditions by presenting complete cumulative distributions. Various other effects owing to change in the traffic model or environment will next be briefly treated by discussing the effect on the 50% frequency point of the cumulative distributions. That is, 50% of the samples have higher average delay. Because of the unsymmetry of the distribution, the expected value is somewhat higher. We will report on FCFS with low horizon only, since the effects of optimization have been pretty well demonstrated in the last section.

Delay as function of length of traffic samples– An individual traffic sample can be thought of as a segment of traffic in which traffic before and after the sample is very light. Figure 16 shows that for relatively brief segments of intense traffic, the average delay per aircraft remains small, even when the arrival rate is higher than runway saturation. Here, the delayed aircraft can be landed quickly after the initial rush is over. However, as the length of the rush period increases, the delays increase sharply, especially for large arrival rates.

Effect of the distribution of arrival times– To obtain the previous results we always used rectangular center boundary arrival time distributions, which were modified by the requirement of 3-min in-trail spacing upon arrival at the Center borders. Figure 2 showed that the actual scheduled traffic is quite peaked. Although we have as yet no actual arrival data, it is likely that the distributions are not rectangular. We will therefore compare results for rectangular distributions with the same total number of arrivals for triangular distributions over the same time-span. This means that in the center of the studied time-span the traffic is especially heavy with light initial and final traffic. Figure 17 shows that such moderate peaking of traffic about doubles the delays. We can conclude that delays are very sensitive to the distributions of ETAs.

Effect of winds and changes in interarrival times on delays– It has been shown (Scheduling Algorithms) that a 20-knot headwind upon landing increases the required time-separations. Figure 18 shows the statistical results, which are very similar to the results for triangular landing-time distributions. The delays approximately double.

As a result of more precise guidance, automation has the potential of reducing the errors in interarrival times. Hence, aircraft may be spaced more closely in time to meet the spatial separations. If we can

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reduce the interarrival times given in the Scheduling Algorithms section by 10 sec, for the nominal traffic mix and a demand of 40 aircraft/hr, the mean delay per aircraft in a sample is reduced from 4.8 to 2.4 min. For a demand of 45 aircraft/hr, the mean delay is reduced from 8.3 to 4.3 min.

Effect of increasing in-trail spacing– The last few changes we studied increased the aircraft delays. One of the methods of decreasing the delays taken by the Center is to take delay outside the Center by increasing in-trail spacing. The inset in figure 19 shows schematically how this changes the distributions of incoming traffic. The number of aircraft is the same, but they are spread more evenly and the excess traffic is added as a tail over a longer period of time. The example is for 1.5-hr samples. It is clear that in-trail spacing is very effective in reducing the average delay at the Center. Of course, this assumes that no second traffic peak is expected in the near future.

CONCLUSIONS

Scheduling was performed in a the three-step sequence: one initial ordering FCFS, and two optimization steps, TA and CPS. Each additional step is computationally more complicated. Unfortunately, the incremental reduction of the average delay time per aircraft becomes less for each additional step.

The TA method can at best reduce the delay of each scheduled aircraft by the same amount that the first aircraft in each group has been time-advanced, which was 1 min in our case and can be somewhat more in practice. Although the left shift of the cumulative distribution curve owing to TA is almost independent of the traffic density, TA for light traffic is more costly for the airlines. This is because more leading aircraft of smaller groups must be time-advanced, which is unnecessary since delays are already small.

CPS is most effective for heavy traffic with large groups of aircraft. For such traffic, CPS can reduce the average time-delay per sample by an additional 20 to 30 sec provided that there exists a relatively even mix between heavy and large aircraft and that traffic density is approximately equal from all directions. For a given traffic sample, this method reduces the average delay per aircraft by a reasonable amount only when position-shifting occurs at the early part of a group, since then all following aircraft in the group have a reduced time-delay. However, in the early part of a group, position-shifting may cause an unrealizable time-advance requirement, and thus cannot always be used.

The effects of increasing levels of optimal scheduling are reasonably independent of the actual ETA probability distributions. The basic FCFS delays, however, are very sensitive to these distributions and to the lengths of the traffic peaks. Hence, the data given are meant to show trends rather than to give hard values.

For each landing rate and using our present model of traffic, large deviations from the mean delay occur as a function of the randomness of bunching of the traffic. Although the average delay in the Center airspace can be reduced by reducing the traffic density into the Center by means of ground holding or in-trail spacing, samples with large delays will still occur occasionally, since traffic from different directions is not time-coordinated. Even global scheduling cannot wholly avoid this occurrence, since random atmospheric effects and other uncertainties will always be present.

When the scheduling freeze horizon is set so that aircraft on shorter routes are inserted into the frozen part of the schedule, the average delay per aircraft increases compared with scheduling with a low freeze horizon.

Parametric studies showed that the actual probability distribution of arrival times (triangular vs flat), presence of headwinds on landing, and an increase in the lengths of traffic samples cause large increases in average delays.

In summary, scheduling brings order to an arriving sequence of aircraft. FCFS scheduling establishes a fair order, based on the ETAs and determines proper separations. Because of the randomness of the traffic, gaps will remain in the scheduled sequence of aircraft. These gaps are filled, or partially filled, by TA while preserving the FCFS order. Tightly scheduled groups of aircraft remain with a mix of heavy and large aircraft. Separation requirements differ for different types of aircraft trailing each other. CPS takes advantage of this fact through mild reordering of the traffic, to shorten the groups, thus reducing the average delays. Actual delays for different samples with the same statistical parameters vary widely, especially for heavy traffic.

APPENDIX A

EXACT SOLUTION OF THE CONSTRAINED POSITION-SHIFT PROBLEM
FOR SINGLE-POSITION SHIFT

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INTRODUCTION

The FAA mandates that various separations be maintained between landing aircraft based on their weights; generally, the lighter the aircraft the greater the separation required. Clearly, then, the amount of time required to land a given set of aircraft can depend on the landing order.

One approach to finding an "optimal" landing order is the constrained-position-shift (CPS) concept of Roger Dear of M>I>T. He posited that given an initial arrival ordering, real-world constraints would preclude moving any one of the aircraft more than some small number of positions from its original place in the arrival list. However, he did not present an exact solution to the CPS problem; his method was to examine a window of 2 × the maximum position shift − 1 positions, optimize it (exhaustively) for a single position shift, move the window down one position, and repeat the process.

This appendix presents an algorithm for finding an optimal solution to the CPS problem for a single-position shift.

THE ALGORITHM

Finding the optimal ordering of a set of aircraft can be thought of as a search for the "least-cost" path through a tree of possible aircraft orderings, where the cost is the sum of the time-separations required between each pair of aircraft. For the CPS problem, an initial ordering of aircraft is given, along with a list of delays from the ETAs and the maximum possible time-advance for each aircraft. In the final ordering, each aircraft is constrained to lie within one position of its initial position, and no aircraft must have a time of arrival earlier than permitted by the maximum allowable time-advance. Figure 1 illustrates the tree of possible orderings for the simplest case of MPS = 1. Note that the first aircraft (A) in the initial ordering is in our method constrained to be the first aircraft in the output ordering.

Thus, the only aircraft that can appear in position 2 of the final ordering are B and C, because of the MPS constraint. If the final ordering begins A-B, then C or D may be in the third position. However, if it begins A-C, then B must appear next in the sequence since B can appear no later than in the third position. Reasoning along these same lines produces the rest of the tree.

The algorithm for finding the least-cost path through this tree is essentially an application of the dynamic programming principle: **only extend the shortest path through a given set of nodes terminating at a particular node.** For example, the paths A-B-C-D and A-C-B-D are both valid MPS = 1 paths terminating with aircraft D and containing the same aircraft. In general, however, one of these paths will have less cost than the other, and only that path need be considered in further computations by the algorithm. This is because the optimal ordering of the remaining aircraft is independent of the order of B and C in the path to D. So if, for example, the path A-B-C-D is 15 units cheaper than the other path, the cheapest complete ordering beginning with A-B-C-D will be 15 units cheaper than the one beginning with A-C-B-D; that is, the optimal ordering of the remaining aircraft will be the same for both.

This simple idea allows a great savings in the computation of the least-cost path. For the MPS = 1 case, the algorithm begins by computing and storing the (time) cost of having B follow A and that of having C follow A (the paths A-B and A-C). It then computes and stores the costs of A-B-C, A-B-D, and A-C-B, discarding the two previously computed values. In the remainder of the processing, the dynamic programming principle is applied. For example, both A-B-C-D AND A-C-B-D are computed, but only the value of the lesser-cost path is stored. Once all the values at each level of the tree have been computed, the previous level's values are discarded. It turns out that in this MPS = 1 case there is only one set of aircraft which can precede a given aircraft at a given level (e.g., A, B, and C in some order must precede D, if D is going to be in the fourth position of the final ordering). Thus, only six values (three for the current level of the tree and three for the previous) must be stored by the program to compute the value of the optimal path. This process of extending least-cost paths eventually terminates when each path has N (the number of aircraft) aircraft along it. For the MPS = 1 case, only the last two aircraft in the initial list are candidates for being last in the optimal ordering. Thus, the least-cost paths leading to these aircraft at the lowest level of the tree are compared and the smaller cost path is chosen as the final optimal path.

For example, assume that the separation times required for various pairs of five aircraft are as given below.

Costs	A	B	C	D	E
A	–	2	2	4	3
B	6	–	3	2	4
C	3	2	–	3	2
D	4	5	6	–	4
E	3	2	2	2	–

Each value represents the time that the aircraft labeling the column must follow the aircraft labeling the row by. Notice that the values are not symmetric (e.g., it costs less for A to follow B than vice versa).

Tracing through the tree of figure A-1 (and ignoring the now undefined aircraft F) we find that there are two paths to aircraft D at level four, A-B-C-D and A-C-B-D, and that their respective costs are 8 and 6. Thus A-C-B-D is chosen as the preferred path to this node. Likewise, A-B-C-E is the low-cost path (7) to E at this level and A-B-D-C is the only path (cost 10) to C at this level. Extending these three paths to the fifth and final level, we find that A-C-B-D-E (cost 10) is better than A-B-D-C-E (cost 12),

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but A-B-C-E-D is preferable to both of these (cost 9). This final path is therefore chosen as the overall optimal path.

An additional detail of the algorithm, which has so far been neglected, is the maintenance of the list of best paths to each node of the search tree. This can be handled in a number of ways; a particularly simple way for the MPS = 1 case is to simply maintain three vectors that represent the best path thus far to the leftmost, middle, and rightmost nodes of the tree. For example, when A-C-B is chosen as the best path to D at level four in the example above, this path (the leftmost path at level three) can be copied to the vector for the middle path (position of D at level four) and D can be appended. Of course, care must be taken not to overwrite a vector representing a path at the previous level before that level has been completely processed, so two sets of three vectors (one for current level and one for previous) can be used.

APPENDIX B

COMBINED FCFS AND TIME-ADVANCE ALGORITHM

The combined FCFS and time-advance algorithm uses aircraft data as input. It is called once every time a new aircraft enters the Center air space. Because of the different lengths of the flightpaths, the aircraft are not in the landing order. The input data set for each aircraft consist of aircraft type (heavy or large), ETA, and route identification. The output data consist of STA. The algorithm schedules the aircraft and puts out arrays of aircraft data that are in the order of STAs. The aircraft with the highest index "i" is the aircraft to land last, provided no other aircraft enter the Center. When the first aircraft enters the Center air space, the index $i = 0$ is assigned and STA = ETA. The STA calculations include a time-advance, TA = 1 minute, if selected. An aircraft can be time advanced if it follows a scheduling gap, thus having no delay, and the following aircraft has an original SLT that is a minimum time-interval, dtmin, ahead. The remainder of the algorithm description is without time-advance. TA is treated in the last paragraph.

To calculate the STAs, the time-separation matrix for the succession of various aircraft classes is needed (given in the section on Scheduling Algorithms in the main text).

As a new aircraft enters the Center air space (ith aircraft) we first check if it has an ETA greater than that of the last (and largest) scheduled STA. In this case we assign STA[i] = ETA[i], provided the separation is equal to or larger than the minimum separation time dtmin for the two types of aircraft. If it is not, we delay the newcomer so that it will have the minimum allowable spacing (STA[i] = STA[i – 1] + dtmin).

If the newly arrived aircraft has an ETA smaller than the so-far-largest STA, we first search all STA gaps up to the one that includes the ETA of the new aircraft to see if they are large enough to accommodate insertion of the aircraft without having to reschedule any other aircraft. To achieve this, the time between the earlier scheduled aircraft must be larger than the sum of the appropriate dtmins if the new aircraft were inserted. In addition, the gap between the new aircraft and the next following STA must be equal to or larger than the appropriate minimum separation. If more than one gap fulfills these conditions, the new aircraft is scheduled to result in the smallest delay by being inserted into the earliest possible gap, dtmin ahead of the earlier aircraft.

Sometimes, no gap is available into which the new aircraft can be inserted without rescheduling any other aircraft. Then the new aircraft is scheduled ahead of the first aircraft that has a non-frozen schedule and whose STA is larger than the ETA of the new aircraft. The appropriate dtmin for the last frozen aircraft is used for the new aircraft, provided this does not require a time-advance of the new aircraft. If the ETA of the new aircraft is larger than the frozen aircraft's largest STA, then the new aircraft's STA is chosen to be the larger value of ETA, or STA of the next earlier aircraft plus the required minimum distance between that aircraft and the new aircraft. All later aircraft are then rescheduled to meet the separation standards.

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If a time-advance is desired, it is calculated simultaneously as scheduling proceeds. Whenever we do not schedule STA = ETA, we ask if the last aircraft before the new one had this property. If it did, this would mean that the last aircraft was following a gap and was leading a new group of at least two aircraft. Then TA would be used to reduce the size of the gap by 1 min if the remaining gap was greater than dtmin, or to dtmin, if this would take less than a 1-min time-advance. Once the last aircraft before the new one has been rescheduled (time-advanced), the new STA is calculated, $STA[i] = STA[i-1] + dtmin$.

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TABLE 1.– MEAN DELAYS FOR 40 AIRCRAFT/HR DEMAND FOR DIFFERENT SCHEDULING ALGORITHMS AND TRAFFIC MIX

Traffic mix	Heavy/large = 0.3	Heavy/large = 0.5
Sched. algorithm	Delay, min	Delay, min
FCFS	5.03	7.02
FCFS + TA	4.25	6.20
+ CPS opt	3.88	5.75
+ CPS heur 15-min window	3.93	5.71
+ CPS heur 10-min window	3.94	5.71
+ CPS heur 5-min window	4.02	5.83
+ CPS heur 3-min window	4.15	6.04
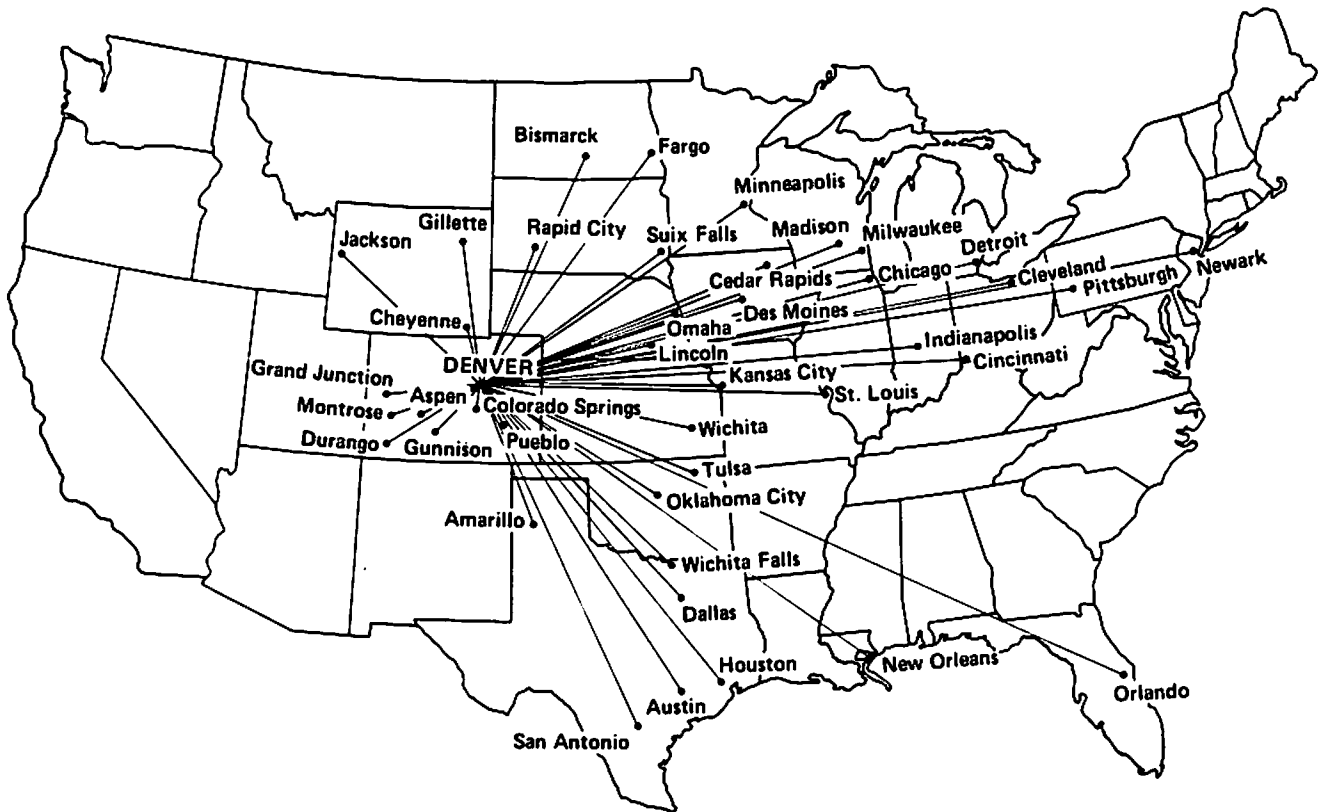
Figure 1.– Denver traffic: 1 March 1987, 7:00-8:35 A.M.

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Number of aircraft scheduled to land
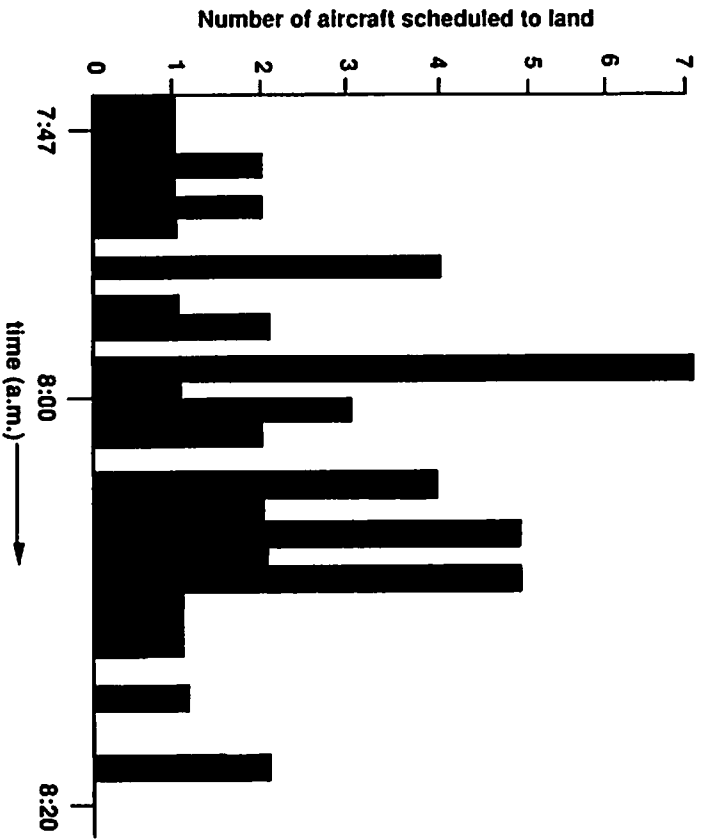
Figure 2.– Scheduled Denver arrival traffic in 1-min intervals.
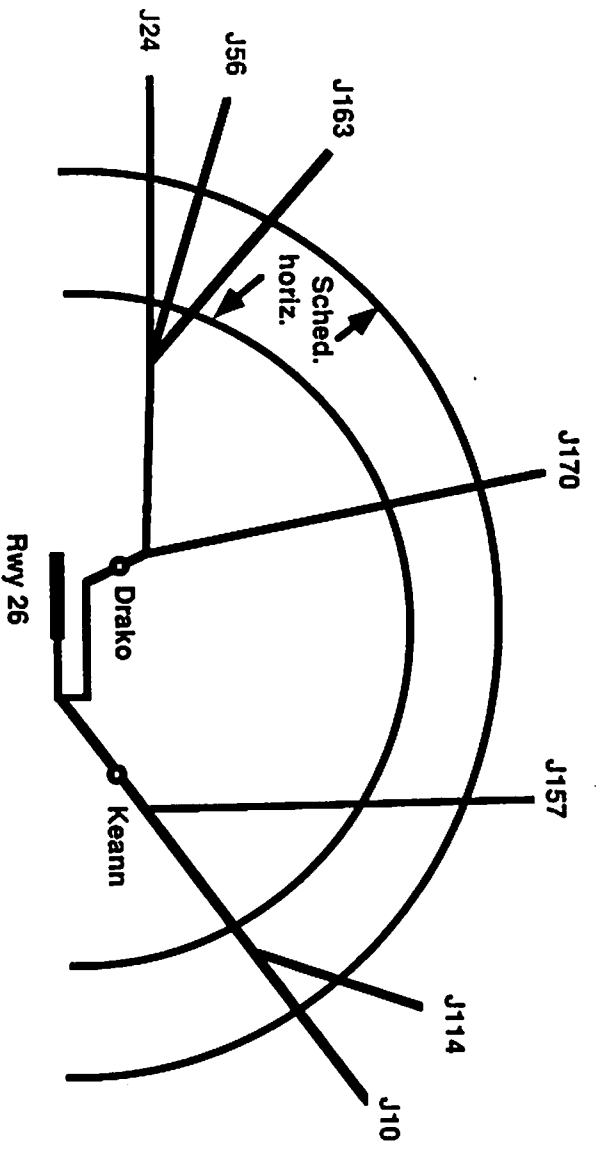
Figure 3.– NW and NE jet routes into Denver.

J24
J56
J163
Sched. horiz.
J170
J157
J114
J10
Drako
Keann
Rwy 26

25

Center boundary time

30   60   90 min

Keann
Drako
ctr boundary t

ETA

FCFS t
dly 0.88

+ TA
dly 0.18

+CPS
dly 0.13

(a)   60   scheduled landing times   90   large aircraft   120 min

heavy aircraft

Center boundary time

30   60   90 min

Keann
Drako
ctr boundary t

ETA

FCFS + TA
dly 0.52

+CPS
dly 0.50

(b)   60   scheduled landing times   90   120 min
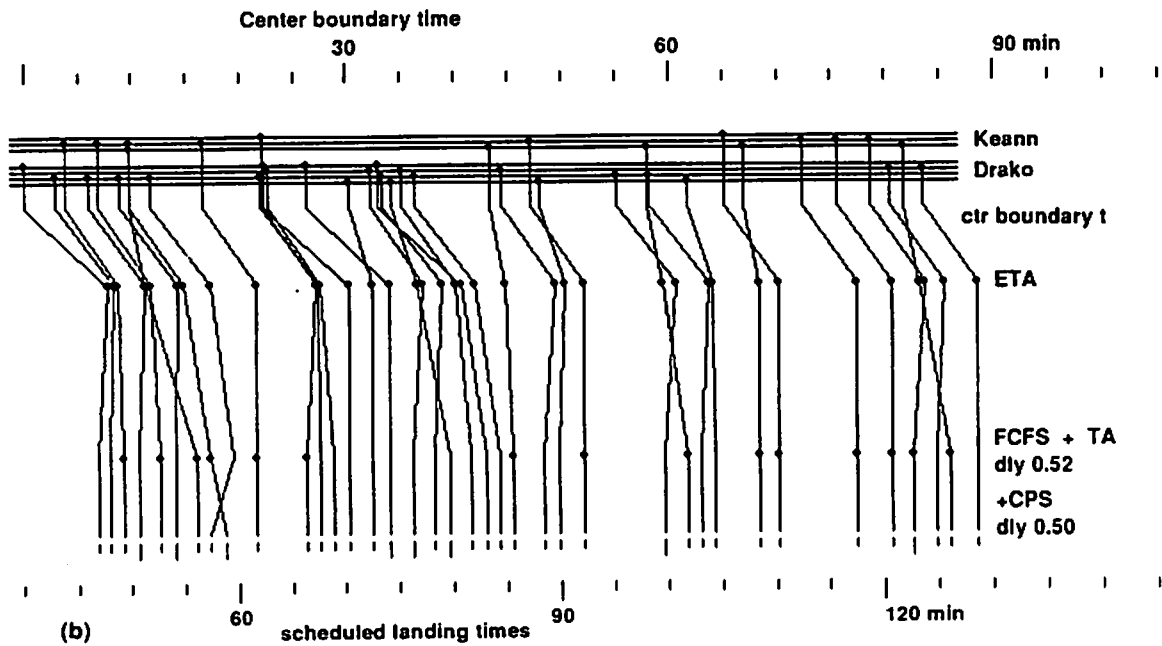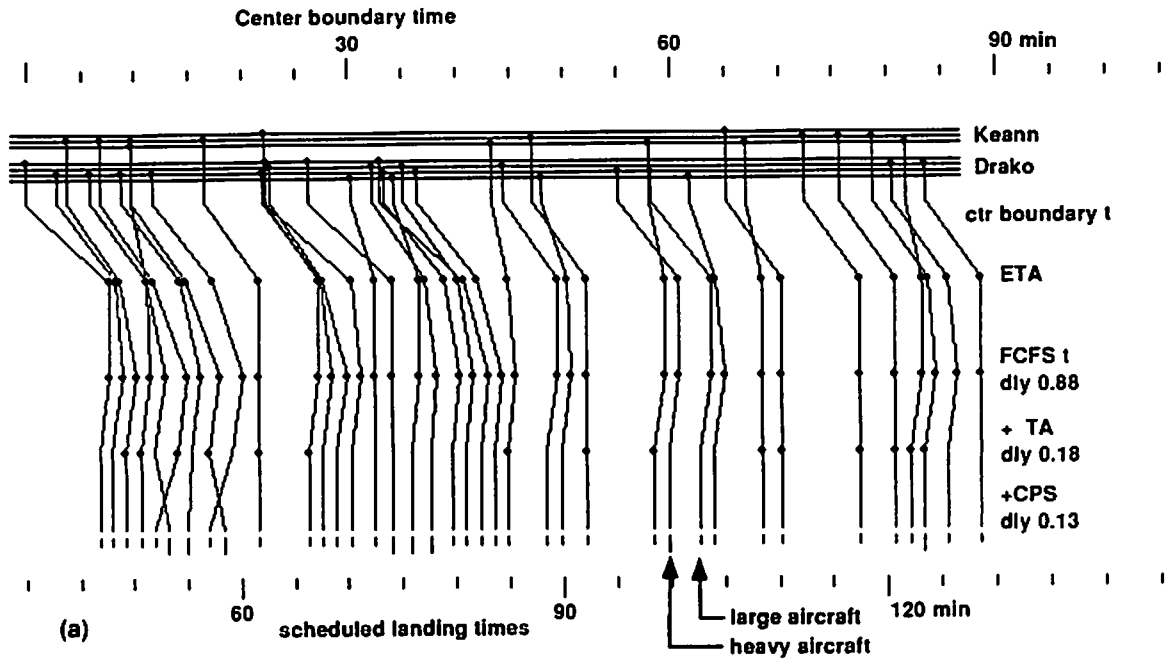
Figure 4.– Representation of scheduled traffic sample. (a) Low freeze horizon; (b) large freeze horizon.
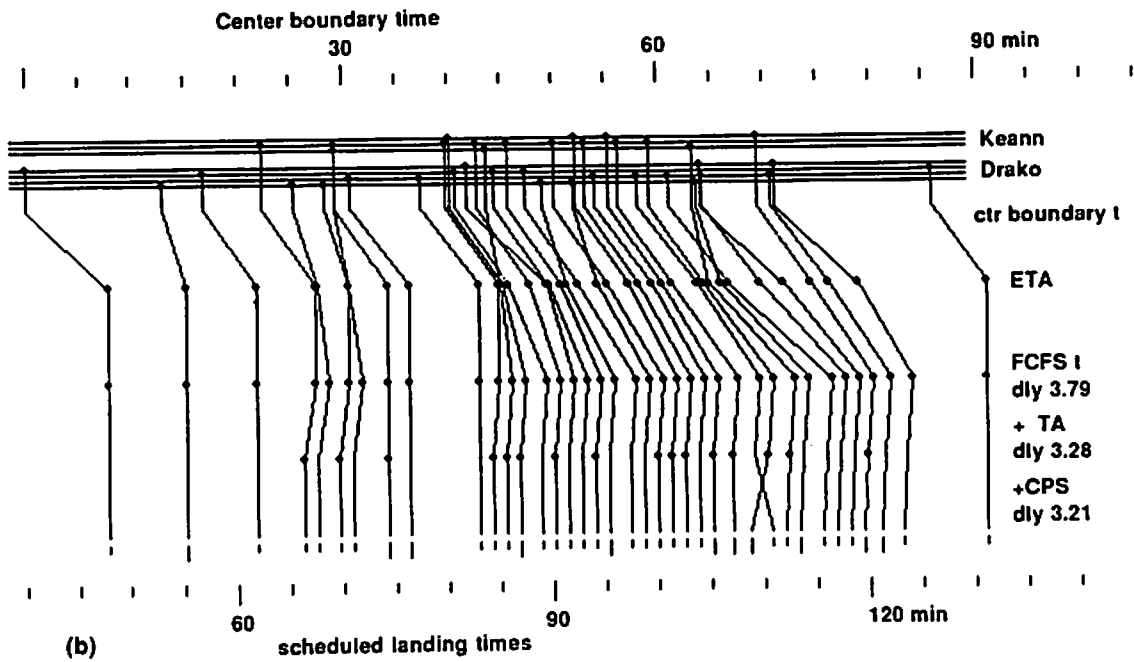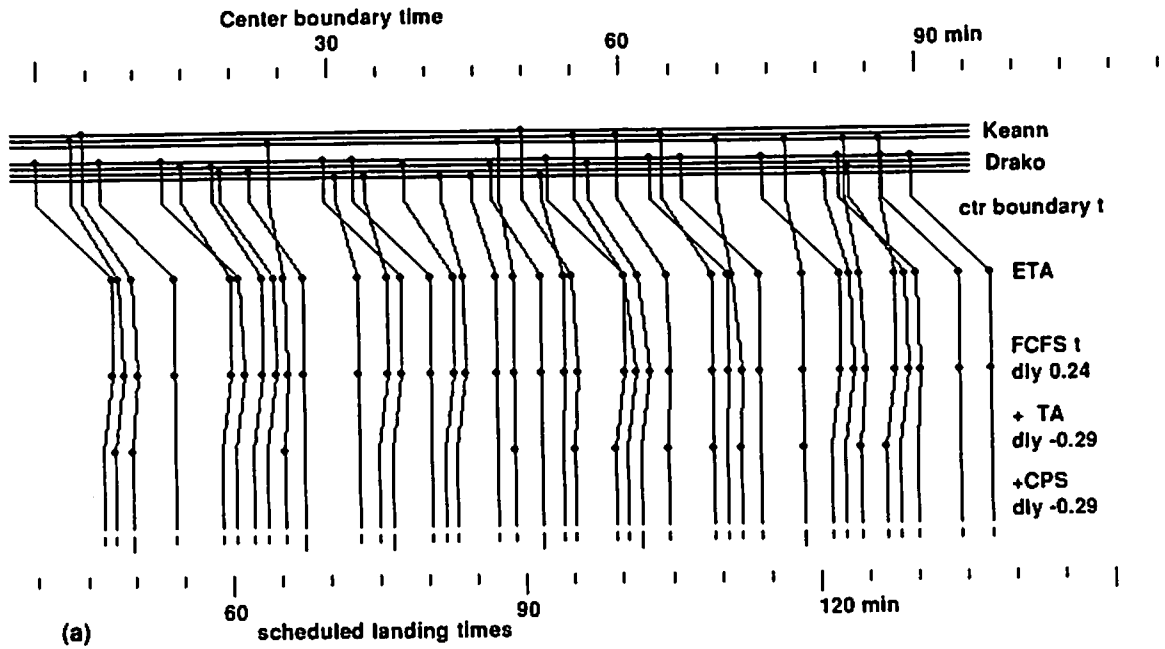
Figure 5.– Traffic sample. (a) Light traffic with well-spread aircraft; (b) light traffic with high delay.
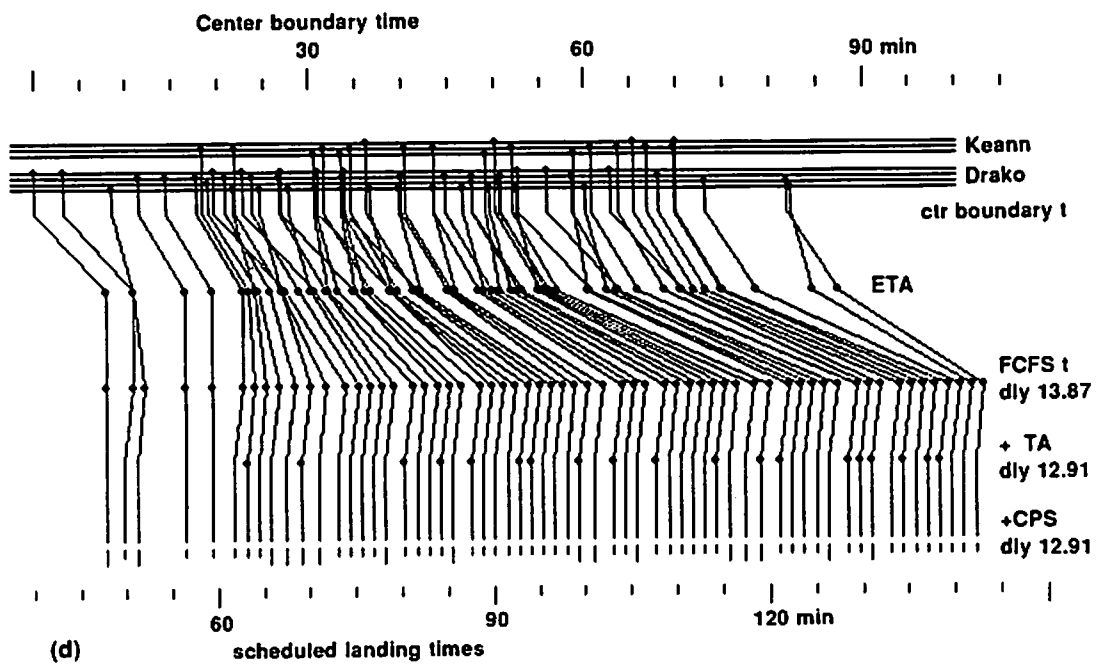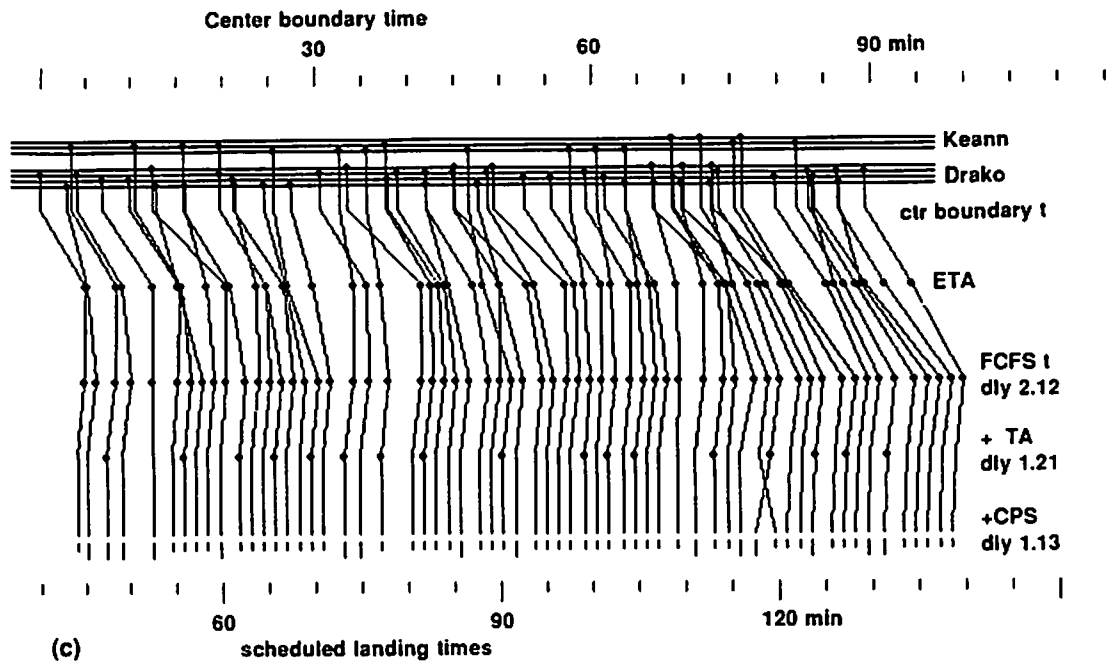
Figure 5.– Concluded. (c) Heavy traffic, well spread out; (d) heavy traffic with large delay.
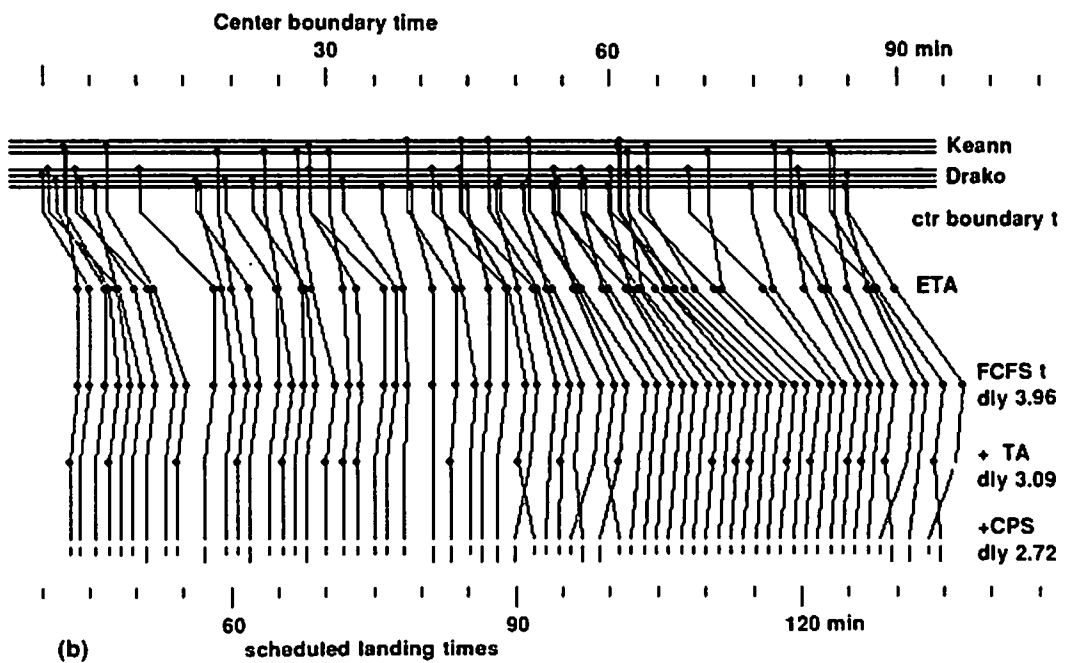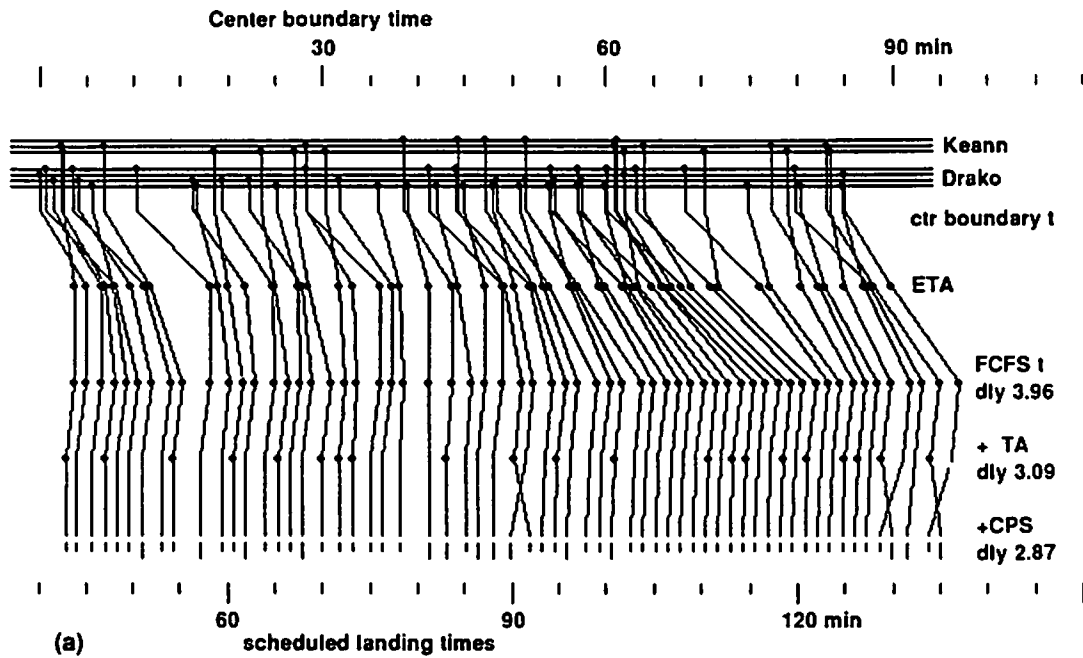
Figure 6.– Sample of heavy traffic with CPS. (a) Overtakes not permitted; (b) overtakes permitted.
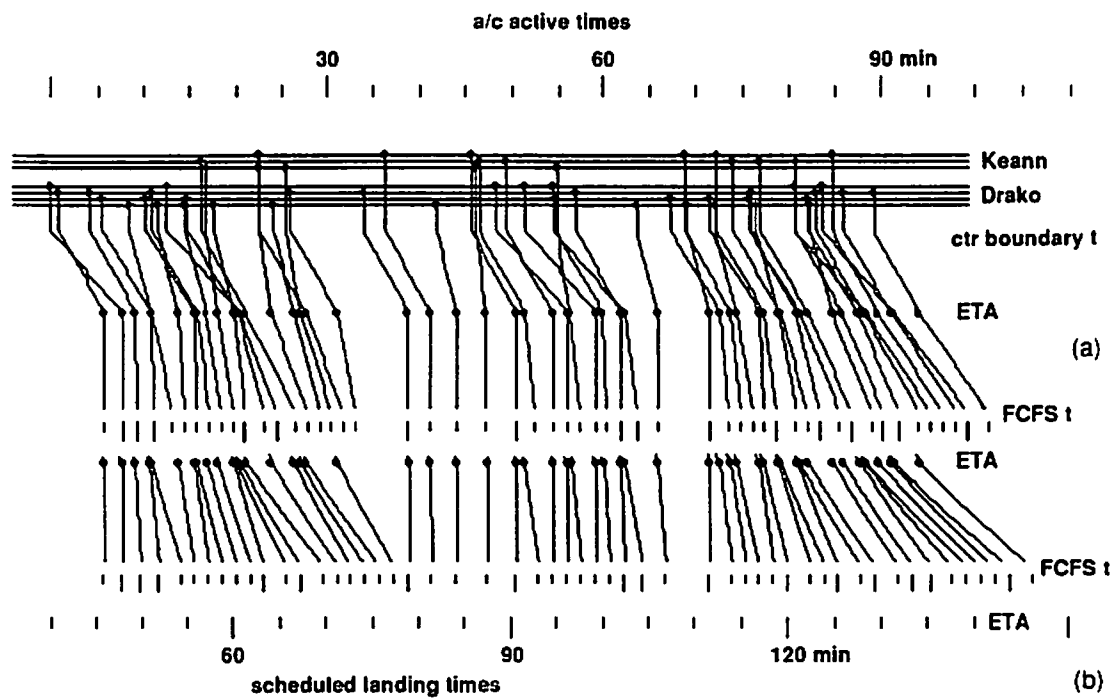
Figure 7.– Scheduled traffic sample. (a) Without wind; (b) with 20-knot headwind.

Heavy aircraft to end of bunch

$1 + 1 = 2$

$1 + 1 = 2$

$1 + 1 = 2$

$1 + 2 = 3$

$2 + 1 = 3$

$1 + 1 + 1 = 3$

$1 + 3 = 4$

$1 + 2 + 1 = 4$

$3 + 1 = 4$
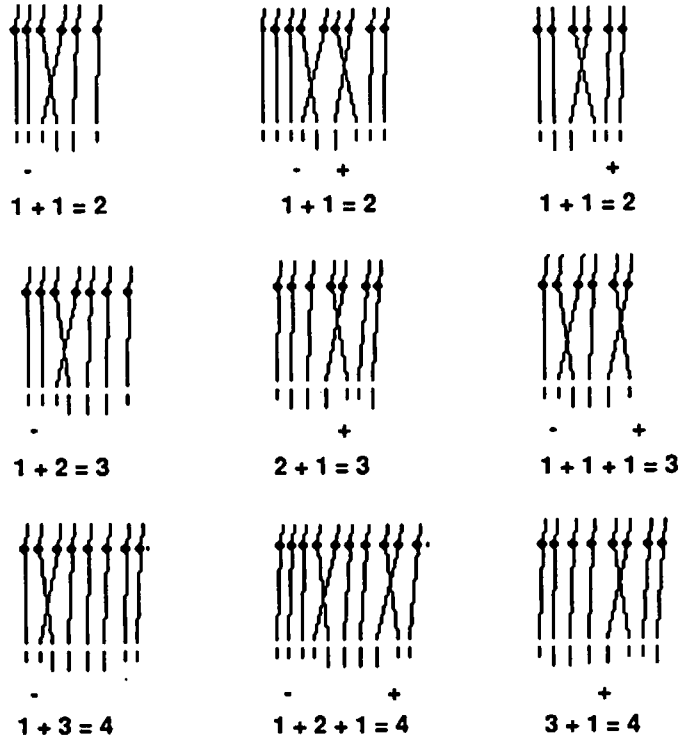
superscript + = advance one position
superscript - = retard one position

Figure 8.– Constrained position-shift examples.

60 90 120 min

scheduled landing times [heuristic CPS]

(d)

SEED was 111

+ TA

CPS 158.97

+CPS

(c1)

(e)

SEED was 111

+ TA

CPS 167.43

+CPS

(c2)

(f)

SEED was 111

+ TA

dly 2.66

CPS 158.97

+CPS

dly 2.65

(c3)

Figure 9.– Concluded. (d) Optimal CPS, remove all position switches in a group if one negative delay <-1 min exists: SEED 111; (e) optimal CPS, keep all position switches but reduce negative delay to <-1 min: SEED 111; (f) heuristic CPS, locally proposed switches are not made if this would result in negative delay <-1 min: SEED 111.

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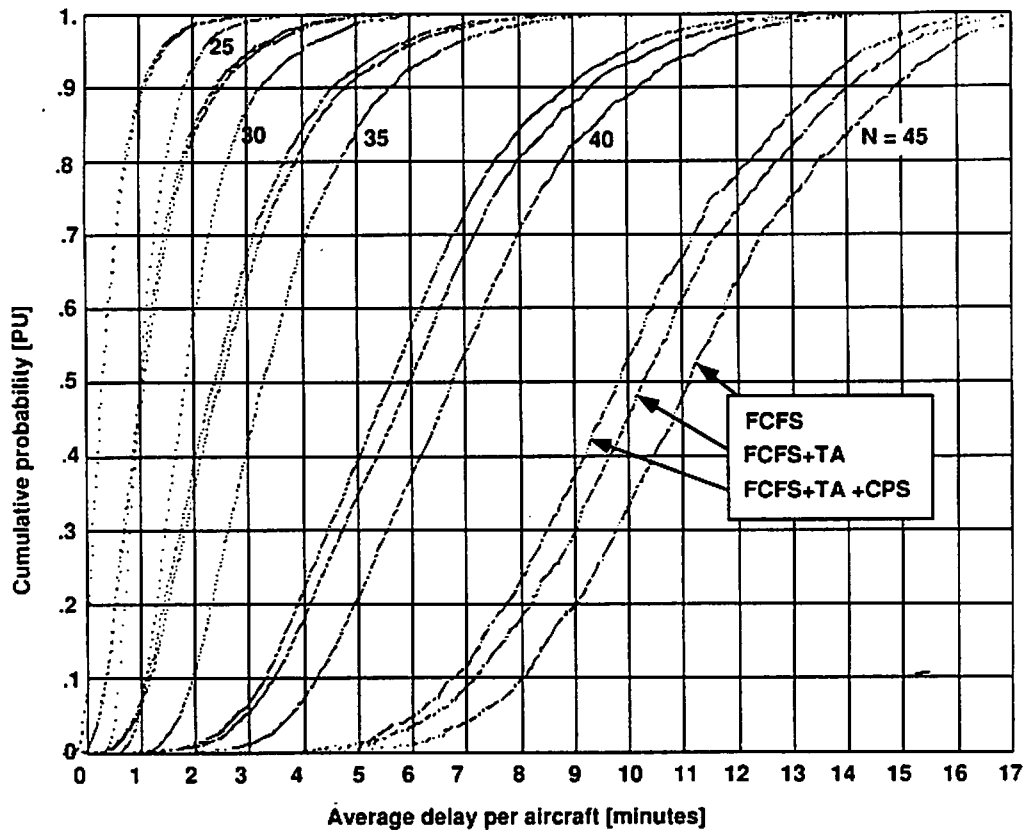
Figure 10.– Cumulative probability distributions for traffic and aircraft type mix best for CPS
(traffic NE/NW and heavies/large = 50%/50%) for 1.5-hr traffic samples.

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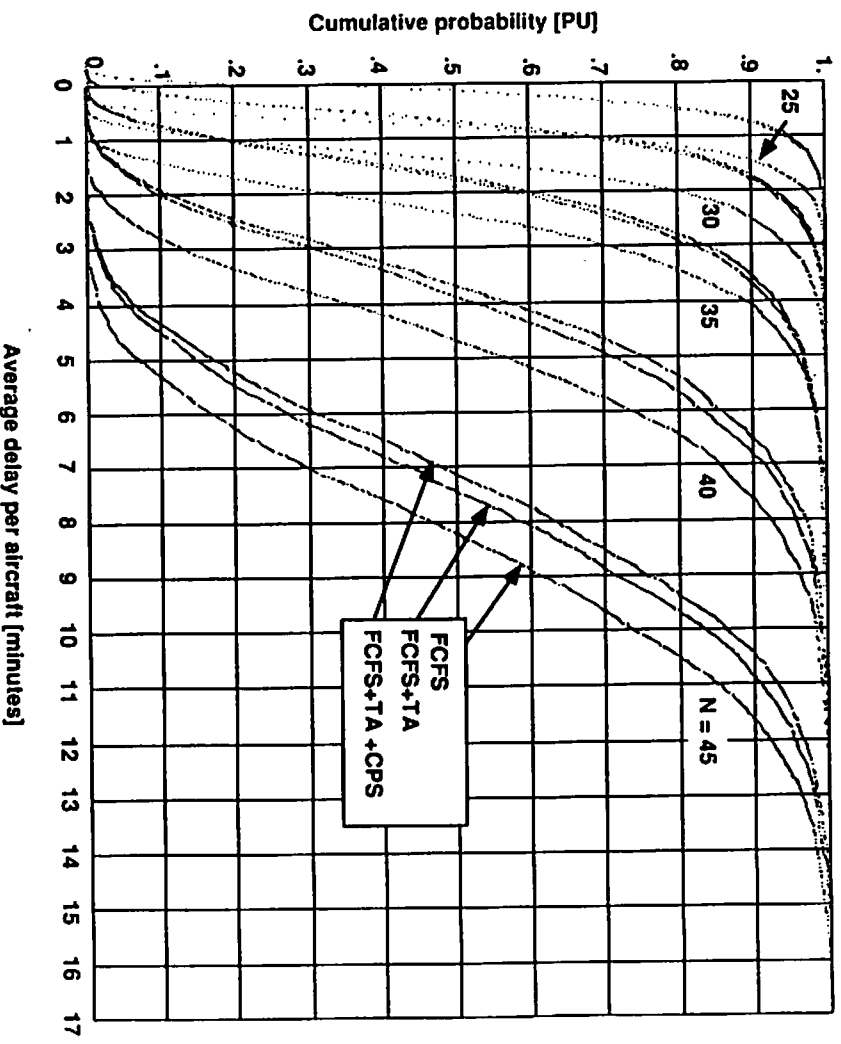
Figure 11.– Cumulative probability distributions for nominal traffic and aircraft type mix NE/NW traffic 66.66%/33.33%, large/heavy = 70%/30%) for 1.5-hr traffic samples.
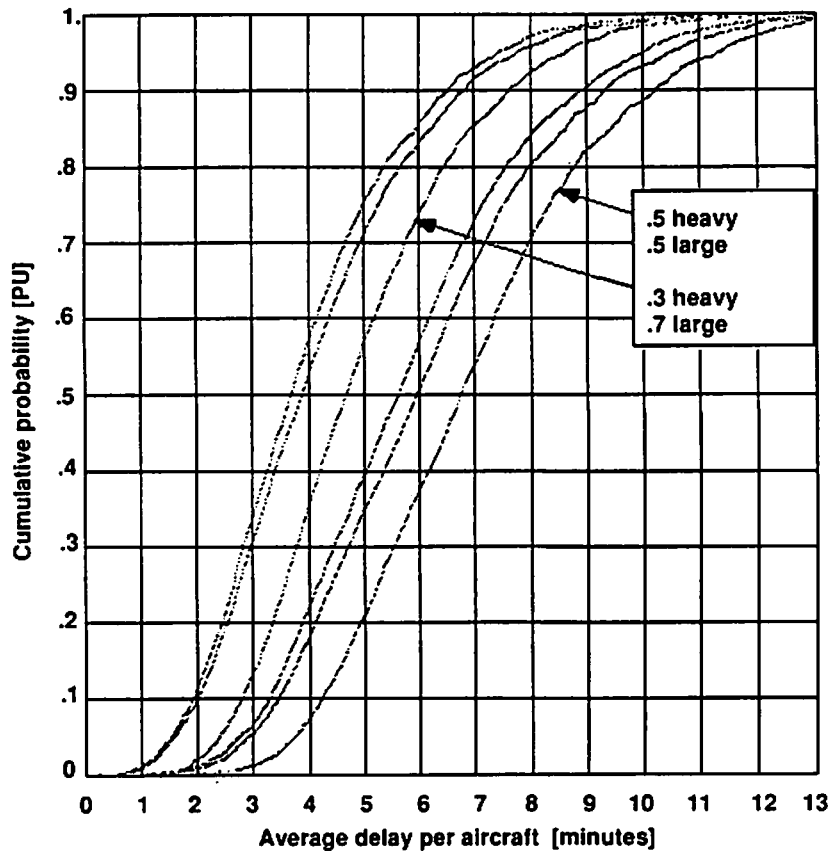
Figure 12.– Comparison of cumulative distributions for different traffic and aircraft mixes, 1.5-hr samples, 40 aircraft/hr.
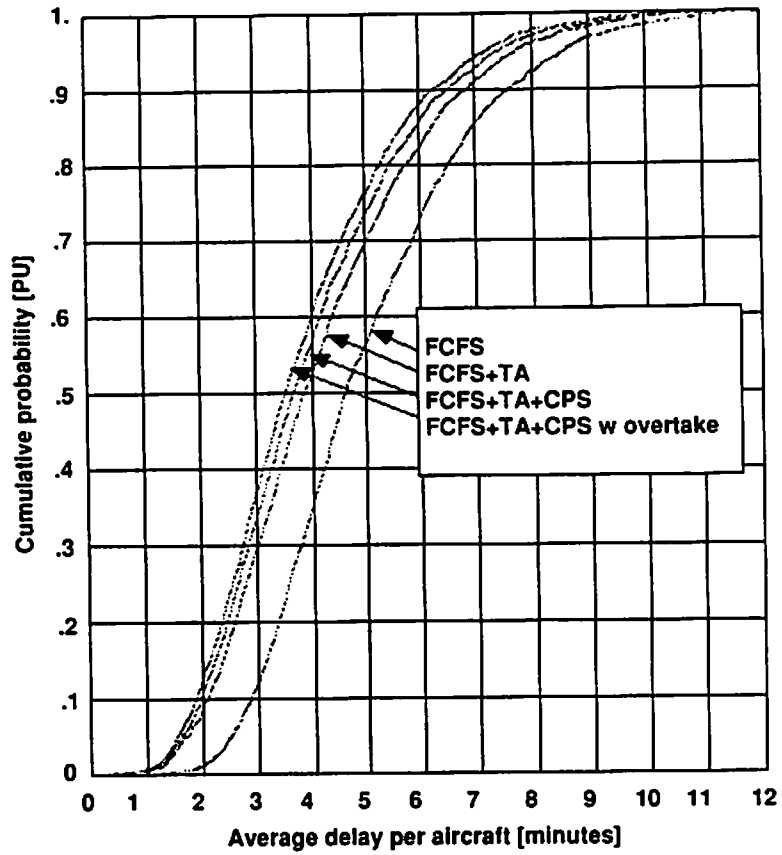
Figure 13.– Cumulative distribution for nominal traffic, 40 aircraft/hr including CPS with overtake.
(a) Optimal CPS performance.
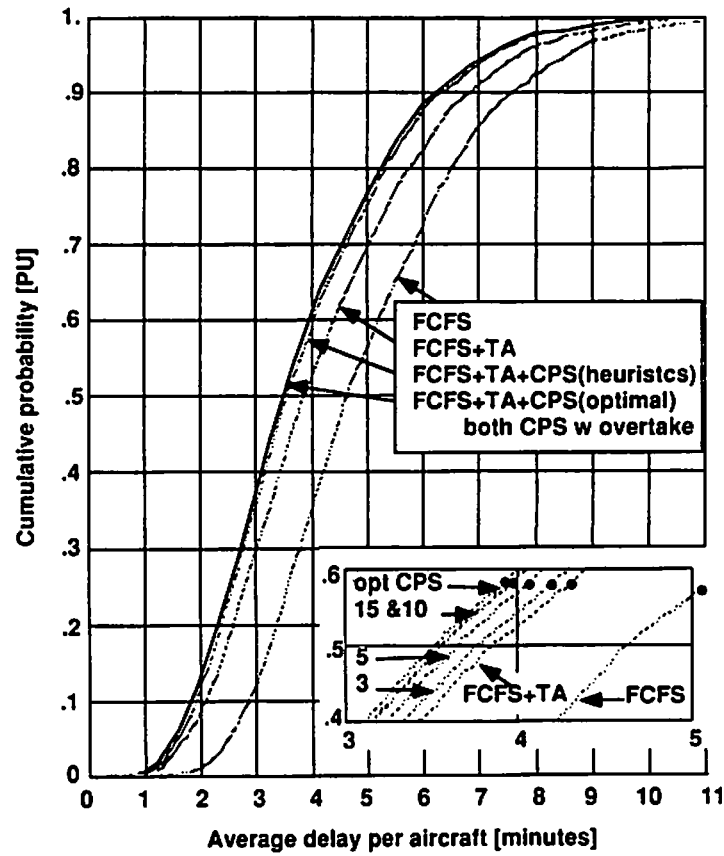
Figure 13.– Concluded. (b) Showing slight decrease in performance for the heuristics CPS vs optimal CPS. Inset shows performance as function of scheduling window size in minutes.
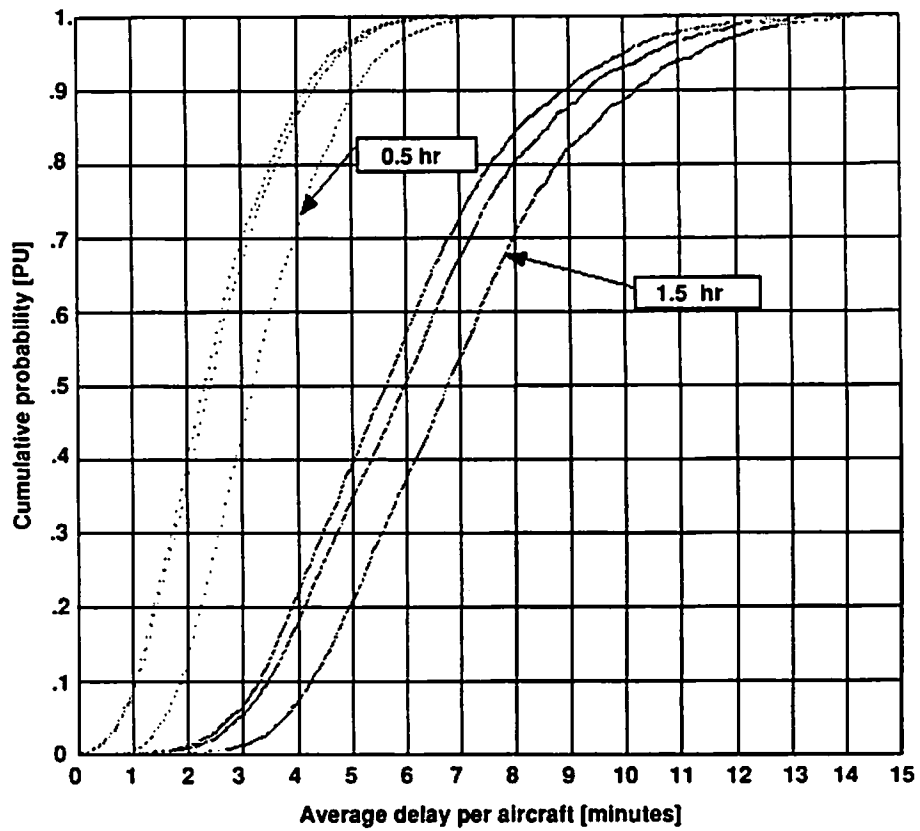
Figure 14.– Effect of length of the traffic sample with otherwise same statistical parameters as shown in figure 13.
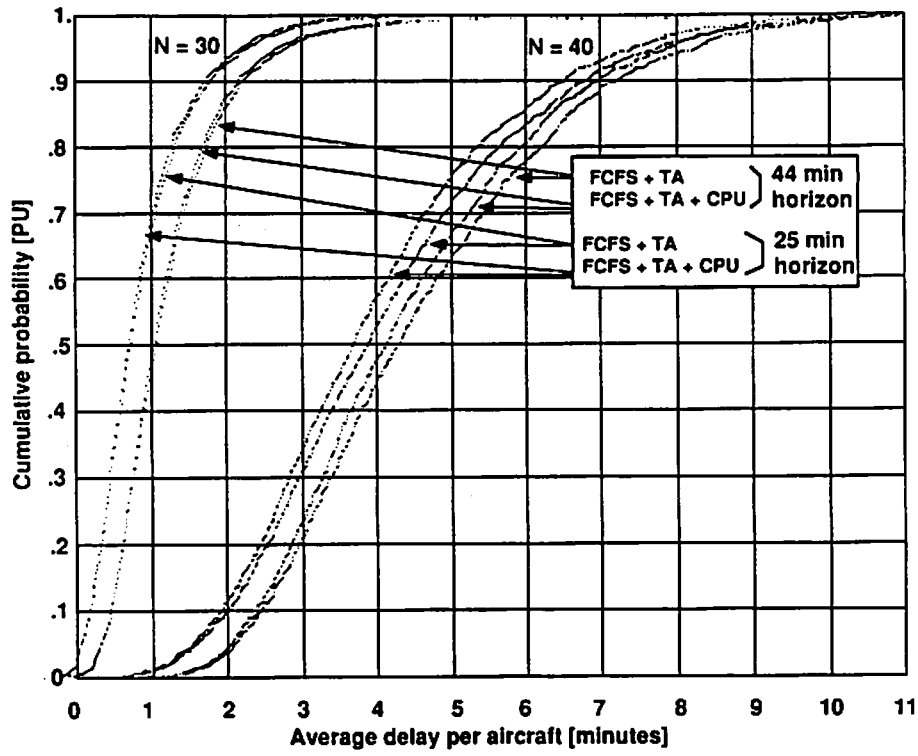
Figure 15.– Effect of changing freeze horizon.
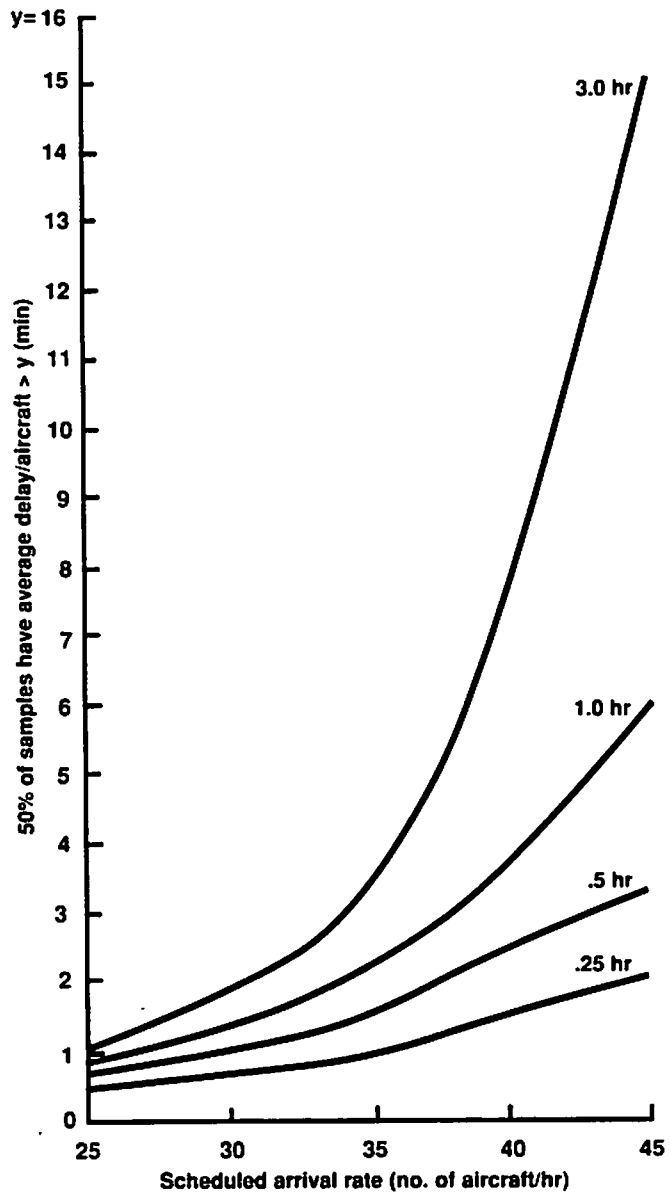
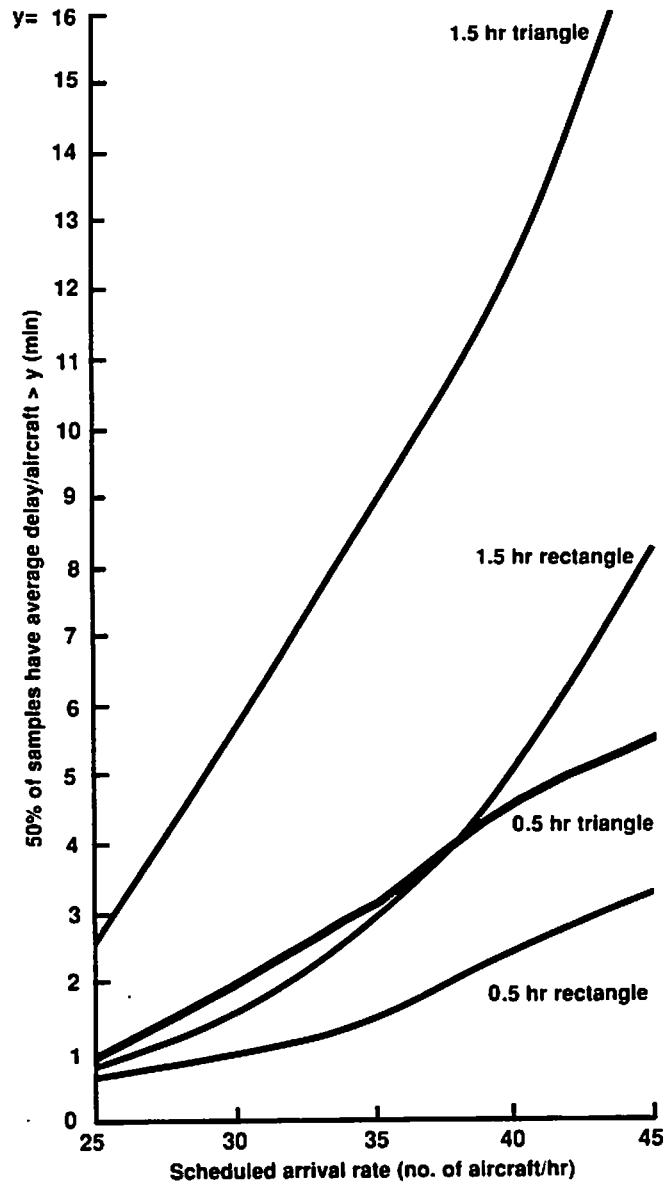Figure 16.– Delay as function of traffic sample length.

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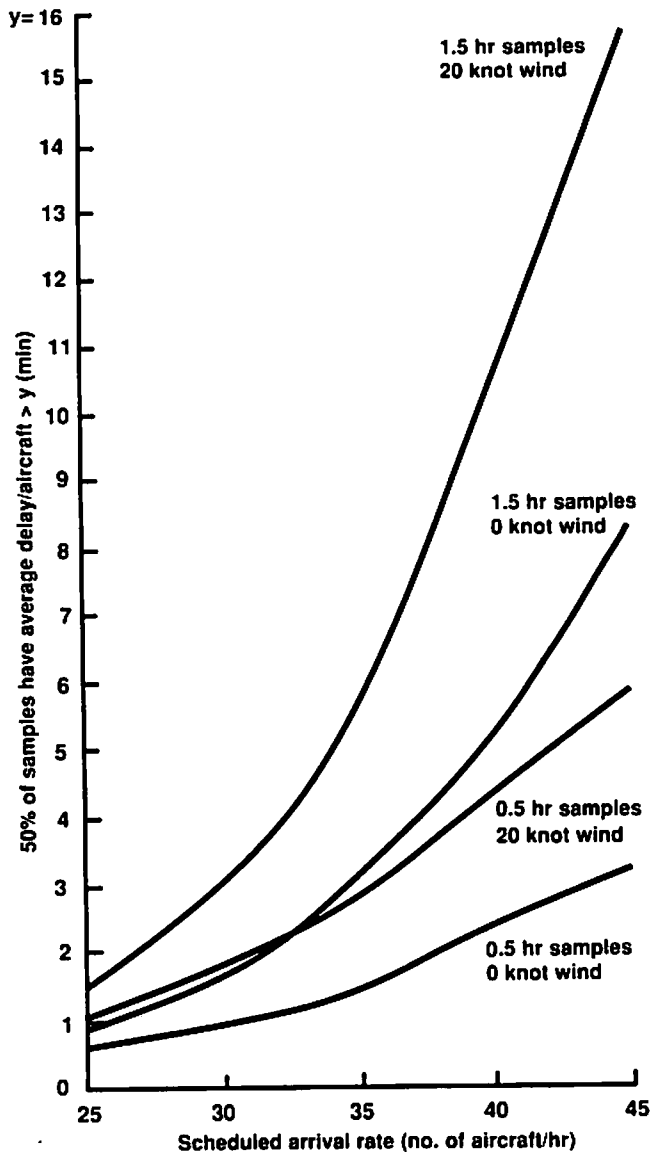Figure 17.– Increase of delay triangular vs rectangular distributions.

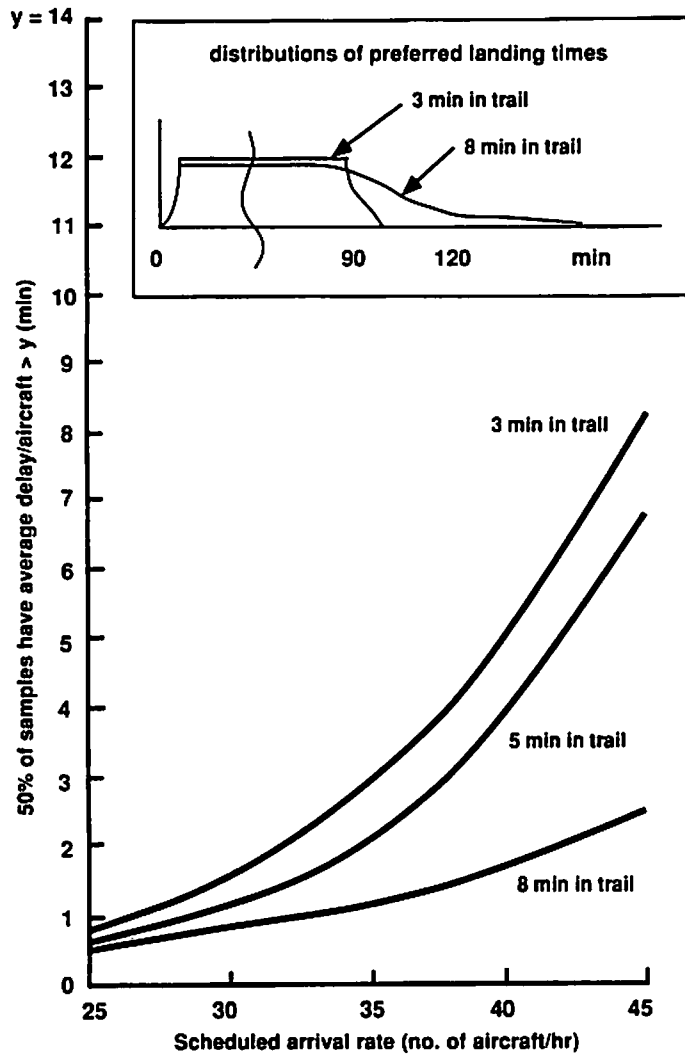Figure 18.– Increased delays with headwind for rectangular traffic distributions.
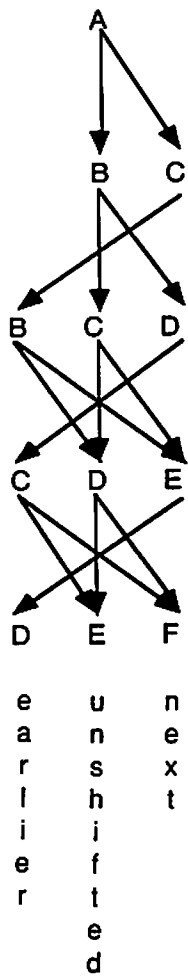
Figure 19.– Effect of variable in-trail spacing.

Figure A-1.– Illustration of all possible re-orderings of aircraft, given initial ordering A-B-C-D-E-....

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16. Abstract

The air traffic control subsystem that performs scheduling is discussed. The function of the scheduling algorithms is to plan automatically the most efficient landing order and to assign optimally spaced landing times to all arrivals. Several important scheduling algorithms are described and the statistical performance of the scheduling algorithms is examined. Scheduling brings order to an arrival sequence for aircraft. First-come-first-served scheduling (FCFS) establishes a fair order, based on estimated times of arrival, and determines proper separations. Because of the randomness of the traffic, gaps will remain in the scheduled sequence of aircraft. These gaps are filled, or partially filled, by time-advancing the leading aircraft after a gap while still preserving the FCFS order. Tightly scheduled groups of aircraft remain with a mix of heavy and large aircraft. Separation requirements differ for different types of aircraft trailing each other. Advantage is taken of this fact through mild reordering of the traffic, thus shortening the groups and reducing average delays. Actual delays for different samples with the same statistical parameters vary widely, especially for heavy traffic.

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