Analysis of the Potential Benefits of Terminal Air Traffic Control Automation (TATCA)

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Abstract

Terminal Air Traffic Control Automation (TATCA) is an FAA research and development program to provide computer-aided sequencing, spacing, and management of air traffic flows in terminal areas. This paper discusses technical and national economic benefits that are attainable with such a terminal automation program.

Introduction

TATCA is an automation program designed for use by terminal area control staff. TATCA will provide software that analyzes the terminal traffic situation (radar data, flight plan data, wind field and weather conditions, flow control restrictions, etc.) and generates a dynamic time-based plan (DTP) for feasible and efficient traffic flow. The DTP facilitates coordination with other NAS functions (e.g., ASP/ESP and AERA), and it supplies a common reference with cohesive objectives for each of the control positions involved in terminal area traffic management. The traffic plan is updated automatically as necessary in response to the actual flow of aircraft and to changes in terminal conditions. In addition, TATCA will provide advisories to assist controllers in maintaining the planned flow and in achieving more precise spacing where needed.

Because TATCA is intended for operational implementation in ATC facilities nationwide, with attendant implementation costs, it has been necessary to estimate on a national scale the economic value of operational improvements that TATCA is likely to realize.

The first section of this paper summarizes the premises and results of the national benefits evaluation, concentrating on benefits to the user community, specifically to scheduled air carriers and their passengers. The main conclusions of the section are that TATCA program benefits far exceed development costs. Also, potential increases in airport arrival capacity have greater economic consequences than any other proposed technical improvement in terminal area ATC.

The second section of the paper assesses the prospects for increasing arrival throughput, particularly IMC throughput, via improved computer-aided control systems. Research on this topic has proceeded intermittently since the introduction of radar-based civilian ATC [1,2]. Computing advances, combined with concern over energy conservation and capacity-related air traffic delays, have led to a resurgence in ATC automation research (e.g., [3,4,5,6]). This paper uses analyses of arrival traffic at Boston, combined with findings of the above studies, among others, to characterize the state of the art in manual control. The intent is to estimate how much potential capacity is currently being lost, and to identify where recoverable capacity losses are occurring in the conduct of operations .

Nationwide Benefits Overview

Three basic sources of benefits from terminal automation are considered in this paper. First among these is increased capacity (throughput). Second is the role that terminal automation plays in supporting fuel efficient descents and delay absorption techniques. Third is the provision for more direct routes from en route airspace to the runway threshold. Benefits themselves are aggregated in three categories: fuel costs, other direct operating costs (ODOC) of operators, and the value of passenger time.

The estimation of benefits is restricted to scheduled air carriers and their passengers,

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since they are the largest user group in controlled airspace, and since information on operating costs and delay distributions is more readily available for air carriers than for other user groups. Table 1 gives summary evaluations of the annual benefits expected from TATCA functions as of the year 2000, a possible target date for implementation of TATCA at major airports nationwide. Calculations underlying Table 1 assume fuel costs of $0.75/gallon, and fuel burn rates and other operating costs for each phase of flight to be the same as reported by airlines for 1986 [7], though all values are reexpressed in constant 1989 dollars. FAA projections of a 2.4% annual increase in departures and a 4.6% annual increase in enplanments between 1987-1999, are used to forecast industry volume at the turn of the century. Passenger time is valued at $22.70 per hour, as in [7]. Other premises underlying Table 1 are discussed below.

Table 1. Annual User Benefits from TATCA Year 2000
(in Millions of constant 1989 dollars)

	Fuel	ODOC	Pass. Time	TOTAL
Increased Capacity	$277	$592	$1,559	$2,428
Efficient Descents	$149	$96	$229	$474
Delay Absorption	$113	$0	$0	$113
Direct Routes	$148	$152	$368	$668
TOTAL	$687	$840	$2,156	$3,683

Fully efficient descent profiles are generally unavailable at busy airports. TATCA will aid controllers in sequencing and spacing aircraft while supporting fuel efficient descents in terminal airspace. Fuel savings with efficient terminal area descents, compared to conventional approaches, have been evaluated at both Denver and DFW [8], averaging 20 gallons per approach in each case. The "present procedure" used as a baseline in [8] is already more efficient than nominal descent profiles in use today. The 20 gallon figure is conservative in this regard. On the other hand, approaches cannot always be optimized fully to minimize fuel consumption or the combination of fuel and time costs, since aircraft must accept constraints to fit in with other traffic. The majority of air carrier approaches (57% in 1986) report a minute or more of airborne delay, and 11% of flights experience airborne delay exceeding 10 minutes [9]. For aircraft subject to delay the economy issue inclines toward efficient delay absorption, which is discussed later in this section. Also the economical profile in [8] assumes advanced avionics equipment, and in that sense it is rather optimistic. The figure of 20 gallons per approach appears to strike a good balance, and it should be representative of efficient descent fuel savings in terminal areas.

Efficient descents may be expected to produce slight but systematic reductions in flight time as well. In the AAS Cost/Benefit study [9] it is recommended that descent fuel savings be converted to a time measure using rates of airborne fuel consumption, and then be reduced by a factor 0.62. That technique is used here.

Direct routes are underutilized in current ATC because they require difficult judgements regarding future traffic separations or because they require coordination activities that cannot be supported because of workload. TATCA planning and advisories will reduce dependence on in-trail arrangements for timing and spacing, and in some cases will permit greater flexibility in the route structure. TATCA will also support the use of MLS curved approaches for reducing the final approach path and shortening downwind legs. It is anticipated that TATCA will permit reduction of the average terminal approach path by 3.0 nmi, or by a factor of about 6%.

Benefits accruing from descent profiles or shortened flight paths are potentially applicable to all arrivals, whether in IMC or VMC, heavy or light traffic. There are fewer constraints on achieving these benefits in relatively light traffic, free of flow rate restrictions and widespread delay absorption. For the approximate valuations needed here it is sufficient to assume that the average savings per approach apply to all air carrier arrivals, numbering 6.6 million in 1986, and forecast to number 9.0 million by 2000.

Capacity gains have significant economic impacts only when demand approaches or exceeds the existing capacity level. This makes the effects of capacity increases site dependent and temporally variable at any given site. At a national level, effects are dependent on overall traffic volume, on airline route systems and scheduling practices, and on FAA traffic management policies. An evaluation of the nationwide impact of capacity increases may be obtained by examining the historical relationship between U.S. air traffic volume and levels of overall national delay, as measured by the

Standardized Delay Reporting System [7,9]. The nature of the relationship between demand, capacity, and delay has been analyzed using simple models of queues during episodes of congestion, and assuming that changes in capacity and changes in demand that occur over time are homogeneously distributed (for example a 10% increase in national traffic volume is assumed to correspond to a 10% increase in the demand profile at all airports). The modelling procedure fits delay history quite well in the years for which data is available, 1976-1986. Figure 1 plots NAS delay against annual departures for the years 1982-1986, and displays two trend lines, one indicating the relationship between volume and delay given current ATC arrival capacity, and the other representing a shift in that relationship, subject to a 16% increase in system capacity. As discussed in the next section, 16% is a nominal estimate of the size of capacity gains attainable with TATCA. In producing Table 1 it was assumed that delays in 2000 will be distributed among the four phases of a flight (gate hold, taxi-out, airborne, and taxi-in) in the same ratios reported for 1986, and that unit operating costs for each phase of flight will be comparable to 1986 unit costs [7].

The cost of delays that remain despite capacity gains may be reduced by absorbing as much airborne delay as possible via speed control and via adjustments in the descent profile, rather than by holding or path stretching. A rough estimate of the potential savings from efficient delay absorption mechanisms may be obtained as follows. The average airborne delay in 1986 was approximately 3.6 minutes per approach. With feasible planning horizons [3] one may anticipate absorbing 4 minutes of delay efficiently during en route transition, and 1 minute within the TRACON. Using the distribution of arrival delays in [9] to estimate the proportion of delays exceeding a five minute control window, an average of 1.7 minutes of delay per approach remains subject to efficient absorption. Using programs derived from [10], speed control in the TRACON is calculated to save approximately 87 lbs of fuel per minute of delay absorbed, compared to the amount consumed by path stretching. En route absorption of moderate delay has the potential for fuel savings of over 200 lbs per minute of delay, compared with path stretching in the TRACON. These are upper bounds, however. To realize them requires requires precise, reliable knowledge of the amount of delay to be absorbed, and the knowledge must be available roughly half an hour prior to landing. Achievable fuel savings will be quite sensitive to the accuracy of these look-ahead delay estimates. Suppose, for example, that the delay estimates are subject to Gaussian error with a standard deviation of 30 seconds. A simple sensitivity analysis indicates that the effective fuel saving drops to slightly over half of the upper bound values, while also penalizing capacity slightly (2-3%). As indicated by an example in the next section, delay estimate errors can easily exceed 30 seconds, even in well executed control. TATCA assists efficient delay absorption by providing more reliable delay objectives. A tentative estimate of the net effect nationwide is an average of 15 gallons per approach.

Capacity Estimation and Enhancement

Nomenclature

IAT	interval between threshold crossings
σ	standard deviation of IAT distribution
dA	required separation, lead aircraft inside the final approach fix (weight dependent)
dR	required separation, lead aircraft at the runway threshold (weight dependent)
V_L	approach velocity of the lead aircraft
V_T	approach velocity of the trail aircraft
h	length of the common final path
o	increase in separation on the common final path if the lead aircraft is faster
α	missed approach rate
b	buffer applied for separation assurance $(b = \Phi^{-1}(\alpha))$
r	distance from the runway threshold at which the tower can provide visual separation

Basic Model

A simple but convenient model for IFR interarrival spacing, illustrated in Figure 2, assumes that every arriving aircraft falls into one of the weight and performance categories listed in Table 2, and adopts the final approach speed indicated there. An aircraft mix typical of IMC traffic at Boston is given in the table.

Table 2. Aircraft Mix

Performance Category	Final Appr. Speed (knots)	IMC Proportion
(A) Small Aircraft	100	2%
(B) Large Prop	110	32%
(C) Large Jet	130	54%
(D) Heavy Jet	140	12%

With this model, the interarrival time between two successive aircraft is,

$$\text{(1a)}\quad \mathrm{IAT} = \frac{dR}{V_T} + b\ ,\ \text{if } V_T \geq V_L\ ,\ \text{else}$$

$$\text{(1b)}\quad \mathrm{IAT} = \min\left\{ \frac{dR}{V_T},\ \frac{dA + (h-dA)\left(1 - \frac{V_T}{V_L}\right)}{V_T} \right\} + b\ .$$

The value for IAT is of course dependent on the performance category of the lead and trailing aircraft. Assuming that aircraft of different categories arrive randomly sequenced, one may obtain the frequency of any category sequence from the marginal probabilities in Table 2. An expected IAT follows immediately, with arrival capacity obtained as its reciprocal.

When considering IMC arrival-only operations, where runway occupancy conflicts are negligible, the model above is roughly equivalent to the FAA Airfield Capacity Model [11]. It is a reasonable model to use for initial evaluation of prospective capacity initiatives. For example, using the 2.5 nmi rule and the parameters in Table 2, permitting a wave-off rate of α=0.05 and taking σ=18 sec, the model gives single runway IMC capacity to be 31 arrivals per hour. With improved delivery precision of σ=9 sec, capacity is rated at over 35 arrivals per hour (an increase of 14.6%).

At the same time, it is clear that the model outlined above fails to represent many factors, particularly stochastic factors, that play a role in real world air traffic control. Several such factors are considered below.

Landing Sequence Optimization

Simply switching the order of a small and a heavy aircraft to place the small in front can free up the equivalent of between two and three landing slots [5]. Boston arrival sequences examined at Lincoln Laboratory show little evidence of preferential sequencing to minimize wake vortex separations. If anything, it is more common to have turboprops and jets in an alternating pattern as segregated arrival streams are interleaved at a merge point. Various studies, including [16], have indicated that capacity gains averaging 4-6% are potentially available even without requiring overtakes, and with a maximum shift of only two landing slots from first-come first-served order. Operational constraints may make some resequencing opportunities infeasible. Nevertheless, a TATCA scheduling function that exploits sequencing opportunities when feasible is expected to provide time-averaged capacity gains of roughly 3-4%.

Variability in Operating Conditions

Table 3 below gives a sampling of arrival rates observed in full IMC traffic at Boston, with weather below vectoring minima. Some of the observation periods included runway changes, and in such cases the runways are listed in order of use, but throughout each period a single arrival runway is in use at any given moment.

Table 3. Sampled IMC Arrival Rates at Boston

Date	Time of Day (EDT)	Arrival Runway	Landings per Hour
9/13/87	16:00-21:00	4R,15R,22L	34.9
12/15/87	16:00-18:00	4R,15R,4R	28.7
5/18/88	16:00-19:00	4R	38.1
6/6/89	16:00-21:00	4R	35.0
6/15/89	17:00-20:00	4R	36.7

Date	Ceiling	Visibility	Wx
9/13/87	500-700	1/8 - 2	R+F
12/15/87	300-500	1/2 - 4	R-, Ice Pellets
5/18/88	300-600	1/2 - 1-1/2	L-F
6/6/89	700	1-1/2	F
6/15/89	600-1800	1-1/2 - 2	R-F

Table 3 demonstrates that capacity of a single runway in relatively poor weather can be substantially higher than the basic model above would anticipate. This is so in part because of control techniques that exploit whatever elements of visual capability remain available, such as circling from a secondary instrument runway, or simply having the tower assume visual separation authority at some point along the main instrument approach path. Such visual capabilities are sensitive to otherwise minor changes in meteorological conditions, and airport capacity when they are being applied is likely to be quite volatile.

A modification to equation (1a) permits the basic interarrival spacing model to express certain types of "intermediate" IFR approaches. Namely, suppose that at a distance r from the runway threshold the tower is able to apply visual separations. If this point is reasonably stable, then radar controllers can arrange for radar separations to be maintained only to that point, after which closing aircraft may continue to close. With this extension, and r known, equation (1a) becomes

$$(1a') \qquad IAT = \frac{dR - r\left(\frac{V_T}{V_L} - 1\right)}{V_T} + b \quad .$$

As an indication of how a volatile environment can be tracked by automation, we shall consider b, h, and r to be unknown (they will vary not only with ceiling and visibility but also with the wind field and with runway surface conditions), and fit the extended model to the 115 arrivals that were timed on 5/18/88. The fit may be performed by least squares solution of the matrix equation

$$(2) \qquad \mathbf{y} = \mathbf{A} \begin{pmatrix} b \\ h \\ r \end{pmatrix},$$

where for the i^{th} interarrival spacing,

$$y_i = IAT - \frac{d}{\max(V_L, V_T)}$$

$$a_{i1} = 1$$

$$a_{i2} = \begin{cases} 0, & \text{if } V_L \leq V_T \\ \frac{V_L - V_T}{V_L V_T}, & \text{otherwise} \end{cases}$$

$$a_{i3} = \begin{cases} \frac{V_L - V_T}{V_L V_T}, & \text{if } V_L > V_T \\ 0, & \text{otherwise} . \end{cases}$$

The fit to the data of 5/18/88 is significant at a level 0.05, and the point estimate of r is 1.79 nmi. (Note that while visibility dropped lower than this amount, tower visibility was reported as 2 nmi during most of the observation period). Residuals from the fit, which may be taken as runway threshold interarrival errors, are shown in the bottom histogram of Figure 3. The standard deviation of the residuals is 19.6 seconds, which is consistent with commonly cited estimates of manual delivery precision [3,12]. It is instructive to note that the sustained high throughput of 5/18/88 is achieved without exceptional delivery precision, compared to other traffic with lesser arrival rates. In effect the high throughput of 5/18/88 can be explained as a byproduct of reduced separation standards. Opportunity remains for increased capacity if final approach spacing can be made more precise. The expected increase in 5/18/88 arrivals, if the standard deviation of runway delivery errors is cut in half, would be 9-10%, more if advanced avionics can reduce final spacing errors to a still lower lever [3].

The wind was moderate and steady on 5/18/88, coming from 50° at 14 knots. Conditions were relatively stable and predictable. Metering and Central Flow Control, which was issuing departure delays as high as 80 minutes, were thus able to maintain a regulated but uninterrupted demand on the arrival runway.

Approach Delivery Errors

The situation on 12/15/87, which by the measure of Table 3 had weather equivalent to 5/18/88, was quite different [14]. A histogram of runway delivery errors for 12/15/87 appears in the upper portion of Figure 3. Throughout the observation period on 12/15 there was holding prior to the main entry fixes into the Boston TRACON. Two runway changes occurred, slightly over 30 minutes apart, the first of them undertaken out of concern that the ceiling was dropping below the CAT I minimum (in fact it didn't) and the second taken to escape strong tailwinds on approach.

Arrival tracks on 12/15/87 were examined and categorized into two groups, the first group consisting of aircraft that entered the final vector area positioned such that it was still possible to achieve a minimum spacing behind the aircraft preceding them in sequence. The second group consisted of aircraft arriving outside of a controllability window, that is, arriving late or arriving subject to constraints that made it impossible to close to separation minima. The prevalence and distribution of runway delivery errors for the two groups is indicated in Figure 4. The runway delivery accuracy in the group able to receive final approach spacing adjustments is again in the range 18-20 sec. Clearly considerable potential capacity was lost in the early stages of approach during this observation period.

When timing objectives are reliable and steady, as in 5/18/88, it appears possible to meter to a fixed acceptance rate, with the metering time accuracy achieved in ERM-1, and without sacrificing appreciable capacity. Poor metering is correlated with an uncertain or variable terminal environment. It is self evident that when the control staff is unable to predict conditions in the terminal area within the planning horizon needed to manage an individual flight efficiently (roughly 30 minutes from the point of view of metering and en route transition, 6-15 minutes within the TRACON), metering and prepatory spacing in the TRACON are going to be suboptimal.

A reexamination of the 05/18/88 traffic, which was metered effectively, illustrates the small scale variability that the ATC system must manage in order to make full use of efficient en route capabilities that require a long planning horizon. The arrivals on 05/18/88 have been binned in groups of 10 successive approaches. The total time elapsed during the landing of each group of 10, and the number of heavies in that group, are given in Table 4.

Table 4. Breakdown of 5/18/88 Arrivals

Group	Time Required to Land the Group (sec)	Number of Heavies
1	955	1
2	1290	0
3	898	1
4	962	2
5	880	1
6	788	2
7	844	3
8	856	1
9	981	0
10	1107	3
11	976	1

The average time required to land a group of 10 was 956 seconds, and the standard deviation of that time was 140 seconds. The variation cannot be accounted for by aircraft mix. It exceeds by more than a factor of two the variability that would be expected from the statistical accumulation of individual interarrival timing errors, if indeed these have a standard deviation of 18-20 seconds. Therefore, Table 4 suggests that scheduling uncertainty will remain a consideration and may routinely interfere with efficient flight operations even if contemporary imprecision in interarrival spacing is completely eliminated.

What is needed to address this unpredictable variability is a mediator which can plan from the runway out and insure that feeder controllers and the en route interface have a coordinated set of timing objectives. Also the mediator must be equipped to maintain and manage an inventory of delay in the TRACON, without requiring excessive workload, that can be used to smooth out irregularities in the traffic flow and the timing objectives. The mediation role is performed by TATCA's Dynamic Time-Based Planner (DTP).

Summary

Overall, capacity gains obtainable with TATCA have been estimated to range between 14% and 24% in most IFR conditions, averaging approximately 16%. The gains arise from landing sequence planning, from final approach timing aids that increase runway delivery precision, and from the DTP's role in maintaining an uninterrupted flow of traffic to the final vector area.

The DTP arrival schedule, along with advisories that enable controllers to execute the schedule, permit air traffic control to offer descent profiles and delay absorption techniques to the user community that are more cost effective than those in use today.

Together, TATCA's capacity increases and improved flight efficiency represent savings to the nation that are estimated to total $3.5 Billion annually.

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Glossary

TATCA	Terminal Air Traffic Control Automation
DTP	Dynamic Time-Based Planner
NAS	National Airspace System
ATC	Air Traffic Control
TRACON	Terminal Radar Approach Control Facility. The radar controllers around an airport (and colloquially the airspace they control)
AAS	Advanced Automation System
Metering	The processing of regulating traffic into a capacity-limited facility to achieve even flow at a designated rate
ERM-1	The ATC metering system in current use
ASP/ESP	Arrival Sequencing Program/ En Route Spacing Program. Near term enhancements of the current ATC metering system
Central Flow Control	An FAA traffic management facility that regulates aggregate NAS traffic flows
AERA	Advance En Route Automation. An FAA program to assist en route controllers in separating traffic and achieving timing objectives
MLS	Microwave Landing System. A radar system for instrument landings that permits curved and segmented approach paths
IMC	Instrument Meteorological Conditions
VMC	Visual Meteorological Conditions
TIMER	Traffic Intelligence for the Management of Efficient Runway Scheduling. A terminal automation concept developed at NASA Langley
ODOC	Other (non-fuel) Direct Operating Costs
DFW	Dallas/Fort Worth International Airport

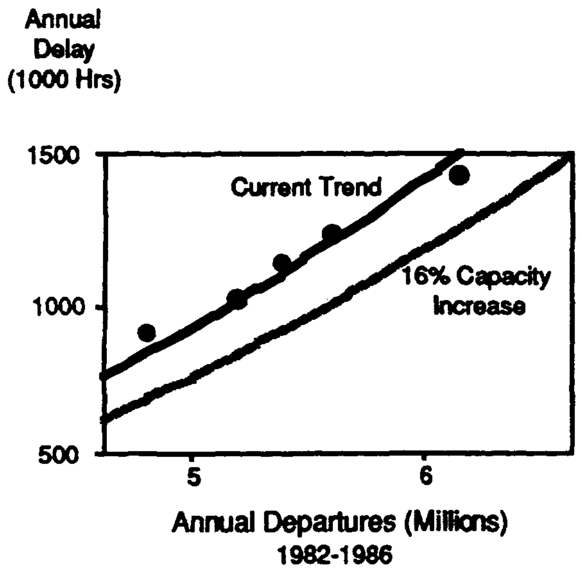

Figure 1. Historical Trends and Modelled Relationship among Demand, Capacity, and Total Air Carrieir Delay in the U.S. Airspace

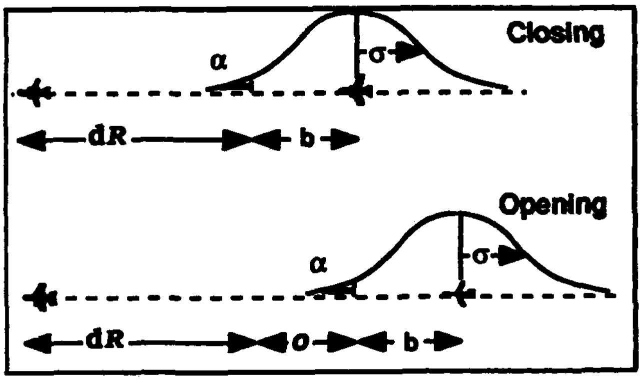

Figure 2. Basic Capacity Model, Arrivals Only

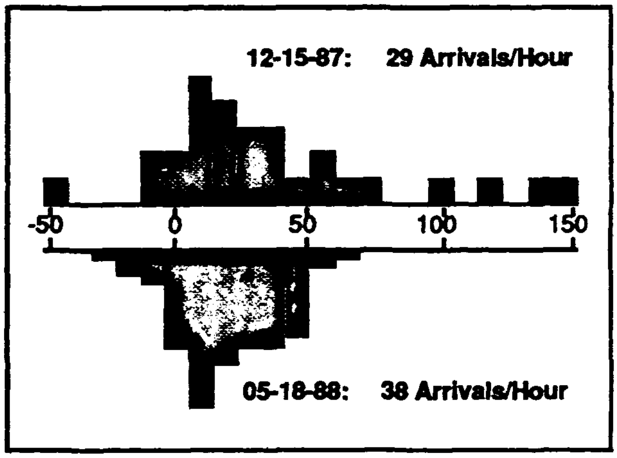

Figure 3. Interarrival Timing Distribution on Two IFR Days -- Deviation from Desired Spacing (seconds)

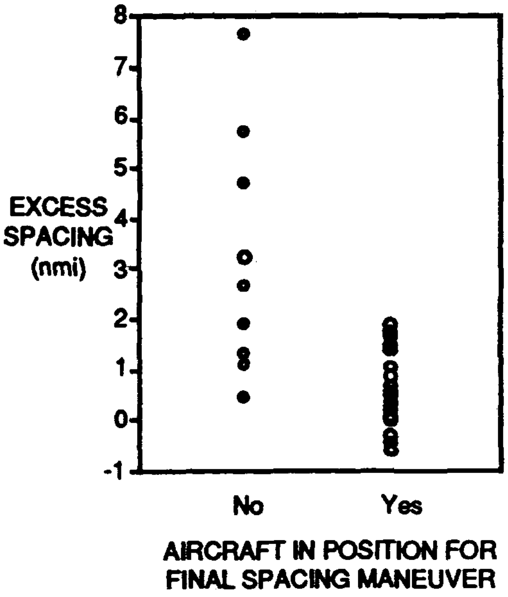

Figure 4. Effect of Approach Delivery Errors on Final Interarrival Spacing, 12/15/87