Optimal Location of High-Speed Runway Exits Using Automated Landing, Rollout, and Turnoff

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The reduction of runway occupancy time through the use of high-speed exits is one of the research activities carried out to improve the operational use of runways. Proper hardware and software technologies are being developed to minimize runway occupancy time per landing aircraft in future air traffic control environments. On the software side, a probabilistic computer model is being used to define exit velocities, exit locations, and turnoff path profiles under automated landing, rollout, and high-speed turnoffs using embedded magnetic cable sensors. However, the computer model does not determine how to combine these exit locations into a practical number of turnoffs that satisfy various aircraft mixes. The focus of this paper is on clustering these exit locations into a minimum number without cost-burdening any one class and violating the objective of minimizing the total runway occupancy time of landing aircraft in a real airport environment.

The success of air transportation is indeed phenomenal. Today it is not only an accepted mode of transportation, it is accommodating a significant percentage of the interstate and international transportation market. In the transcontinental and intercontinental passenger transportation market, it has already become the accepted mode.

Success has been accompanied by sociological, environmental, and operational problems. Capacity and delays, created by the lack of capacity, have become today's primary concerns. The growing public objection against the expansion of present operations and the building of new facilities, however, has narrowed the options available for solving the problem. How to increase system capacity without violating the present norms and degrading system safety is the challenge faced by system developers.

Research and development programs of the National Aeronautics and Space Administration (NASA) and the FAA are addressing several aspects of the airfield problems, foremost of which are improvement of operational use of runways; provision of efficient flow control, spacing, and management of aircraft in the terminal airspace; upgrading computer and communication technology usage; and reducing the effects of wake vortex and aircraft noise *(1)*.

In improving the operational use of runways, the reduction of runway occupancy times by using high-speed exits is one of the research efforts carried by NASA. To achieve an increase in density of arrivals at congested airports, separation distances between aircraft should be decreased and both runway occupancy time and its related standard deviation should be minimized. The research and development (R&D) programs at NASA are working on hardware and software technologies to achieve reduced runway occupancy times. During initial design studies, a goal of 40 sec maximum occupancy time was considered by the Terminal Configurated Vehicle Program. Automated landing, rollout, and high-speed turnoffs using the Microwave Landing System (MLS) and magnetic cable sensors embedded in runway pavements as navigational aids are being studied as ways of reducing runway occupancy time *(2–6)*.

A probabilistic computer model has been developed by Douglas Aircraft *(7)* to define exit velocities, exit locations, and turnoff path profiles. The model comprises two parts, namely, (a) a routine that establishes the time required from threshold to start of exit with a probability determination of an exit velocity and (b) a subroutine of time required in the turnoff to clear the runway using an optimized path. The times determined from each part are added to yield the total runway occupancy time that, probabilistically, will be the unique value selected for this study—occupancy times not exceeding 40 sec. This time interval is measured from the instant the aircraft crosses the runway threshold until it completely clears the runway.

The model is capable of determining the runway exit location and turnoff path geometry for any specific aircraft model, subject to the selected maximum runway occupancy time of 40 sec. In a real airport environment, however, the established exit locations need to be bunched into fewer numbers while conforming to regulatory restrictions and aircraft operational and maintenance cost constraints (tire and brake wear). Bunching is required not only for economic reasons (fewer turnoffs mean less required concrete) but also to obviate possible confusion of the pilot in choosing an exit.

PROBLEM

It becomes apparent that the solutions provided by the probabilistic model need to be modified to be practically feasible. More specifically, the practical number and the optimal locations of turnoffs from a single runway to accommodate a wide variety of aircraft have to be determined, subject to the following study constraints:

1. The maximum runway occupancy time is maintained for each landing aircraft (40 sec in this study),

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2. The reliability of the system must be such that there is a 99.99 percent chance that an aircraft will exit at the optimally designated location, and
3. The FAA minimum standard separation between exits of 750 ft is not violated.

In synthesizing the various model results into a feasible turnoff configuration, two major problems exist. The first concerns the multiplicity of options imposed by the several input parameters of the model. These parameters, which are aircraft landing characteristics (such as velocities and deceleration rates at various points on the runway), can be individually varied, and, consequently, different runway occupancy times and reliabilities are achieved. This problem can be addressed by reducing the dimensionality of the available options so that only variables for which the model results are highly sensitive will be varied in the analysis.

The second problem concerns the effect of combining several exit paths in one location. The critical path is determined by choosing the aircraft that is most constrained by lateral motion. That aircraft, which exhibits the largest turning radius, tends to follow an exit path closer to the runway. Thus, if such a critical path is adopted, aircraft with slower speeds and smaller radii of exit path need more time to clear the runway and might violate the maximum time constraint of 40 sec.

Figure 1 shows this phenomenon; CD is the resultant exit location after the path profiles of a fast and a slow aircraft are combined. The most plausible solution to this problem is to iterate lower deceleration rates for the slower aircraft so that it can exit at a higher speed. The other option, imposing higher deceleration rates on faster aircraft, translates to increased tire and brake wear.

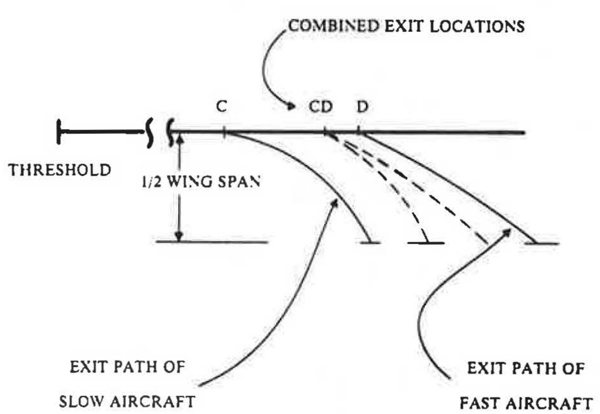

FIGURE 1 Problem of combining exits.

The results of a study conducted as an attempt to provide a practical solution to the problem of optimizing high-speed exit locations for a single runway under the operating constraints defined previously are presented in the remaining sections of this paper. A modified version of the referenced probabilistic computer model, which runs on an IBM PC/XT, was used to analyze the turnoff path profiles, exit velocities, and exit locations of several generic and several specific aircraft types corresponding to Terminal Planning System (TERPS) A, B, C, and D categories.

PROBABILISTIC COMPUTER MODEL

The Probabilistic Computer Model of Optimal Runway Turnoffs, developed by McDonnell Douglas Corporation for NASA, is a simulation routine that tracks the aircraft from touchdown location to runway clearance. It stochastically draws normally distributed samples of touchdown speeds, touchdown locations, exit velocities, and speeds at different distances from the exit entrance. The algorithmic approach employed by the model is discussed briefly herein. However, a more complete discussion of the model, its components, and the pertinent mathematical equations and variables is presented in a separate document *(7)*.

The runway operations being modeled are shown in Figure 2. After reading the input data set consisting of aircraft landing characteristics and their related deviations, the program sequentially computes (a) Distances A and B; (b) speeds during landing; (c) standard deviations of the speeds; (d) occupancy times at each point; (e) Distances A, B, and C, together with the corresponding speeds, for aircraft traveling one standard deviation below the average; (f) occupancy times to Points A, B, and C for aircraft traveling one standard deviation below the average; (g) specification of arbitrary speed ranges and the probability associated with them; (h) probability of exiting; (i) minimum occupancy time; (j) Z-values of occupancy time (assumed to be normally distributed); (k) interval midpoints; (l) average runway occupancy time; (m) percentage of aircraft exiting; and (n) average speed at exit.

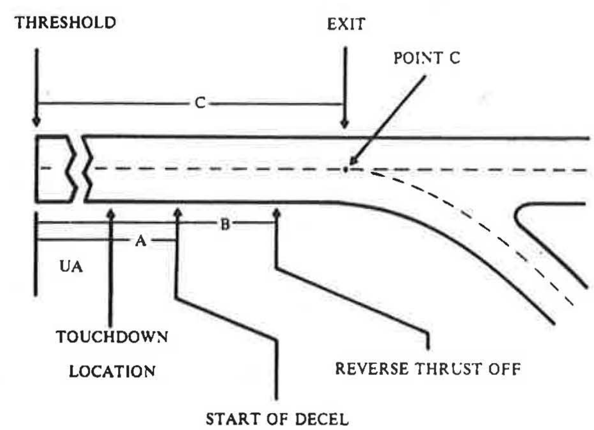

FIGURE 2 Runway operations simulated *(7)*.

A flowchart outlining the computational procedures and the internal manipulations involved is shown in Figures 3 and 4. The main program (Figure 3) and the subroutine called EXPATH (Figure 4) *(7)* are iterated until reliability and maximum runway occupancy time requirements are satisfied. The final outputs of the model for an aircraft defined by its touchdown speed, deceleration rate, weight, and estimated exit location include runway occupancy time, exit speed, probability of making such an exit, and coordinates of points along the turnoff path.

CATEGORIES AND CHARACTERISTICS OF AIRCRAFT

A variety of aircraft, from the general aviation type to the wide-body jet transport, operates in an airport environment.

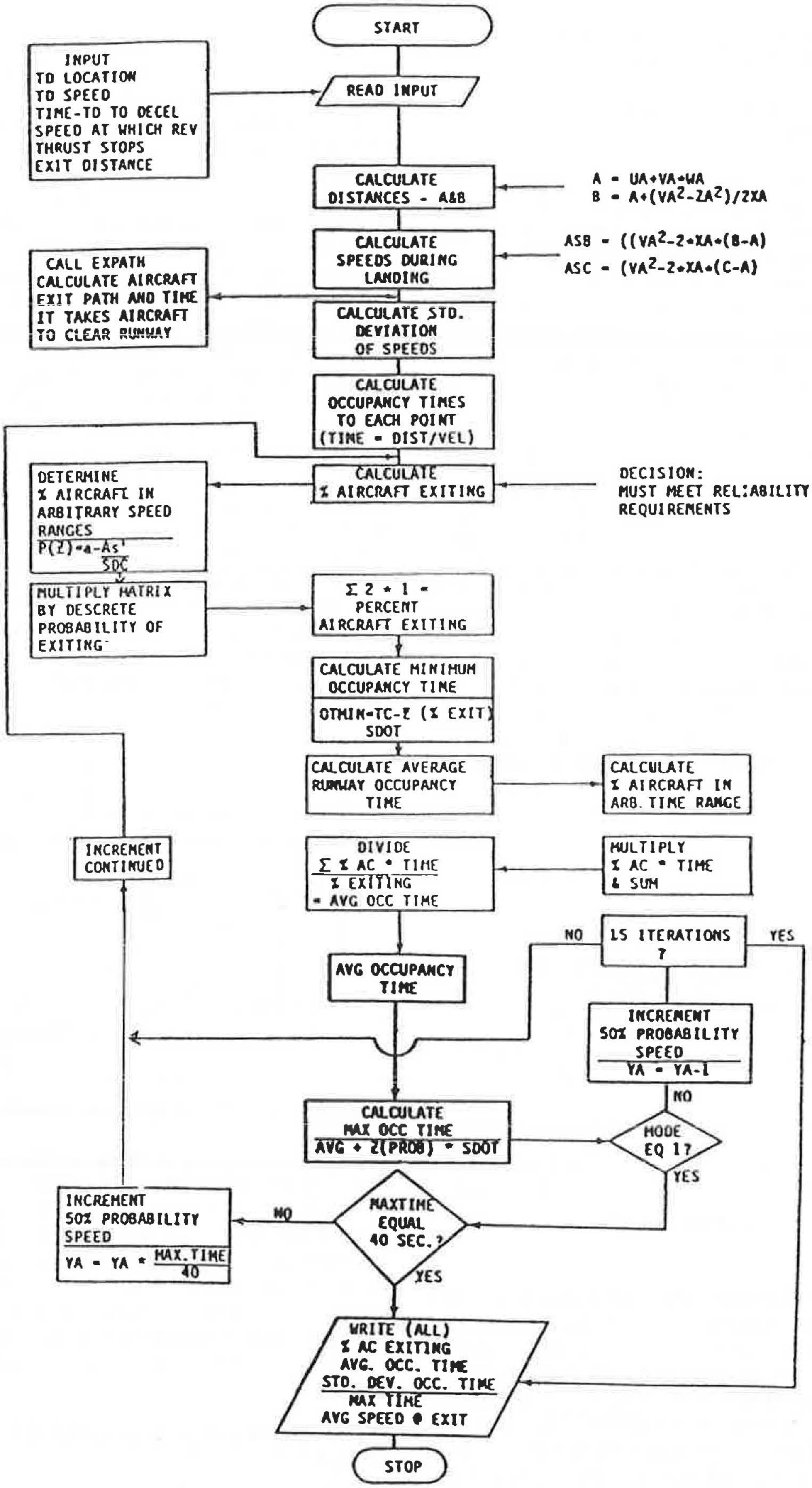

FIGURE 3 Flowchart of the model *(7)*.

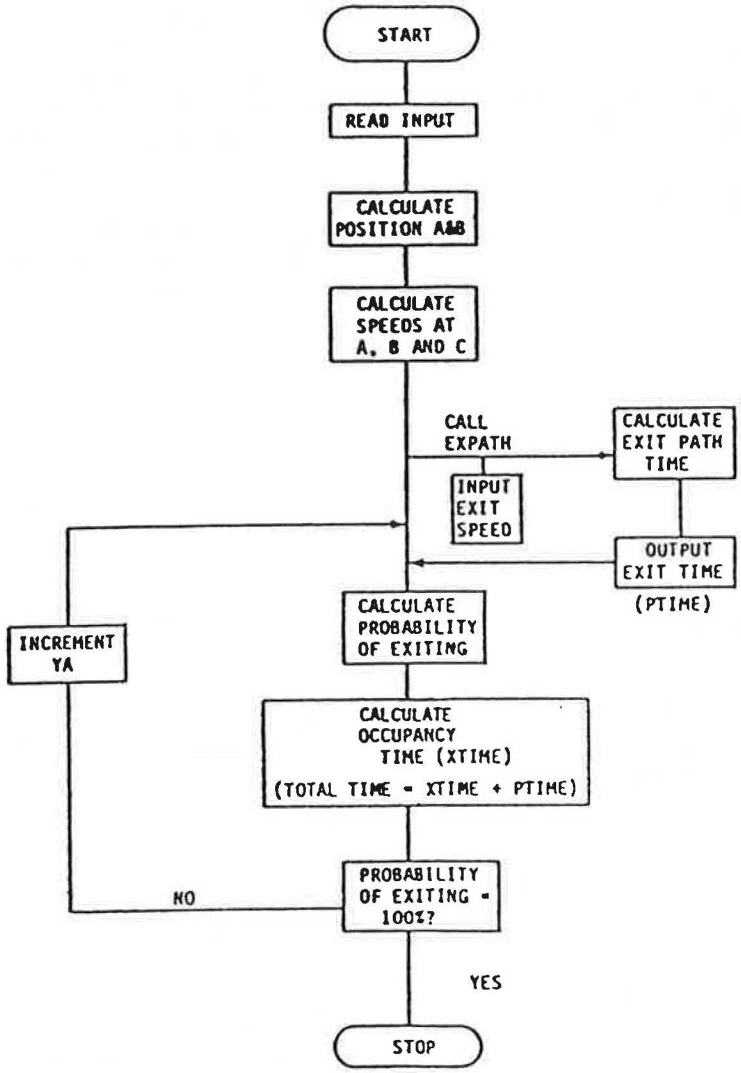

FIGURE 4 EXPATH subroutine *(7)*.

Characteristics such as aircraft weight, dimensions, and cornering limits play important roles in the design of airfields in general and the design of high-speed exits in particular. To bracket the high-speed turnoff performance variability that can occur in a particular category, two generic aircraft, S (slow/small) and F (fast/large), are defined in each of the four TERPS categories. Such categorization is influenced primarily by the range of approach speeds and aircraft weights.

The TERPS generic aircraft used in the study, together with their associated landing characteristics, are given in Table 1. Two specific aircraft, the Boeing 747 and the Lockheed F104, are included to demonstrate extreme landing conditions. The B747, in particular, was included because it is the largest and most difficult commercial aircraft to maneuver, so that a design based on it would tend to be on the conservative side.

ANALYSIS OF RESULTS

Figure 5 shows the optimal exit locations for the eight generic aircraft considered. Shown are the eight different exits, located between 1,286 and 5,860 ft from the threshold, needed to individually accommodate the eight generic aircraft. The optimal exit locations for the B747 and the F104 are 5,170 and 8,400 ft, respectively. An exit is considered optimally located when the constraints of maximum runway occupancy time of 40 sec and a reliability of 1 miss for every 10,000 landing aircraft are met.

Clustering the possible exits into the smallest practical number is accomplished in two stages. Initially, the separation distances, shown in Figure 5, are examined to determine the mutually exclusive exits on the basis of the criteria defined previously. The mutually exclusive paired exit locations, those that have little separation distances, are at 2,285 and 2,355 ft; 3,654 and 4,225 ft; 4,225 and 4,805 ft; 4,805 and 5,515 ft; and 5,515 and 5,860 ft from the threshold. In the second stage, a series of computer runs is made to analyze the sensitivity of the model results and to select the final configuration. It was found that the model results are highly sensitive only to the location of the exit and the deceleration rate before turnoff *(9)*. Consequently, the investigation involved only these two parameters.

Each exit location is taken as a candidate to represent a cluster of several exits. By considering the reliability and maximum runway occupancy time criteria stated initially, the turnoff performance and the path profiles along all candidate exits are evaluated. The results are summarized in Table 2.

TABLE 1 AIRCRAFT LANDING CHARACTERISTICS (Millen, Scott, Rivera and Tutterow, A Probabilistic Runway Occupancy Time and Exit Path Optimization Study with Lateral Ride Comfort, unpublished NASA report; *8*)

	Landing Characteristics										
Generic Aircraft	UA	US	VA	VS	WA	WS	XA	XS	YS	ZA	NTIP
AS	500	10	66	5	3	1	2.5	1	1	55	39
AF	500	10	118	5	3	1	2.5	1	1	55	40
BS	1000	20	110	10	4	1	4.0	.5	1	90	34
BF	1000	20	164	10	4	1	4.0	.5	1	155	56
CS	1500	30	181	10	5	1	5.0	.5	1	155	48
CF	1500	30	230	10	5	1	5.0	.5	1	175	103
DS	1500	30	211	15	5	1	5.0	.5	1	175	87
DF	1500	30	260	15	5	1	5.0	.5	1	255	150
Specific Aircraft											
B747	1500	30	230	10	5	1	5.0	1	1	190	130
F104	1500	30	370	25	5	1	6.0	2	1	150	35

LEGEND:

UA = Touchdown Location from threshold (ft)
US = Standard Deviation Of UA (ft)
VA = Aircraft Speed at Touchdown (ft/sec)
VS = Standard Deviation Of VA (ft/sec)
WA = Time from Touchdown to Start of Deceleration Before Exit (sec)
WS = Standard Deviation of WA
XA = Deceleration Rate of Aircraft Before Exit (ft/sec/sec)
XS = Standard Deviation of XA (ft/sec/sec)
YS = Standard Deviation of YA, the 50-percentile cumulative normal distribution of speeds at exit entrance (ft/sec)
ZA = Speed at which Reverse Thrust is Shut Off
NTIP = Distance from Aircraft Nose to Wingtip

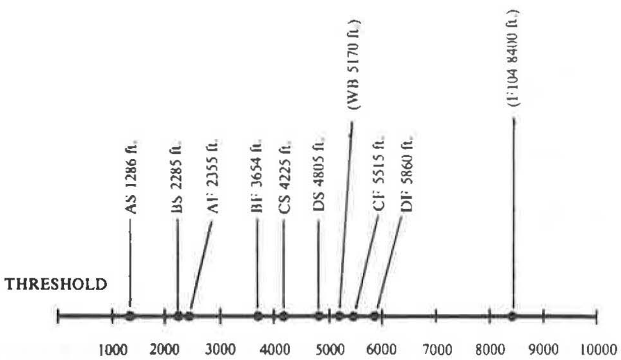

FIGURE 5 Exit locations.

TABLE 2 EVALUATION OF POSSIBLE EXIT SOLUTIONS

Exit Location (ft. from threshold)	Clustered Generic Aircraft	Comments
1286	AS	Lone candidate
2285	AF, BS	Small lateral displacement results in BS exceeding 40 sec maximum occupancy time
2355	AF, BS	Preferred solution
3654	BF, CS	Preferred solution
4225	BF, CS	BF requires risky deceleration maneuver to take this exit
4805	DS	Only possible solution to meet the time requirement
5515	CF, DF	Too close to the 4805 ft exit
5860	CF, DF	Preferred solution

The final configuration, showing the five optimal exit locations for the eight generic aircraft and the corresponding path profiles, is shown in Figures 6 and 7. Separate exits would be needed for military F104 and jumbo aircraft such as the B747 because of their landing speed and size, respectively, that affect cornering characteristics. Moreover, the final solution is unique. If the 5,515-ft exit were chosen to accommodate generic aircraft CF and DF, the previous exit would be located 4,225 ft from the threshold, and the 3,654-ft exit would not exist. It is apparent that, in the latter case, at least two generic aircraft (BF and CS) would not meet the established requirements.

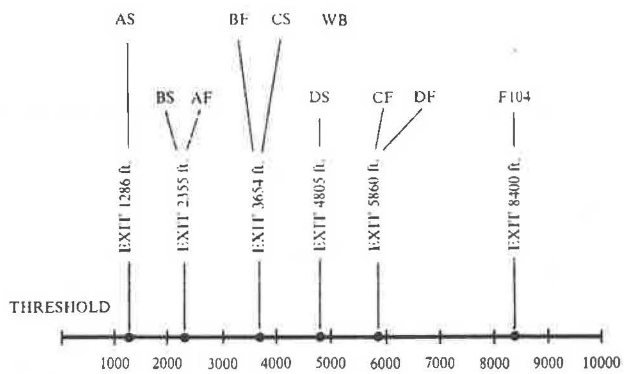

FIGURE 6 Final solution.

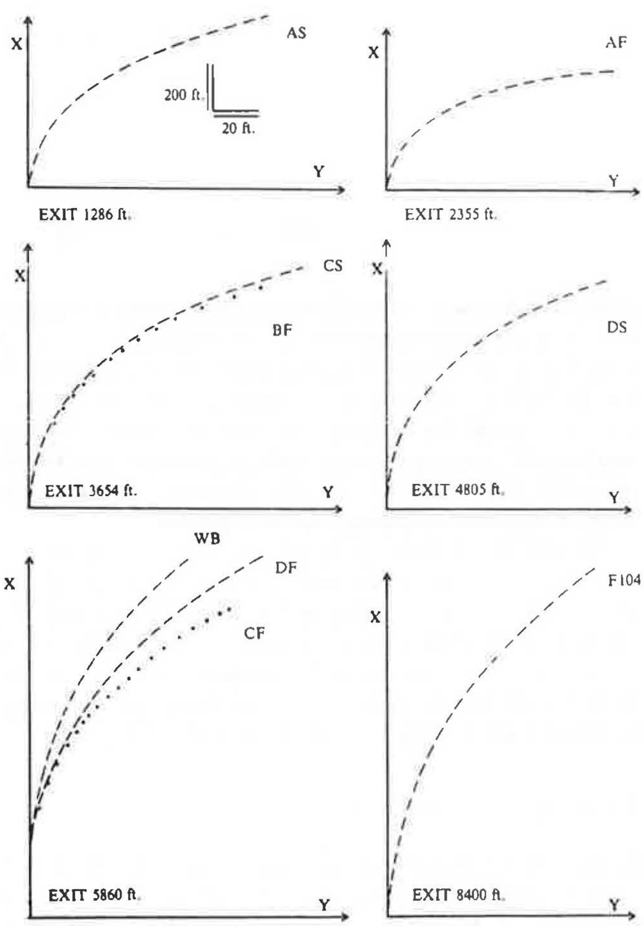

FIGURE 7 Exit path profiles.

CONCLUDING REMARKS

The use of high-speed turnoffs to support a high density of runway operation in future air traffic control environments appears promising. However, a study of combining the exit locations of TERPS generic aircraft into a minimum number of exits has shown that a reduction from eight to five exits for TERPS classes means that any future plans to install embedded automatic turnoff guidance facilities at airports serving all TERPS category aircraft must include a multiplicity of embedded paths. The difficulty of finding a final solution is further compounded if, instead of generics, specific aircraft models are used in the analysis. An alternative solution to this problem is the use of a modified Brandt drift-off system. Unlike the original version, which extends almost throughout the entire runway, the modified version can be localized along the critical points where the accommodation of certain aircraft, say the B747, with other aircraft appears to be a problem.

In cases in which the combination of several exits in a single location is indeed possible, there is still the problem of a slow aircraft clearing the runway without violating the maximum runway occupancy time. Several path profiles emanating from the same exit location are too confusing. A single path, on the other hand, will require a conventionally slow aircraft to exit at unusually high speed and low deceleration rate, which can prove dangerous. A possible solution to this is use of a "fanned exit" wherein the two extreme path profiles for the clustered aircraft exits are used to define inner and outer radii for the compound exit curve. Such an exit is shown in Figure 8.

Although the probabilistic computer model is sufficiently general to include the major factors of aircraft performance, it does not include site-specific parameters such as airport altitude, temperature norms, effective runway gradient, or different runway configurations and turnoff designs. A further improvement can be achieved by adding a subroutine to ease the computational procedure of bunching several exits for different aircraft with varying deceleration rates.

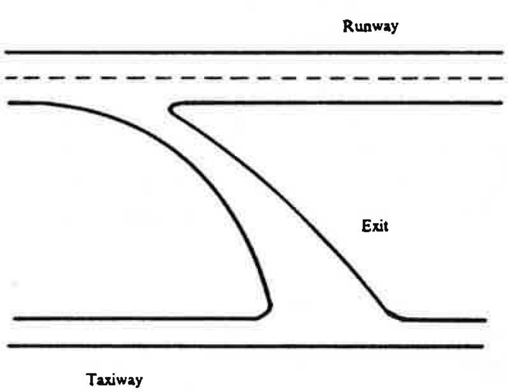

FIGURE 8 Fanned exit.

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