

MICROCOMPUTER MODEL FOR DESIGN AND LOCATION OF RUNWAY EXITS

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(Reviewed by the Air Transport Division)

ABSTRACT: An interactive microcomputer program referred to as runway exit design interactive model (REDIM) has been developed to optimally locate and design high-speed runway exits at airports. The model uses kinematic equations to characterize the aircraft landing dynamics and a polynomial-time dynamic programming algorithm to find the optimal locations of the high-speed exits. The objective of the optimization algorithm is to minimize the weighted average runway occupancy time (ROT) of an aircraft mix selected by the user. A data base of aircraft characteristics for four terminal airspace procedure (TERP) categories has been included in the model to facilitate its use in a large variety of airport environments and conditions. The data-base file relieves the user's data-input burden, specially when the aircraft mix consists of many different types of aircraft. The program is developed to be used as a design and a planning instrument by engineers. Hence, considerable effort has been devoted to user interface such as menu system, interactive data editing, and graphical and tabular outputs.

INTRODUCTION

In the 1990s, airport delays are expected to increase as the air-travel demand builds from 480 to 815 billion passenger revenue miles in 2003 ("Aviation Forecast" 1992). Although delays are attributable to various components of the aviation system (i.e., airspace, runway, taxiway, gate, terminal, and ground access subsystems), the airspace operational procedures in the vicinity of the airport and the runway subsystem seem to be the paramount limiting factors in increasing overall airport capacity. In that regard, the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and airport authorities and planners are focusing on improving the operational capabilities of airport runways to increase airfield capacity.

In addressing this particular concern, the FAA and NASA are evaluating high-speed runway exits to improve the service rate of existing and future runway facilities. The capacity of a runway under mixed aircraft operations is influenced in general by air traffic control (ATC) condition, aircraft runway occupancy time (ROT), and interarrival time (IAT), separations be-

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tween airplanes (Harris 1972). Consequently, an effort to increase the runway capacity should be targeted toward reducing both IAT and ROT. In the existing ATC system, aircraft separation standards have been reduced, allowing smaller spacings between small and medium-size aircraft ("Airport capacity" 1989). However, in terms of ROT there have not been significant reductions in the preceding fifteen years, according to field observations documented in the literature [Howard, Needles, Tammen & Bergendorff (HNTB), unpublished report, 1975; Koenig 1978; Ruhl 1990]. Two reasons seem to be responsible for this fact. First, the variety of aircraft population operating today necessitates a larger number of runway exits in order to satisfy most of its users. Second, one cannot overemphasize the importance of pilot behavior while exiting at high speeds, which has contributed to unusually large margins between the runway exit design speeds and those seen in actual practice. If new aircraft separation criteria (2/4/5 nm or 3.7/7.4/9.25 km) is implemented as anticipated by FAA for 1996, it might be desirable to reduce even further the average ROT in order to maintain a desired level of service on the runway subsystem (Swedish 1979). One particularly useful way to achieve this would be to strategically locate runway exits tailored specifically for every airport scenario. This tailoring process should account for the operating aircraft mix and airport environmental factors and could possibly incorporate pilot behaviors unique to the facility under consideration.

The problem today resembles that faced by Robert Horonjeff and a team of researchers at the University of California at Berkeley (Horonjeff et al. 1958, 1959, 1960). They conducted a careful evaluation of runway exit geometries to satisfy an emerging population of large four-engine transports and high-performance military aircraft. Today, the significant variations in aircraft performance observed in a larger aircraft population make the problem of optimally locating runway exits a difficult one. This is further compounded by large variations in pilot behavior observed during aircraft landing operations (HNTB unpublished report, 1975; Koenig 1978; Ruhl 1990).

RESEARCH SCOPE AND APPROACH

The primary purpose of this research is to develop a microcomputer program that determines the optimal location of runway exits so as to minimize the weighted sum of expected ROT of an aircraft mix. The program is PC-based, easy to operate, and interactive with the user. It is built around two different models: (1) a kinematic model of the aircraft landing process designed to estimate distance and time requirements for landing; and (2) an optimization model developed to determine the optimal exit locations.

The kinematic model estimates the deceleration distance to reach a specific exit speed and corresponding ROT for each aircraft. The location of an exit is closely related to the deceleration capability of the aircraft expected to use that exit. The landing process, however, involves the uncertainties associated with aircraft approach speed, touchdown point, deceleration rate, etc. Thus, the deceleration distance is probabilistic in nature, and so is the deceleration time. The following paragraphs explain how the parameters of the deceleration distance and time distributions are estimated.

The landing process in the kinematic model is broken down into five phases: flare phase, first free-roll phase, braking phase, second free-roll phase, and turnoff phase (Fig. 1). The flare phase accounts for the aircraft's maneuver from runway threshold to the touchdown point. The braking phase determines the ground deceleration distance, while the turnoff phase

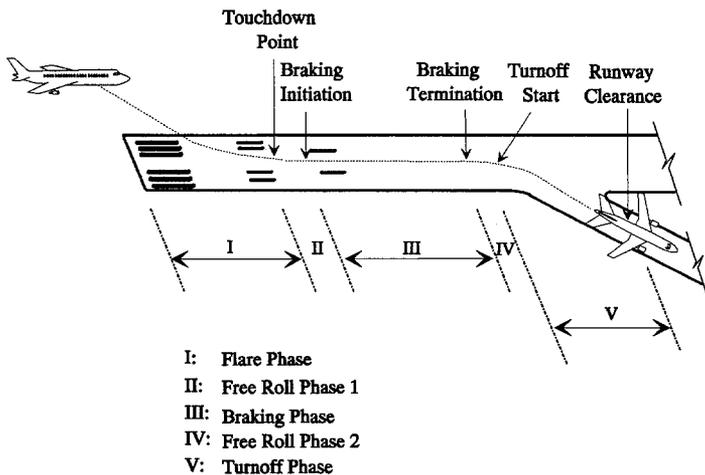


FIG. 1. Aircraft Landing Process

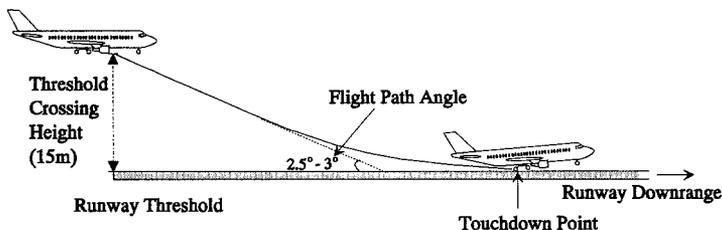


FIG. 2. Air Distance

calculates the distance and time taken by the airplane to execute the turning maneuver—which starts with the turnoff procedure and terminates with runway clearance. An aircraft has cleared the runway when no portion of its body remains inside the runway boundary. Two free-roll phases account for gaps between the different aircraft maneuvers.

Among the five phases just described, the flare phase and the braking phase are the major contributors to the landing process. The flare distance is defined as the distance from the runway threshold to the touchdown point and is estimated based on the following equation (Lan and Roskam 1981):

$$s_{\text{air}} = \frac{h_{th}}{\gamma} + \frac{V_{fl}^2 \gamma}{2g(n_{fl} - 1)} \dots \dots \dots (1)$$

where s_{air} = flare distance; h_{th} = threshold crossing height; γ = tangent value of flight path angle; v_{fl} = flare speed; g = acceleration of gravity (9.81 m/s²); and n_{fl} = flare load factor. The first term of (1) accounts for the linear descending distance from the runway threshold to the touchdown aiming point, and the second term accounts for the circular flare maneuver distance for the smooth landing as shown in Fig. 2. FAA regulates the threshold crossing height be 15.24 m (50 ft). The descending flight path's angle varies from 2.5° to 3° to simulate instrument landing system (ILS) flight path. Recommended values for the flare load factor range from 1.15 to 1.3. The flare speed can be calculated as 1.24 times the stalling speed

(v_{stall}) or 95% of the approach speed. The stalling speed is determined by the aircraft geometric and performance characteristics and the environmental factors, using the following formula:

$$v_{\text{stall}} = \sqrt{\frac{2Mg}{\rho c_{\text{atm}} c_{l_{\text{max}}} A_w}} \dots \dots \dots (2)$$

where v_{stall} = stalling speed; M = aircraft mass; g = acceleration of gravity, ρ = standard air density; c_{atm} = correction factor for atmosphere condition; $c_{l_{\text{max}}}$ = maximum landing lift coefficient; and A_w = wing area. The mass, wing area, and landing lift coefficient are the intrinsic characteristics of aircraft and vary from aircraft to aircraft. The air density in the standard atmosphere condition, sea-level altitude, and 15°C temperature is 1.225 kg/m³, and c_{atm} reflects the variation in the air density according to the change of atmosphere condition. The value of c_{atm} is determined by the standard linear temperature lapse rate method.

The braking distance, defined as the distance required for an aircraft to decelerate to a specified exiting speed from the touchdown speed, is estimated based on the following equation:

$$s_{br} = \frac{(v_{ex}^2 - v_{td}^2)}{2a_{acf}} \dots \dots \dots (3)$$

where s_{br} = braking distance; v_{ex} = exit entrance speed; v_{td} = touchdown speed; and a_{acf} = average ground deceleration rate. The exit entrance speed is the design parameter provided by the analyst. The analyst may expect a lower ROT with higher exit entrance speeds. The exit entrance speed, however, should be limited considering the aircraft stability during the turning maneuver. The upper limit of the exit entrance speed for transport-type aircraft is perceived as 35 m/s. Another limiting factor on the exit entrance speed is the lateral spacing between the runway and the taxiway. Generally speaking, a higher exit entrance speed requires a greater lateral distance from the runway to the parallel taxiway or the parallel runway. Thus, the exit entrance speed should be decided according to the available space around the runway. The exact lateral spacing requirement, of course, is determined by the deceleration rate on the exit and the speed at the junction of the exit and the parallel taxiway as well as the exit entrance speed.

The touchdown speed is usually 90% of the approach speed. The deceleration rate is the most elusive variable in our kinematic model. Little empirical data are found for the deceleration rate in the braking phase of the aircraft landing. Moreover, a general method that can be applied to any type of aircraft is required to be incorporated in the kinematic model. A formula is derived to estimate the deceleration rate in the braking phase, which utilizes the total landing run distance from the runway threshold for the aircraft to stop completely. The landing run distance is provided by manufacturer for every aircraft type. The formula is

$$a_{acf} = \frac{-v_{td}^2}{2(l_r - s_{\text{air}} - s_{fr1})} \dots \dots \dots (4)$$

where a_{acf} = deceleration rate in the braking phase; v_{td} = touchdown speed; l_r = landing run distance provided by manufacturer; s_{air} = flare distance; and s_{fr1} = free-roll distance before braking. The flare distance is calculated

via (1). The free-roll distance is determined by multiplying the touchdown speed by a suitable free-roll time for the pilot to apply the brakes.

For computation of the distances in free-roll phases, the first and second free-roll times are allowed to be set by the analyst. The corresponding free-roll distances are found by multiplying the free-roll times by v_{td} and v_{ex} , respectively. The turnoff time is estimated using an algorithm developed by Schoen et al. (1985). The primary function of this algorithm is to calculate the x - y coordinates of the geometry of the high-speed exit for various aircraft type. The turnoff time is determined by tracing the position of the wing tip as the aircraft progresses along the geometry of the high-speed exit until the wing tip leaves the runway boundary.

As mentioned earlier, the landing process is not deterministic. To account for the uncertainty in the landing process, the flare phase and the braking phase are assumed to be probabilistic events. That is, the mean value of the flare distance is computed using (1) and (2) for each aircraft type. The standard deviation is assumed as a certain percentage of the mean value, say 10%. The standard deviation of the braking distance is computed based on an assumed standard deviation of the deceleration rate. With the normal distribution and independence assumption of these phases, the distribution information of total deceleration distance and ROT is found for an exit speed specified by the analyst for each aircraft type. This probabilistic kinematic model provides the following advantages:

- It frees the analyst from relying on field data on aircraft landing distances, which are not available in most cases.
- It reflects the effects of the airfield environmental factors such as elevation and temperature.
- It is a general model, which can be applied to any aircraft type.

The kinematic model can be applied to any airport with any aircraft mix. However, the calibration of the model will be performed in the near future via the flight-simulator experiment at the FAA Oklahoma City test facility and the statistical analysis on the empirical data collected from several real airports.

The optimization model finds a set of exit locations that minimizes the weighted average of ROT of this aircraft mix. If we move an exit upward or downward from a certain location, some aircraft of the mix will take less ROT while others will take more ROT. In other words, ROT of an aircraft type is sensitive to the exit locations. Hence, there should be a tradeoff analysis of gains and penalties in ROT caused by moving the exit locations. The optimization model developed performs this analysis and determines the set of optimal exit locations.

A conservative assignment policy is made for the optimization, which allows an aircraft type to be assigned to one exit only. This policy naturally makes a lower bound for the location of the exit for a particular aircraft. Suppose, for example, the total landing distance of an aircraft is distributed from a point x to a point y . Then, the exit for this particular aircraft should be built beyond point y to fulfill the assignment policy and point y becomes the lower bound for the location of the exit for the aircraft. On the other hand, suppose there exists a tolerable upper limit on ROT, say 100 s, for an aircraft type and suppose, as well, the aircraft type takes less ROT than the limit if this aircraft executes the turnoff ahead of a point z . Then, point z becomes the upper bound for the location of the exit for the aircraft type.

Combining the lower bound and upper bound, an admissible range where an exit should be built to serve an aircraft type can be determined for every aircraft type included in the mix. An advantage of this approach is the reduction in the variation of ROT of an aircraft type with a possible price of a slightly higher average ROT. Another restriction in locating the exits on the runway is the minimum separation standard between two consecutive exits. The minimum separation standard, referred to as D_{\min} , is imposed by the FAA to prevent possible interference of two aircraft moving on neighboring exits. Based on the admissible ranges and D_{\min} restriction, the solution space for the optimal exit location is reduced to a discrete set of candidate locations from a continuous real line representing the runway. The candidate generation algorithm and the assurance of optimality appear in Sherali et al. (1992) and Trani et al. (1990).

Suppose the candidate locations are indexed as $k = 1, \dots, K$ in increasing order from the runway threshold. With this set of candidate locations, a mathematical model was formulated as follows:

$$\text{Minimize } \sum_{r=1}^R \sum_{k \in A(r)} w_r T_{rk} y_{rk} \dots \dots \dots (5a)$$

$$\text{subject to } \sum_{k \in A(r)} y_{rk} = 1; \quad \text{for } r = 1, \dots, R \dots \dots \dots (5b)$$

$$\sum_{k \in S_t} x_k \leq 1, \quad \text{for } t = 1, \dots, \tau \dots \dots \dots (5c)$$

$$\sum_{k=1}^K x_k \leq N \dots \dots \dots (5d)$$

$$y_{rk} \leq x_k, \quad \text{for } k \in A(r), r = 1, \dots, R \dots \dots \dots (5e)$$

$$\bar{x}, \bar{y}, \text{ binary } \dots \dots \dots (5f)$$

where r = index for aircraft type; R = number of aircraft types comprising the aircraft mix; k = index for candidate location; K = total number of candidates; $A(r)$ = set of candidates that belong to the admissible range of aircraft type r ; w_r = proportion of aircraft type r ; T_{rk} = average ROT of aircraft type r when it makes turnoff at candidate location k ; t = index for candidate location derived for incorporating D_{\min} restriction; S_t = mutually exclusive set of candidates where at most one exit can be built; and N = maximum number of exits to be built.

In this model, x_k is a binary decision variable, which is set to 1 if candidate k is selected for an exit location or set to 0 otherwise. Another binary decision variable is y_{rk} , which is set to 1 if candidate k is selected as the appropriate exit for aircraft type r or set to 0 otherwise. The objective function (5a) represents the weighted sum of ROT. The sum of ROT is minimized, to achieve an increase in runway capacity. As secondary objectives, the sum of taxing distance from the runway to the gate and the minimization of construction cost may also be considered (Tosic et al. 1985; Joline 1974). The weight factors w_r are the relative frequencies for aircraft types that use the airport under consideration. FAA annually publishes the airport activity statistics showing this information ("Airport activity" 1990). Since runway design is targeted to meet saturated conditions, the relative frequencies in peak periods are strongly recommended for the weight factors.

Constraint (5b) assures that each aircraft type is served by an exit. Constraint (5c) prevents two exits from being built in D_{\min} distance. Constraint (5d) limits the number of exits found by the model to N . Constraint (5e) reflects the logical relationship between the binary decision variables. This mathematical model is so versatile that it may be applied to the improvement scenario. The improvement scenario assumes that there already exist some exits on a runway and a few more exits are to be built to improve the performance of the runway. For this purpose, some x_k s corresponding to the existing exits should be set to 1 instead of setting them as free binary variables.

The minimization problem can be solved using a standard mathematical programming algorithm. An efficient solution algorithm, however, is developed for the PC implementation. The solution algorithm is based on the dynamic programming technique, in which the weighed sum of expected ROT over different sets of exit locations are compared, and finally the set of exit locations which produces the minimum weighed sum of ROT is found. Readers concerned about the optimization model and its solution algorithm may refer to Sherali et al. (1992).

SOFTWARE FUNCTIONS AND FEATURES

As stated earlier, the software package referred to as REDIM (runway exit design interactive model) is a fully interactive software package designed to determine the runway exit locations and the corresponding geometries that minimize the average ROT of an aircraft mix. The software allows users to control the program flow, to edit data files, to execute optimization analysis, and to view output interactively. The software is designed to be used by airport planners, managers, and designers, and has three major functions: Evaluation of an existing runway; improvement of an existing runway; and design of a new runway.

The evaluation option examines the effectiveness of an existing runway configuration with respect to a weighted average ROT of an aircraft fleet using the runway. This option requires information about the existing runway configuration, such as the number, locations, and types of exits, as input data. The model produces both the aircraft assignment to the existing exits with the corresponding ROT and probabilities of exiting, and the weighted average ROT as results of the analysis.

The improvement option determines where new exits would be added to an existing runway. This analysis requires as input the number of existing exits, the locations of existing exits, the types of existing exits, and the number of new exits to be constructed. The results are optimal exit locations, aircraft assignment to the existing and new exits, weighted average ROT minimized by the optimal exit locations, and turnoff geometries of the new exits.

The design option determines the exit locations on a new runway. The number of new exits is the main input parameter for this analysis. The outputs are similar to that of the improvement option, except for the fact that only new exits are considered for aircraft assignment in this analysis.

In addition to the major functions just listed, the following features are incorporated REDIM for the user's convenience: First, the software is menu driven. Users do not need to master the operation of microcomputers completely to use the software. They can control the program flows by selecting their choice from the menu screens provided by the software at each step.

Second, the software includes a data-base file, named MAST.DAT, to

alleviate the data-input burden. For every analysis, the user has to select aircraft types comprising an aircraft fleet. The data-base file stores 51 current aircraft names and nine data items for every aircraft. If an aircraft is selected, the corresponding data will be transferred to a working data file automatically. The working data file is a data file that contains a complete set of data necessary for analyses and can be created and edited inside the software. Similar provision has been made to modify the data-base file as the addition of new aircraft becomes necessary.

Third, the software offers both graphical displays on the screen and hard copies of the results on the printer.

Fourth, the software has a limited input-data validation facility. If some input data are out of the feasible range, REDIM asks the user to correct them instead of producing unreasonable outputs.

Fifth, the software has a brief on-line help facility, which describes the choices in every menu.

Sixth, the software can handle up to 25 aircraft and find up to 10 optimal exit locations at a single analysis.

SOFTWARE STRUCTURE

REDIM can be broadly divided into five components and three accompanying data files: main menu, input module, dynamic module, optimization module, and output module; and working data file, master data file, and output file (Fig. 3). Each is described in detail in sections that follow.

Main Menu

The main menu is placed at the top of the software structure and provides the user with the highest level of control over the program. It provides the following seven options: (1) Start a new problem; (2) edit data; (3) begin analysis; (4) edit master (data) file; (5) go to output module; (6) help; and (7) quit. Choices 1, 2, and 4 lead the program flow to the input module, choice 3 leads to the dynamic module and optimization module, which are followed by output module, and choice 5 connects the user to the output module directly.

Input Module

The input module is a collection of subroutines necessary to perform three procedures: start a new problem, edit data, and edit master file. All the procedures are conducted interactively with users. The user has control over the procedures via menu screens and can edit data files on the edit screens provided by the input module.

Dynamic Module

The dynamic module consists of several subroutines used to compute the distance and time requirements of a landing operation according to the kinematic model. The computations in dynamic module are repeated for each aircraft type with different aircraft characteristics, eventually producing the admissible ranges for the given aircraft mix.

Optimization Module

The goal of the optimization module is to find a few turnoff locations, say 2, 3, or 4, at which all aircraft under consideration can exit the runway with the minimum weighted sum of ROT. The optimization module is a

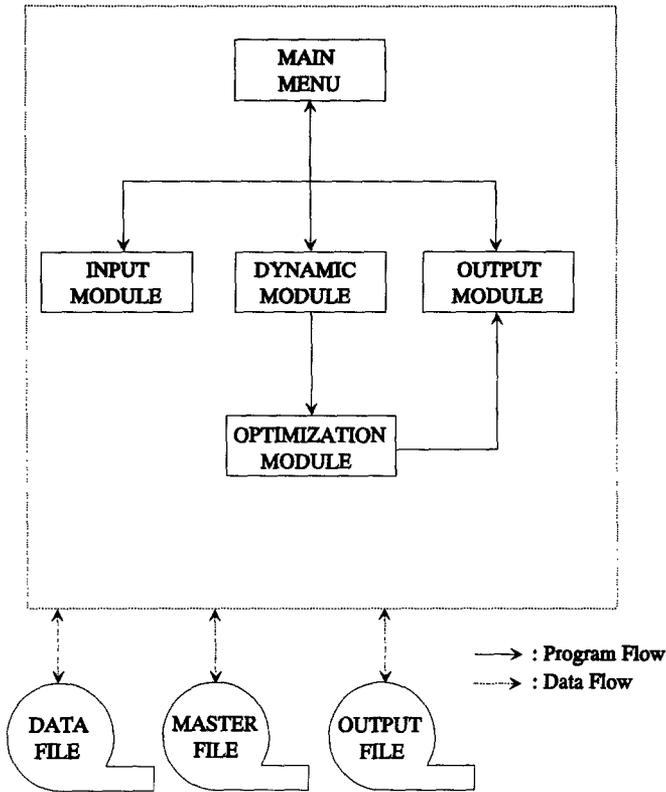


FIG. 3. REDIM Structure

collection of computational subroutines to find the given number of optimal exit locations. Since each aircraft and each surface condition can have different relative frequencies, the weighted sum of ROT is minimized during the optimization according to the solution algorithm for the mathematical model, (5).

Output Module

The output module is structured so that at each stage the user is prompted with specific questions and guidelines that are to be followed in order to view the appropriate results. A significant feature in this module is that in each type of analysis, the screens clearly display information regarding the aircraft and the airport data. This information provided at the top of each screen helps the user to identify the general information pertaining to a specific type of analysis. The output module can be accessed directly by selecting “go to output module” in the main menu or can be connected automatically after completing the analysis.

Working Data File

The working data file stores all input data necessary to perform an analysis. Input data are classified into six categories for the user’s convenience, so that when the user wants to change some of the input data, he has to

review only a category instead of scanning the whole data file. The following paragraphs define the categories in more detail.

Analysis type and related data: The program provides the user with three choices for the type of analysis to be performed. For each type of analysis, there are some accompanying data, which vary depending on the user's choice. That is, information about existing exits is necessary for evaluation or improvement analysis but is not necessary for design analysis.

Aircraft mix and characteristics data: In this category, the percentages of the aircraft comprising the aircraft mix population and their geometric characteristics are included.

Airport operational data: In this category, the free-roll time between the touchdown and the beginning of braking, the free-roll time between the end of braking and the beginning of turnoff, the taxiing speed, and their standard deviations are included. A safety factor for the pavement impending-skid condition is also included in this category.

Airport environmental data: The parameters of wind speed, wind direction, airport elevation, airport temperature, runway orientation, minimum distance between two adjacent exits, runway width, and distance to the nearest taxiway are included in this category.

Runway gradient: In this category, runway length and the effective gradient for every one tenth of runway are included.

Weather and exit speed: The relative frequency of dry and wet runway surface conditions are included in this category. The desired exit speeds of each aircraft category under each runway pavement condition are also included here.

Master Data File

The master data file is a data-base file that stores all aircraft names and their geometric characteristics. This file can be edited with a procedure named "edit master file," which is provided as a part of the input module. The user can add new aircraft data or change the contents of the file. If an aircraft is selected as a member of an aircraft population, its name and characteristics data will be transferred to the working data file automatically.

Output File

The output file stores the results of the analysis. The contents of the file can be displayed graphically on the screen or can be printed on the printer by procedures provided by the output module.

PROCEDURES

REDIM provides the user with numerous procedures including "create a new working data file," "edit data file," "begin analysis," "view output," and so forth. In this section, the application of the software is discussed with a hypothetical example showing the actual screens displayed by REDIM.

Suppose an airport official plans to increase the capacity of a runway that is 3,000 m long by adding a few new exits or redesigning the exit locations completely. The runway is built to serve transport-type and commuter of aircraft. That is, aircraft classified in TERP A category are not allowed to land on this runway. The runway has four exits located at 900 m, 1,500 m, 2,300 m, and the end of the runway. The first exit is designed to serve commuter aircraft classified in TERP B category. The geometry of this exit

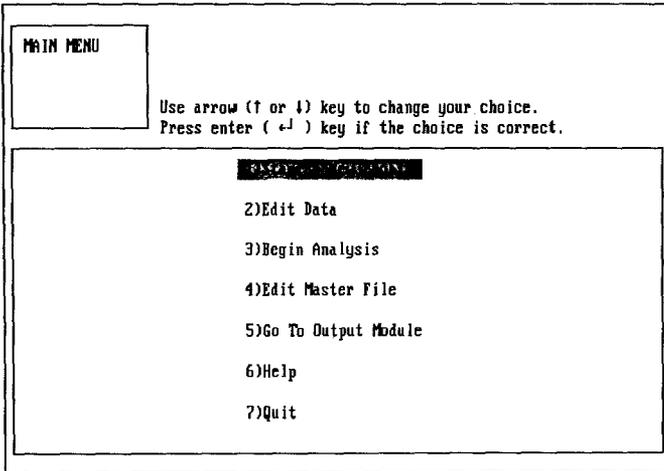


FIG. 4. Main Menu

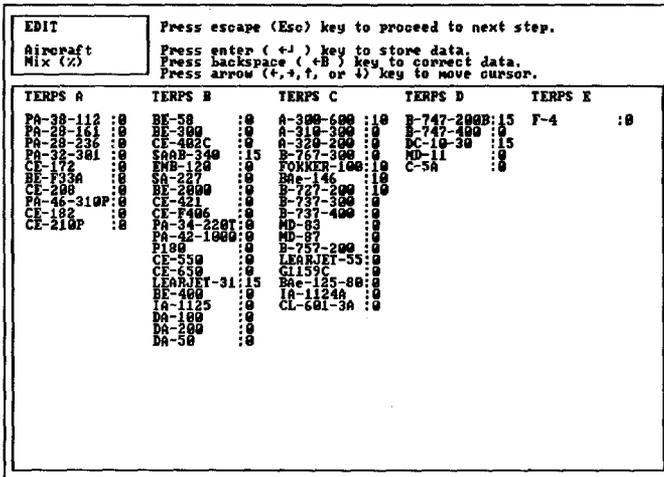


FIG. 5. Screen for Aircraft Mix Data Edit

is designed according to the FAA standard 45° exit. The second and third exits are intended for use by large (TERP C) and heavy (TERP D) aircraft, respectively. Their geometries follow FAA 30° exit standards. The last one is built to serve the aircraft that missed the previous exits, and it follows the FAA standard 90° exit geometry. The aircraft mix consists of 30% of TERP B, 40% of TERP C, and 30% of TERP D. For the sake of simplicity, it is assumed that two aircraft of type TERP B, four aircraft of type TERP C, two aircraft of type TERP D comprise the aircraft mix.

Using REDIM as an analysis tool, the airport official begins by evaluating the existing configuration as a reference performance. The "main menu" screen (Fig. 4) is displayed as the user begins running the software. The

EDIT	Press escape (Esc) key to proceed to next step.										
SAAB-340 Char. Data	Press enter (↵) key to store data. Press backspace (⌫) key to correct data. Press arrow (←, →, ↑, or ↓) key to move cursor.										
<table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%;">A/C Wheelbase (m): 7.14</td> <td style="width: 50%;">A/C Wheeltrack (m): 6.71</td> </tr> <tr> <td>A/C % Load on Mains (%): 98.98</td> <td>A/C Landing Mass (Kg): 12820</td> </tr> <tr> <td>A/C Landing Distance (m): 1140.45</td> <td>A/C Maximum CL : 2.5779</td> </tr> <tr> <td>A/C Wing Area (M²): 41.89</td> <td>A/C Wing Span (m): 21.44</td> </tr> <tr> <td>A/C N.Gear to W.Tip (m): 7.74</td> <td></td> </tr> </table>		A/C Wheelbase (m): 7.14	A/C Wheeltrack (m): 6.71	A/C % Load on Mains (%): 98.98	A/C Landing Mass (Kg): 12820	A/C Landing Distance (m): 1140.45	A/C Maximum CL : 2.5779	A/C Wing Area (M ²): 41.89	A/C Wing Span (m): 21.44	A/C N.Gear to W.Tip (m): 7.74	
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A/C N.Gear to W.Tip (m): 7.74											
Above data are transferred from MASTER FILE.											

FIG. 6. Screen for Aircraft Characteristics Edit

EDIT	Press escape (Esc) key to return to EDIT MENU.								
Airport Env. Data	Press enter (↵) key to store data. Press backspace (⌫) key to correct data. Press arrow (←, →, ↑, or ↓) key to move cursor.								
<table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%;">Wind Speed (m/s) : 0</td> <td style="width: 50%;">Wind Direction : 0</td> </tr> <tr> <td>A/P Elevation (m) : 0</td> <td>A/P Temperature (C) : 15</td> </tr> <tr> <td>Min.Exit Interval (m) : 213</td> <td>R/W Orientation : 0</td> </tr> <tr> <td>R/W Width (m) : 45</td> <td>Dist. to Taxiway (m) : 183</td> </tr> </table> <p style="margin-top: 10px;">Wind Direction - Defined according to the standard wind rose convention. Enter between 0 and 36.</p> <p>Wind Speed - The magnitude of the absolute wind velocity vector.</p> <p>Runway Orientation - Defined according to the standard planning convention. Enter between 0 and 36.</p> <p>Min. Exit Interval - The minimum distance between two adjacent exits.</p>		Wind Speed (m/s) : 0	Wind Direction : 0	A/P Elevation (m) : 0	A/P Temperature (C) : 15	Min.Exit Interval (m) : 213	R/W Orientation : 0	R/W Width (m) : 45	Dist. to Taxiway (m) : 183
Wind Speed (m/s) : 0	Wind Direction : 0								
A/P Elevation (m) : 0	A/P Temperature (C) : 15								
Min.Exit Interval (m) : 213	R/W Orientation : 0								
R/W Width (m) : 45	Dist. to Taxiway (m) : 183								

FIG. 7. Screen for Airport Environmental Data Edit

user must first establish a “working data file” by selecting “start for a new problem” procedure. In this procedure, the user specifies all the data needed to perform the analysis sequentially according to the data categories discussed in the previous section. Since the user wants to evaluate the existing configuration, “evaluation of an existing runway” option needs to be selected in the “analysis type selection” menu, which provides three choices of the analysis type in a similar format as “main menu.”

Fig. 5 shows the “aircraft mix data” screen, at which the user specifies the aircraft types comprising the aircraft mix and their proportions. Once the aircraft mix data are specified, “aircraft characteristics” screens (Fig. 6) follows for each aircraft type selected as aircraft mix components. Nine items need to be specified for each aircraft type. Default values are stored

ROT / RELIABILITY TABLE
(This is for Evaluating an Existing Runway)

Exit #	Location (m)	1	2	3	4
Exit Type		900	1500	2300	3000
		45-Deg	30-Deg	30-Deg	90-Deg
SAAB-340	ROT	33.77	49.25		
DRY	REL	0.18	0.90		
(7.5%)					
WET	ROT	35.15	48.12		
(7.5%)	REL	0.01	0.99		
LEARJET-31	ROT	30.53	49.62		
DRY	REL	0.79	0.21		
(7.5%)					
WET	ROT	31.54	48.96		
(7.5%)	REL	0.47	0.53		
A-300-600	ROT		40.42	72.58	
DRY	REL		0.90	0.10	
(5.0%)					
WET	ROT		41.55	68.24	
(5.0%)	REL		0.45	0.55	
FOKKER-100	ROT		41.32		
DRY	REL		1.00		
(5.0%)					
WET	ROT		39.80	72.32	
(5.0%)	REL		0.94	0.06	

ROT - Runway Occupancy Time in Secs
REL - Reliability
Average ROT = 58.10

Press any key to continue

FIG. 8. Aircraft Assignment and ROT Table (Evaluation Scenario)

**TURNOFF LOCATIONS
AND THEIR
GEOMETRIES**

AIRPORT CONDITIONS

Temperature (C) : 15.00
Elevation (m) : 0.0
Wind Speed (m/s) : 0.00
Weather (%) : Dry - 50 & Wet - 50

RUNWAY EXIT LOCATION DISPLAY

Runway Down Range (m) →

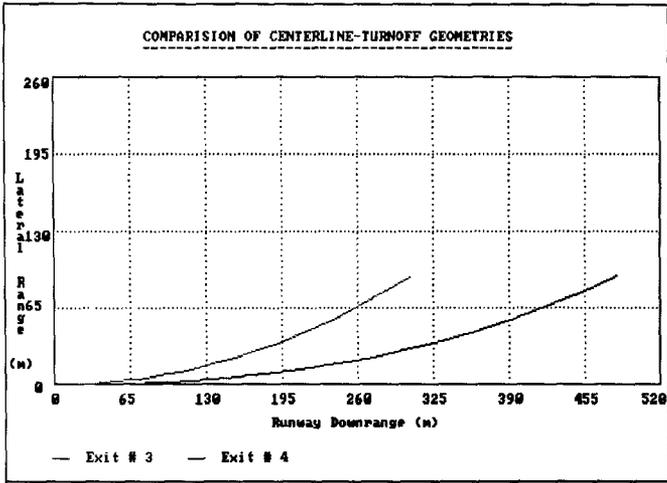
EXIT #	LOCATION	EXIT #	LOCATION
1	900.00	3	2300.00
2	1500.00	4	3000.00

Enter the Exit Number
to view the complete
Turnoff Geometry.
(Enter '0' to exit)
Example) 2
====> █

FIG. 9. Exit Location

in a data-base file named "master data file" and are transferred automatically to this screen. Fig. 7 shows the "airport environmental data" screen where wind speed and direction, elevation, temperature, etc. are edited. In a similar manner, "airport operational data," "runway gradients data," and "weather data" are requested to be input.

The model's computational analysis is initiated by the user selecting the "begin analysis" option on main menu screen. The "output menu" screen is displayed after the analysis is completed. On the screen, the user has options of "view the output" and "print the report." The latter option produces printouts including summaries of input data and analysis results. The first option summons another menu screen named "view menu." The



Press any key to continue

FIG. 11. Exit Centerline Comparison

ROT / RELIABILITY TABLE
(This is for Designing a New Runway)

Exit # Location (m) Exit Type	1 1250.6 New	2 1750.3 New	3 2199.0 New
SAAB-340			
DRV 7.5% ROT	38.70		
MET 7.5% ROT	37.91		
LEARJET-31			
DRV 7.5% ROT	38.58		
MET 7.5% ROT	38.36		
A-300-600			
DRV 5.0% ROT		44.39	
MET 5.0% ROT		43.80	
FOKKER-100			
DRV 5.0% ROT		44.58	
MET 5.0% ROT		44.25	

ROT - Runway Occupancy Time in Secs
Reliability in % = 95
Average ROT = 42.32

FIG. 12. Aircraft Assignment and ROT Table (Design Scenario)

The analysis is initiated again by selecting the "begin analysis" option on the main menu. The user will get the same output menu screen as before. In this example, REDIM suggests 1,750 m and 1,250 m for the locations of the first and second additional exits, resulting in the average ROT of 47.8 s and 43.0 s with one and two new additional exits, respectively. Fig. 11 shows the difference between the center lines of the 30° exit and the new high-speed exit geometry generated by REDIM. The geometry suggested by REDIM (exit 4) allows an aircraft to turn more smoothly at higher speed than the standard high-speed geometry (exit 3).

The user is now wondering what will happen if the existing exits are ignored and three new exits are constructed. To get the results, the user

has to return to the main menu and change the analysis type to “design” as was done for “improvement.” REDIM suggests 1,250 m, 1,750 m, and 2,189 m for the locations of the three new exits. With only three new exits, the average ROT will be 42.3 seconds as shown in Fig. 12, which also displays the aircraft assignment for each exit.

CONCLUSION

REDIM outputs recommend optimal locations and geometric designs of high-speed exits under various airport scenarios. They are primarily accomplished via a kinematic model based on the dynamics of aircraft landing and an optimization model. The kinematic model calculates the mean and variance of the landing distance for a specified exit speed considering the uncertainties involved in the landing maneuver. The optimization model determines the turnoff locations of an aircraft mix for a given set of airport environmental conditions using the dynamic programming technique. REDIM also has interactive user interface facilities, where the user is able to control and edit such items as program flow, data, and so forth.

It is important to note that the uncertainties in aircraft landing processes are usually associated with variations in the pilot’s execution of certain manual control tasks, such as flight-path angle, activation time of braking mechanism, acceptance of a particular exit, gate location, and so forth. The kinematic model for aircraft-landing dynamics in REDIM are expected to be calibrated in phase II of this research via aircraft simulator experiments and empirical studies in real airport environments for more-precise predictions of aircraft behavior during the landing roll maneuver. These experiments are intended to evaluate the acceptance of the pilots to the REDIM outputs and eventually to refine the results for real-world applications.

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