I. INTRODUCTION

Past research has demonstrated the importance of runway occupancy time in the overall effectiveness of an airport to handle traffic. The location of runway exits, however, has been determined using simple aircraft landing roll approximations aided by common sense. With the proliferation of more aircraft types, locating exits optimally becomes a fairly complex issue requiring rigorous quantitative approaches to achieve a meaningful solution. The purpose of the Runway Exit Interactive Design Model (abbreviated REDIM 2.0 hereon), a computer program developed at the Center for Transportation Research at Virginia Tech University, is to expedite the optimal location and geometric design features of runway exits at airports under realistic conditions (i.e., multiple aircraft and varied environmental conditions).

The approach used in the development of REDIM 2.0 is a combination of Monte Carlo simulation modeling to represent the random behavior of aircraft landing distributions coupled with a dynamic programming optimization routine to select optimal exit locations from a large set of candidates. The program requires an IBM or compatible computer with EGA capabilities. An Intel-based 80386 with a math coprocessor is suggested to run the program for faster results. However, the program will also run on 80286-based computers having no floating point unit support. A complete description of the program's algorithms and logic is contained in DOT/FAA report RD-92/6, II [Trani and Hobeika et al., 1992].

The Runway Exit Design Interactive Model version 2.0 (REDIM 2.0) developed in this research effort considers specific airfield variables that affect the landing performance of the aircraft as well as important operational constraints (e.g., aircraft mix) that have a direct impact on the selection of the exit location and their geometries. The model is comprised of five modules: 1) main menu, 2) an interactive input module, 3) a dynamic simulation to estimate the ROT times for individual aircraft, 4) optimization module to find optimal exit locations and 5) an output module to show graphically and in tabular form the suggested runway exit configuration and display some measures of effectiveness of aircraft landing operations. The program also contains a library of geometric and operational aircraft characteristics allowing an analyst to choose from a wide selection of aircraft operating under various airport conditions. Enhancements to the input module allow quick prototyping of various runway scenarios through very simple data input screens. Enhancements to the output module of the program have been also made for helping users to understanding of analysis results.

The program considers four broad types of analyses: 1) evaluation of an existing runway, 2) improvement of an existing runway 3) design of a new runway facility and 4) individual aircraft landing roll behavior. In the evaluation mode REDIM estimates several measures of effectiveness indicative of the operational capabilities of an existing runway facility. In this mode the user inputs the number, type and location of existing exits as well as the relevant aircraft population data and the model predicts the weighted average runway occupancy time (WAROT), the particular exit(s) that an aircraft can take, and the probability of each aircraft taking the assigned exit(s). Another potential use of this mode is to serve as a benchmark to perform valid comparisons between different runway configuration alternatives.

The second mode of operation deals with the redesign of a runway facility. In this scenario it is expected that the user might want to explore the possibility of adding new high-speed exits to an existing runway and examine their impact in the operational efficiency of the facility. Inputs in this mode are the number and type of existing exits, their locations and the number of new exits to be constructed. The outputs are the location and geometry of each new exit, the weighted average runway occupancy time, and an aircraft assignment table containing individual runway occupancy times and the individual aircraft probabilities of taking existing and new exits.

In the third mode of operation REDIM estimates the optimal location of runway exits and their corresponding geometries. An assignment table is given to the user indicating the exit(s) associated with each aircraft and their individual runway occupancy times. The weighted average runway occupancy time is also estimated as a global runway operational parameter and sensitivity studies can easily be conducted by changing the number of exits allocated to a specific runway. Inputs by the user in this mode are the number of exits to be constructed and the desired exit reliability parameter.

The fourth mode addresses an individual aircraft landing roll scenario where the user wants to know specific results about the expected runway occupancy time and the distribution of landing roll distance of a particular aircraft. This mode is primarily envisioned to serve as a tool for the critical aircraft analysis.

Example problems of these four modes of operation will be given in the remaining chapters of this manual. REDIM blends the principles of simulation with those of mathematical optimization to find the best exit locations and corresponding exit geometries for a myriad of possibilities. The program was designed to be interactive and a great effort was made to reduce the number of inputs expected from the user. A large aircraft data base is included to simplify the analyst input task but flexibility is also built-in to allow future aircraft additions. The overall effort was to make the program interactive and easy to use. Many suggestions from previous users have been incorporated in this new version and extra features have been added to extend the flexibility of the program.

1.1 Monte Carlo Simulation Technique

In the development of REDIM 2.0 a great deal of effort has been made to realistically simulate aircraft operations as they would occur in actual practice. The stochastic nature of aircraft landing roll deviations observed in practice prompted the use of a Monte Carlo simulation procedure in the dynamic simulation algorithms embedded into REDIM 2.0. The Monte Carlo simulation technique used here was primarily to estimate landing roll distance dispersions using aircraft normal distributions for some of the aircraft parameters dictating landing roll performance.

Weight factors are used in the program to represent more accurate aircraft landing conditions at the airport facility of interest. The aircraft weight factor is a non dimensional parameter varying from 0 to 1 representing the proportion of the useful load carrying capacity of an aircraft at any point in time. The landing load factor is a major determinant of the aircraft nominal approach speed. The load carrying capacities of certain aircraft make their approach speed range large enough to justify the inclusion of this parameter in REDIM 2.0. A Boeing 727-200, for example, has a 30 knot differential in the approach speeds at the operating empty and maximum landing weights [Boeing, 1986]. The reference landing runs at these two extreme landing weights are 1190 and 1615 m., respectively, thus providing an idea of the large variations in landing roll performance for transport type aircraft.

1.2 Range Solution for Optimal Exit Location

It is necessary to generate large number of aircraft operations through a Monte Carlo simulation procedure in order to assess accurately the landing distance dispersions of a large aircraft population. The optimization procedure may be conducted based on the entire set of aircraft landing operation data or based on a fraction of the complete set and then repeated.

The first approach will provide a point solution for each exit, while the second approach will produce a range solution, which usually contains the point solution of the first approach, if an adequate number of aircraft operation data are used. REDIM 2.0 employs the second approach, thus provides range solution to the exit location problem. The motivation behind this approach is to allow users to decide the exact location of exit in the provided range where the construction of a new exit yields similar WAROT values for a given aircraft population, considering other layout parameters. The range solution for exit location is derived from five internal iterations performed for the aircraft mix selected by the user.

1.3 Aircraft Landing Processes

The landing aircraft kinematic model used in REDIM incorporates a pseudo-nonlinear deceleration heuristic algorithm to simulate the aircraft behavior on a runway. The aircraft landing phases modeled in REDIM are: 1) an flare phase, 2) a free roll segment between touchdown and the initiation of braking, 3) a braking phase, 4) a second free roll phase between the end of the braking phase and the start of the turnoff maneuver and 5) the turnoff maneuver phase. These landing phases are depicted graphically in Fig. 1.1. It can be seen from this figure that major contributors to runway occupancy time (ROT) are the braking and turnoff phases as these usually take about 60% and 25%, respectively of the total ROT.

1.4 Landing Data Generation via Simulation

The landing roll performance of an aircraft is highly stochastic in nature. For example, the touchdown location and deceleration profile varies for each landing resulting in somewhat different landing roll distances. In order to incorporate this stochastic nature of landing process into the model, four variables are selected as random variables for analysis: the threshold crossing altitude, final flight path angle, landing weight and deceleration. These variables have been selected because they can be measured and they account for most of the differences in a normal approach and flare maneuver prior to touchdown. For example, the landing weight dictates the approach speed while the braking deceleration used determines to a great length of the landing roll maneuver on the ground.

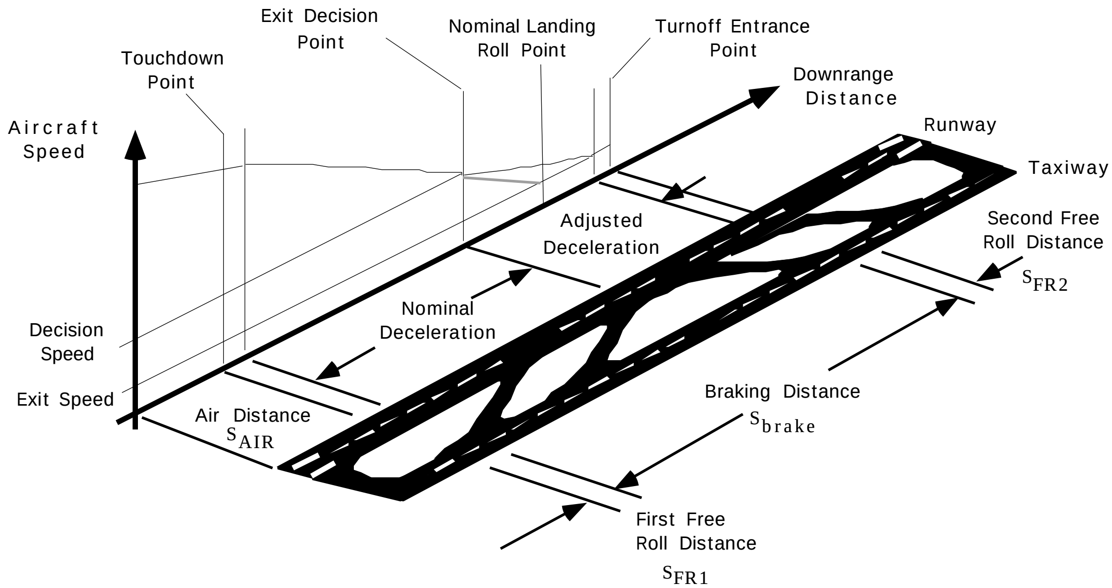


Figure 1.1 Aircraft Landing Segmentation.

For an optimization analysis, 200 landing roll distance data points are generated for each aircraft type via a Monte Carlo simulation. The Monte Carlo simulation is a tool for analyzing a stochastic system by generating random numbers for each random variable involved in the system. In the analysis of the landing roll performance, each landing distance value is generated via following steps:

1. Generate four random numbers from the uniform distribution on the interval [0, 1].
2. Generate the values of the threshold crossing altitude, flight path angle, landing weight factor and deceleration rate from truncated normal distributions using the random numbers generated in step 1.
3. Calculate the landing distance and deceleration time by substituting the values of four random variables into the kinematic formulation.
4. Repeat the step 1 to 3 two hundred times.

Step 1 is performed by utilizing RND() function of Microsoft BASIC version 7.0. Step 2 is performed by the inverse transform method using truncated normal distributions with parameters described previously. Since normal distribution does not have a simple closed form of the inverse cumulative density function, a polynomial approximation of inverse cumulative density function is used for generating the random numbers from normal distributions [Beasley and

Springer, 1977]. The method for generating random variables from a truncated distributions is described in Law and Kelton [Law and Kelton, 1982]. Step 3 is a simple calculation, because all the equations and the values of all the variables are known.

A heuristic aircraft landing deceleration model has been implemented in REDIM to represent the pilot's behavior on the runway under real airport conditions. To illustrate this method adopted in REDIM 2.0 refer to Fig. 1.2 where two distinct aircraft deceleration phases are identified: 1) a nominal deceleration phase where the pilot applies an average braking effort and 2) an adjusting braking phase where the pilot modifies continuously the aircraft deceleration schedule to achieve a predefined turnoff speed at the next available runway exit location. A decision point is defined in order to establish the transition between the nominal and the adjusted deceleration phases.

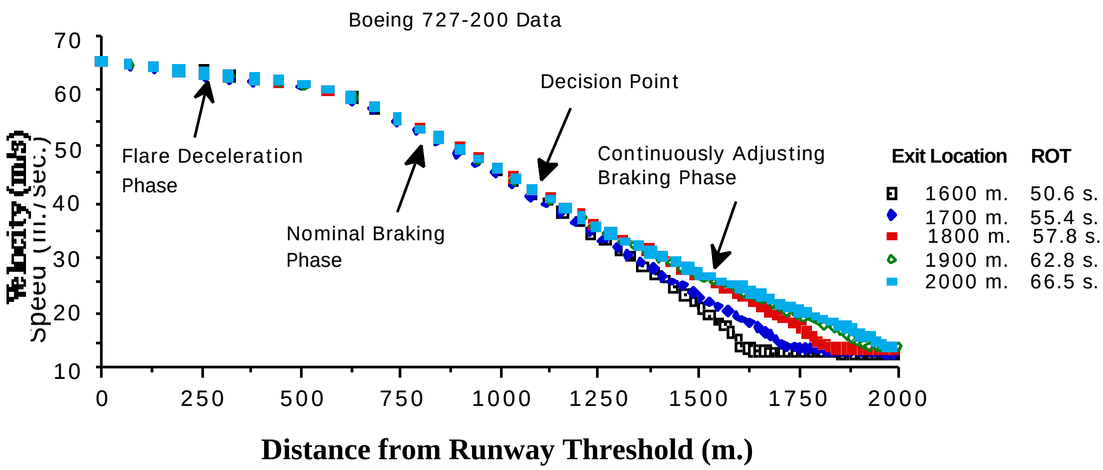


Figure 1.2 Normative Aircraft Landing Roll Model.

The decision point will generally be a function of variables such as the pilot's eye position with respect to the ground, the airport visibility, the aircraft state variables (i.e., speed, deceleration, etc.), the pilot's situation awareness (i.e., information of various exit locations and their design speeds), and the instantaneous crew workload. Since many of these variables are difficult to validate a simple heuristic rule is used in this approach to determine the decision point in terms of aircraft approach speed solely. The faster the aircraft in the approach phase the sooner decisions will have to be made in order to maintain a reasonable safety margin in the landing roll operations. Also, the approach speed is somewhat correlated with the pilot's eye position in the cockpit for commercial aircraft. This implies that heavy jets will have a definite advantage over general aviation aircraft in reaching their decision point at an earlier stage as pilots have a much better perspective of the location of downrange exits.

In practice pilots flying into an airport facility will probably have knowledge of the approximate exit locations and types of exits available for the active runway thus it is likely that they will adjust the aircraft behavior to reach a comfortable exit location at or near a desired exit speed. Figure 1.2 illustrates this heuristic principle using data typical of a Boeing 727-200. The computer simulation results show the adjusted deceleration algorithm and the corresponding individual runway occupancy time for five different exit locations and a desired exit speed of 15 m/s. From Figure 1.2 one can see that the braking adjustments start at the decision point for all runs since the same aircraft speed parameters were used in the simulation. The differences in runway occupancy time are solely due to the different adjusting braking rates present once the decision point has been reached. Note that the adjustments made to the deceleration rate can be easily linearized with little loss in accuracy. This linear approximation of deceleration rate has been embedded into REDIM to simplify the number of internal computations of the model thus reducing CPU time.

1.5 Turnoff Algorithm

The turnoff trajectory simulated in REDIM 2.0 uses a reduced order model to approximate the instantaneous radius of curvature described as the aircraft executes the turning maneuver. The validation of a turning movement procedure has been carried out with the use of a fourth-order aircraft dynamic model considering three degrees of freedom of displacement (lateral, horizontal and vertical motions) and the yawing motion associated with a turning ground vehicle. This model was used to verify the simplified, one degree-of- freedom aircraft dynamic behavior proposed by Schoen et al. [Schoen et al., 1983] and later adapted by Trani et al. [Trani et al., 1990]. The model estimates the boundaries of a maximum effort turn to verify whether or not a specific exit geometry would be feasible under realistic manual control conditions [Trani and Zhong, 1991].

The computation of turnoff times is explicitly modeled for every aircraft/exit candidate as turnoff times generally account for 15-25% of the total runway occupancy time depending upon the exit type being analyzed. This estimation is executed in REDIM 2.0 using a continuous simulation algorithm predicting the turnoff trajectory for every aircraft from point of curvature to the point where the aircraft wing tip clears the runway edge [Trani and Hobeika et al., 1992].

1.6 Optimization Model and Solution Algorithms

The capacity enhancement of a runway by minimizing weighted average ROT (WAROT) of an aircraft mix by locating exits optimally is the primary focus of this section. WAROT is the sum of individual ROT weighted with the landing frequency of aircraft comprising the aircraft mix. The individual ROT (IROT) of an aircraft is defined as time interval from the instance at which the aircraft passes over the runway threshold to the clearance point of the runway. This time interval can be broken down into two components: 1) deceleration time to reach designated exit which includes the air, braking and free roll deceleration phases described before and 2) the turnoff time. The deceleration time accounts for the flying time from the runway threshold to touchdown point and the ground running time from the touchdown point to the designated exit. The turnoff time accounts for the duration of the turning maneuver from the beginning of the turn to the complete clearance of runway.

Mathematical Model

Suppose there are R types of aircraft in an aircraft mix, and K environmental scenarios are considered. Since the purpose of the optimization is to find a set of exit locations that minimizes the weighted sum of expected IROT's of the aircraft mix, the objective function should be:

$$Minimization \sum_{r=1}^{R} \sum_{k=1}^{K} w_r \, p_k \, E[IROT]_{rk}$$

where w_r is the proportion of aircraft type r, and p_k is the chance of scenario k occurring. The expected value of IROT is indexed by 'rk' because IROT should be estimated for each aircraft type and environmental scenario. Suppose N is the total number of exits to be built. Notice that $IROT_{rk}$ is a function of exit locations or decision variables $(x_1,\ldots,x_N)$.

Obviously, x_i's lie on the runway. Hence, $0 < x_i <$ runway length (or RL), for i=1,...,N. If we index x_i in an increasing order, then $0 < x_1 < .. < x_N <$ RL. A distance restriction is usually imposed on two adjacent exits for identification and safety reasons. Let the minimum distance between two adjacent exits be D_{min}. Then constraints $x_{i+1} - x_i < D_{min}$, for i=1,...,N-1 should be added. The resultant mathematical model for optimal exit location problem is

$$WROT: \quad Min \sum_{r=1}^{R} \sum_{k=1}^{K} w_r \, p_k \, E[IROT;(x_1,...,x_N)]_{rk}$$

$$Subto \quad x_{i+1} - x_i \geq D_{\min}, \quad for\ i = 1,..., N-1$$

$$x_1 \geq 0, \; x_N \leq RL$$

The optimization procedure is executed using a polynomial time dynamic programming technique exploiting the structure of the problem. This procedure has been judged to be superior computationally to linear programming and thus adopted for this research. A complete discussion on this topic can be found in Trani and Hobeika et al [Trani and Hobeika et al., 1992].

1.7 Turnoff Compatibility Issues

REDIM 2.0 considers two sets of geometric constraints while suggesting an exit geometry: 1) geometric compatibility with near by facilities such as neighboring exits and parallel taxiway and 2) operational aircraft limitations while taking the exit. The geometric limits of an exit are dictated by its mathematical characterization in terms of x-y Cartesian coordinates. For example, a 30 degree angled exit should not be constructed geometrically when the distance between a runway and taxiway centerline is below 400 ft as this will result in a continuous curve without a turnoff deceleration tangent portion.

The operational limits refer to aircraft imposed limits of entry and exit speeds on the turnoff maneuver. For example, a large transport aircraft entering an exit at high speed will necessitate a finite deceleration distance on the exit to reach a reasonable exit speed for maneuvering. About 190 airports in United States have implemented FAA standard high speed geometries [FAA, 1983]. As many of these facilities were originally planned in the late forties and fifties they adopted lateral taxiway design standards that were not necessarily compatible with the lateral requirements of high speed exits. Many of these facilities have separation distances between runway and parallel taxiway centerlines of only 122 m. (400 ft.). These distances are, in general, inadequate to expedite aircraft from an arrival runway at high speed unless a different exit design philosophy is adopted and smaller exit angles are used replacing existing 30^o geometric standards. A 122 m separation distance between the runway and a parallel taxiway leaves pilots with very little room for decelerating an aircraft on the exit tangent and this might well be one of the contributing factors in the poor use of existing high speed runway exits at various airports [Koenig, 1978; Ruhl, 1990]. The main safety consideration in this regard is the little deceleration time pilots will have in bringing in their aircraft to a reasonable taxing speed once an exit is taken near its design speed.

In order to illustrate this lets consider a heavy aircraft of the type of a Boeing 747-400 as it takes a standard FAA 30 Degree angle geometry at 26.7 m/s (60 MPH) which is considered to be the design speed for this exit [Horonjeff et al., 1960]. Figure 1.3 illustrates the general layout of a high speed exit showing two distinct radii of curvature associated with two curves called lead-in and lead-out turns. Using continuous simulation it is possible to derive lateral distance-speed plots to understand the aircraft kinematic behavior.

Figure 1.4 represents minimum lateral distance requirements for a large transport aircraft executing a modified 30^o angled exit (with a 1400 ft. spiral) varying exit angle. These curves were derived using a constant -.75 m/s^2 deceleration on the tangent with a third order time lag mechanism to represent a delayed braking schedule. Note that values shown in this figure represent distances between runway and taxiway centerlines and could be used for design standardization in future airport projects. The net effect of reducing the exit angle is a corresponding reduction in the minimum lateral space requirements needed to implement high speed exit geometries. Taking an final speed of 15 m/s as a reference point from Fig. 1.4, it can be seen that a reduction of 34 % in the lateral distance requirement is possible if the exit angle is reduced from 30 to 20 degrees (e.g., from 183 m. for 30^o to 120 m for 20 ^{o}). It is expected that all previous assumptions usually will hold under low visibility and wet pavement conditions as pilots act with conservatism and take high speed exits at lower entry speeds. Curves such as the ones shown in Fig. 1.4 have been hard coded in REDIM 2.0 to warn about possible violations of the lateral and longitudinal constraints while executing a runway analysis.

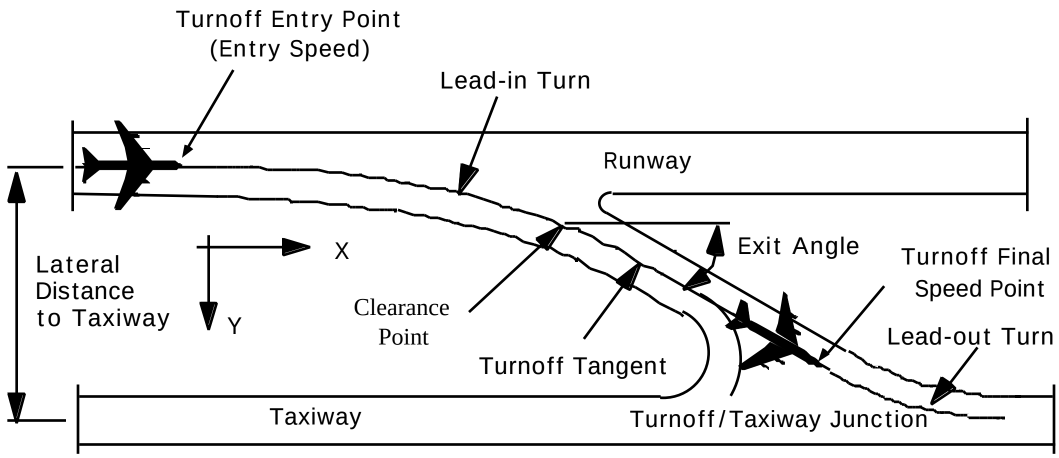


Figure 1.3 General High Speed Exit Geometry.

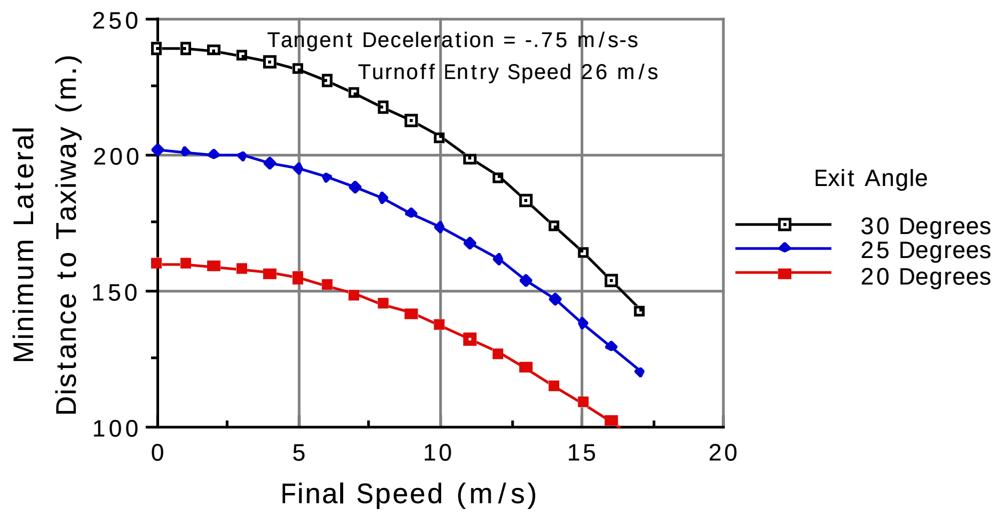


Figure 1.4 Recommended Runway to Taxiway Separation Criteria for Standard FAA 30 Degree, Acute Angle Geometries.

The implications of taxiway proximity cannot be taken lightly in this respect as there is some evidence that in many of the existing airport facilities having small lateral distances between a runway and taxiway centerlines cannot productively use high speed exits [Koenig, 1978; Ruhl. 1990]. The prospect of using a modified 30^{o} exit with a 427 m. entrance spiral (1400 ft.) as stipulated in FAA AC 150/5300-13 increases the pilots' capability to decelerate an aircraft to more comfortable speeds before reaching the exit-taxiway junction as the curved portion of the exit increases in length as that of the standard 30^{o} geometry .

II. GENERAL MODEL STRUCTURE

REDIM 2.0 encompasses five code modules and three data files: Main Menu, Input Module, Simulation Module, Optimization Module, Master File, Data File and Output File (Figure 2.1). The Main Menu placed at the top of the structure offers the users the choice among 'Edit,' 'Analysis,' 'Output' or 'Quit.' The Input Module is a collection of subroutines which make it possible for the users to control the program flow and to edit data files on the screen. The Simulation Module consists of subroutines which generate aircraft landing roll distance data using a kinematic model and the Monte Carlo simulation generation technique. The kinematic model is formulated so as to mathematically predict the aircraft's landing roll behavior on a runway. The Optimization Module, like the Simulation Module, is a collection of computational subroutines to execute the solution algorithm of the runway exit location optimization model. Readers, interested in the details of the kinematic model and optimization model, are referred to Trani and Hobeika et al. (Trani and Hobeika et al., FAA-RD-92/6 II, 1992). The Output Module is devoted to present the analysis results in tabular or graphical forms on the screen or to provide print-out.

Since the design and the evaluation of an airport should be established accordingly to the aircraft mix using the facility, the aircraft mix is the most important and the very first data set to be defined in REDIM. The Master File is a database file containing the characteristics of more than 60 aircraft including general aviation, commuter and transport type aircraft. Users have to specify only the percentage of aircraft using the runway facility and then all the aircraft characteristics data are transferred to a working Data File internally. The working Data File contains all the information required to perform the runway analysis, including the mix and aircraft characteristics, landing weight factors, airport operational and environmental data, runway length and gradients and runway surface conditions. The Output File contains the results of the analysis in a predetermined format. The users may access this file through the programs in Output Module.

REDIM 2.0 is a menu-driven package, where users can control the program flow by selecting their choice from the given menu. The hierarchy of REDIM's menu system is depicted in Figure 2.2. By selecting the 'Edit', the users may edit the Master File or Data File. By selecting 'Analysis', users may initiate an analysis from four choices:

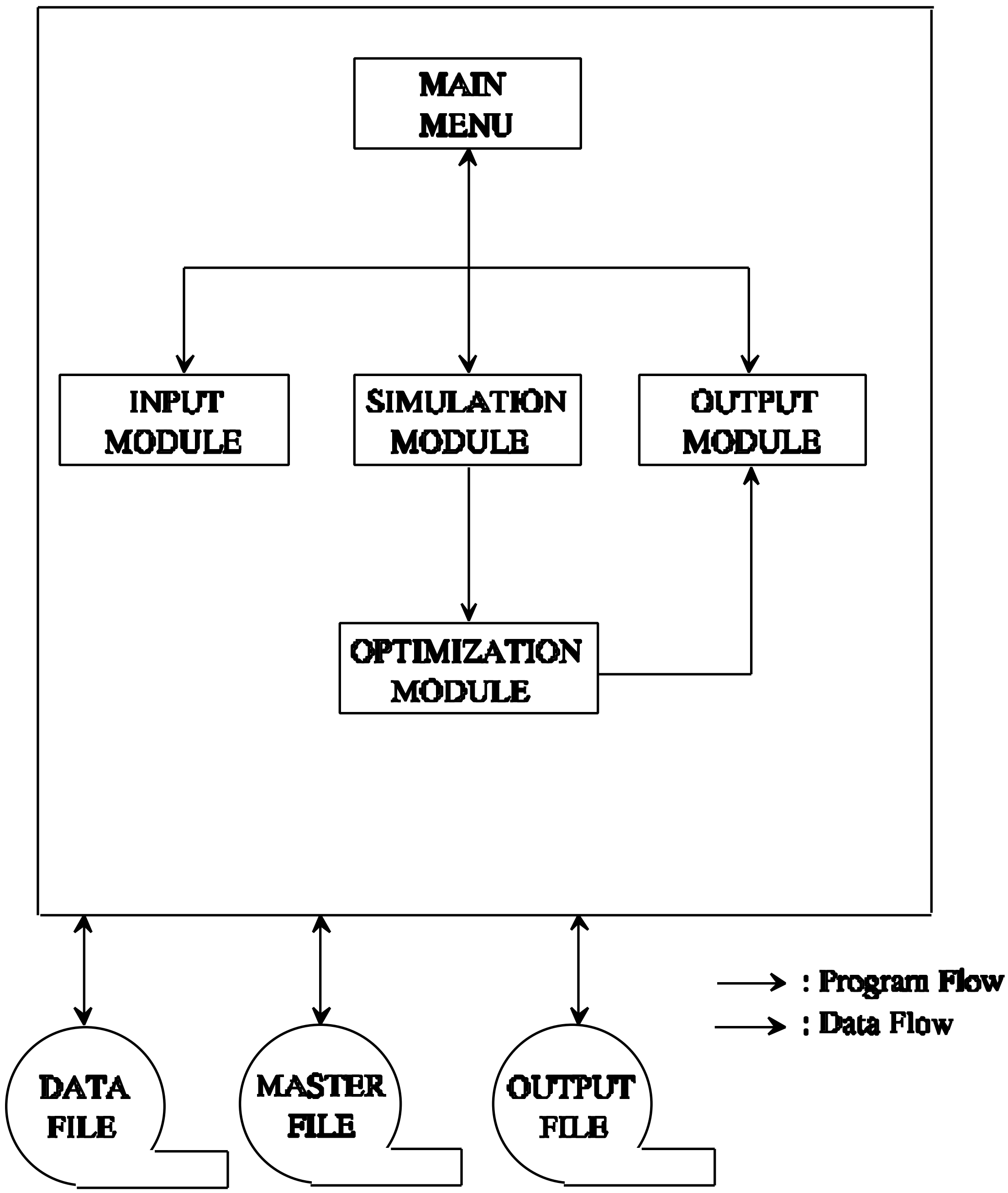


Figure 2.1 REDIM Structure.

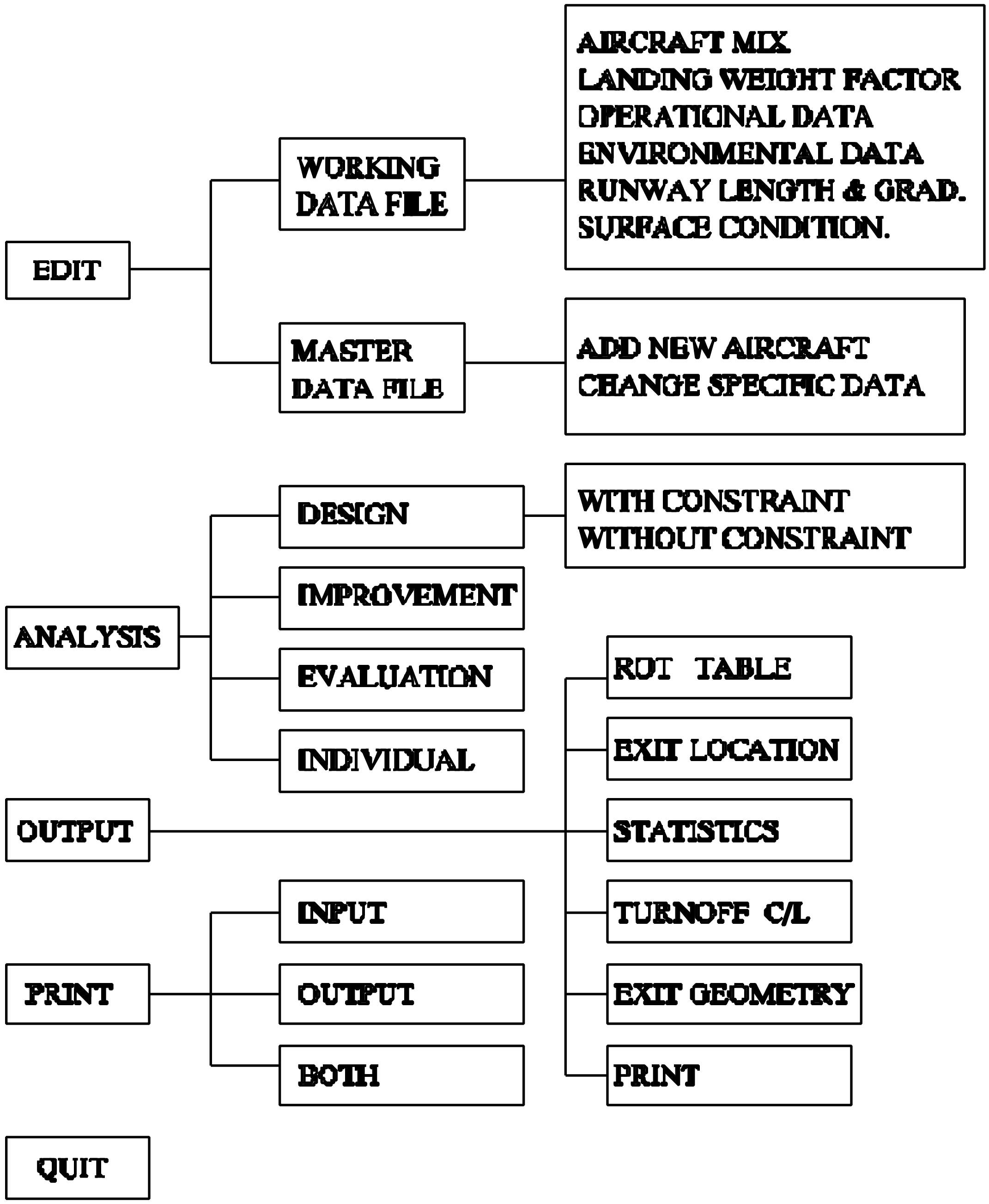


Figure 2.2 REDIM Menu Hierarchy.

'Evaluation,' 'Improvement,' 'Design' and 'Individual.' The choice of 'Output' sends the program control to the Output Module where users may view the analysis results on the screen or may obtain a hard copy of the results through a printer. The contents of the output results vary slightly depending on the analysis type as described in the following section.

2.1 Input/Output Relationship

REDIM 2.0 offers users four types of analyses: design a new runway, improve an existing runway, evaluate an existing runway and individual aircraft's landing performance. The primary purpose of 'design' analysis is to optimally locate a user-defined number of exits on a runway. The optimal locations of the given number of exits, the exit utilization by each aircraft in the mix and the resultant ROT are the major outputs of this analysis. The 'improve' analysis has the same purpose of the 'design' analysis except that it considers the existing exits on the runway as well as the new exits. Hence, the output is same as that of 'design' analysis. The 'evaluate' analysis predicts the exit utilization by each aircraft in the mix and the resultant ROT without the addition of new exits. The major output of these three types of analysis is presented in a tabular form which is called ROT/Assignment Table. In addition, REDIM provides secondary outputs to help users to comprehend the performance and geometry of the runway/exit configuration. These are exit location diagram, ROT statistics, turnoff centerline plot and a scale drawing of the exit geometry.

The purpose of 'individual' analysis is somewhat different from that of the previous analyses. This analysis estimates the probability distribution of an aircraft landing distance to decelerate to various exit speeds.

Regarding the inputs, there are certain data required by all the types of analyses, while each type of analysis also requires data unique to the analysis. Let's call the former type-independent data and the latter type-dependent data. Type-independent data include aircraft mix, landing weight factors, airport operational and environmental data, runway length and gradients and surface conditions; these are all stored in the (working) Data File.

Aircraft mix and aircraft characteristics:

This category includes the percentages of the aircraft which comprise the mix. REDIM allows user to select up to 20 aircraft. The Data File also retains the characteristic of the aircraft selected.

Landing weight factors:

The landing weight factor is defined as the difference between the actual landing weight and the operational empty weight divided by the difference between the maximum landing weight and the operational empty weight. Hence, a landing weight factor of 1 implies that the aircraft lands at its maximum weight whereas a value of 0 means that the aircraft lands without any payload. The landing weight factor is an important input parameter, because the landing weight greatly influences the aircraft's landing performance. The landing weight factor is modeled as a random variable. An assumption in REDIM is that landing weight factor is normally distributed. Hence, users are required to specify two parameters, mean and standard deviation, to fully describe the distribution for each aircraft group for in trail separation.

Operational data:

In order to predict the landing performance of an aircraft in the Simulation Module, the landing process is segmented into 5 phases: the flare phase, the 1st free roll phase, the braking phase, the 2nd free roll phase and the turnoff phase. Among these phases, two free roll phases are the slack times between the different aircraft maneuvers. Users may specify the duration of these two phases, although we recommend the duration be at least 3 and 2 seconds, respectively. For detail design of the turnoff geometry, REDIM takes input from users on the safety factor for the impending skidding condition. The safety factor is recommended to be between 50 to 100 percent. The safety factor of 0% would generate the turnoff geometry where the aircraft is about to skid laterally.

Environmental data:

Wind conditions, airport elevation, temperature and runway orientation belong to this category. These parameters should be considered in designing runway, as they have some influence on the aircraft's landing roll performance.

Runway length and gradients:

The runway length and the effective gradients for every one tenth of runway are included in the category. The gradients have some effect in the aircraft's ground deceleration capability.

Surface conditions:

The wetness of runway surface also affects the aircraft's ground deceleration capability. REDIM requires user to input the relative frequencies of dry and wet runway surface conditions at the facility in percentage.

Type-dependent data vary depending on the analysis type, as stated earlier. For 'design' analysis, users have to specify the number of new exits, distance between the runway and taxiway, exit angle, runway/taxiway junction speed and the exit speed for each aircraft category, The number of exits and the exit speed are determinant parameters deciding the location of exits and ROT. In addition to the data required to the 'design' analysis, information on the existing exits should be entered for the 'improve' analysis. Here users enter the number of existing exits, their location, their type, their entrance speed and their utilization status. For 'Evaluate' analysis, only the data on the existing exits are required. For 'individual' analysis, users have to specify whether the surface is dry or wet and to select an aircraft type among the mix. The input/output relationships for all types of analyses are summarized in Figure 2.3.

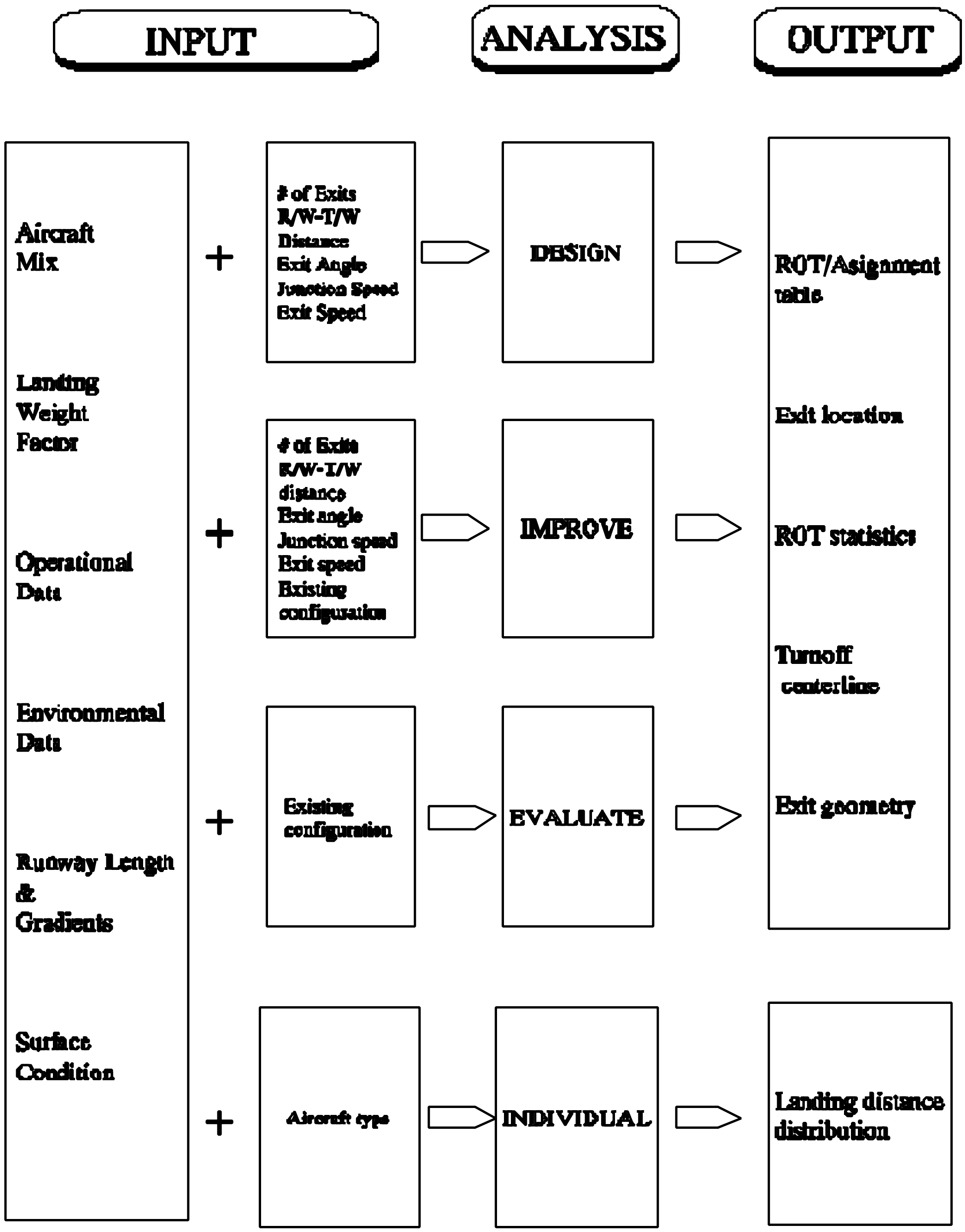


Figure 2.3 REDIM Input/Output Relationships.

III. USING REDIM

3.1 Getting Started

Users may activate REDIM by entering 'redim20' at the sub directory where 'REDIM20.EXE,' 'MASTREV.DAT,' and 'QUIN.DAT' are located. The two data files should be at the same sub directory so that REDIM can access them. The first screen users face is the title screen shown in Figure 3.1. Users enter the (working) data file name at this screen. REDIM lists all the available data files at the sub directory. If users enter a data file name among the list, REDIM opens that file. Otherwise, REDIM creates a new file containing default values. Working data files have the common extension '.REM.' The second screen is the introduction screen where a brief explanation on REDIM is given to users. Users also select the type of airport and the type of operation. The type of airport decides the default value for landing weight factors. Since there are two types of operation, users may keep two different aircraft mixes in the same data file. This screen is shown in Figure 3.2.

After the introduction screen, users face the aircraft mix screen where the proportion of each aircraft in the population mix should be specified in percentage. The default values of percentage are '0's for all aircraft. To change the percentage values, users have to:

1. Move the cursor to a intended position using 'arrow-keys' (, , and ≠) or enter-key ( ). The current position of the cursor is displayed in **gray** color.
2. Erase the existing numerical values by pressing 'backspace-key'.
3. Put new numerical value using 'number-keys' (0 to 9 and decimal point '.').
4. Repeat the above steps.

The number of aircraft selected and the sum of their percentages are displayed at the lower right corner of the screen as shown in Figure 3.3. The step 2 and 3 are effective for editing numerical values throughout REDIM.

3.2 Editing a Data File

Now, we entered the menu system described in Figure 2.2. The Main Menu always appears at the top portion of the screen, with a **red** colored item indicating the current

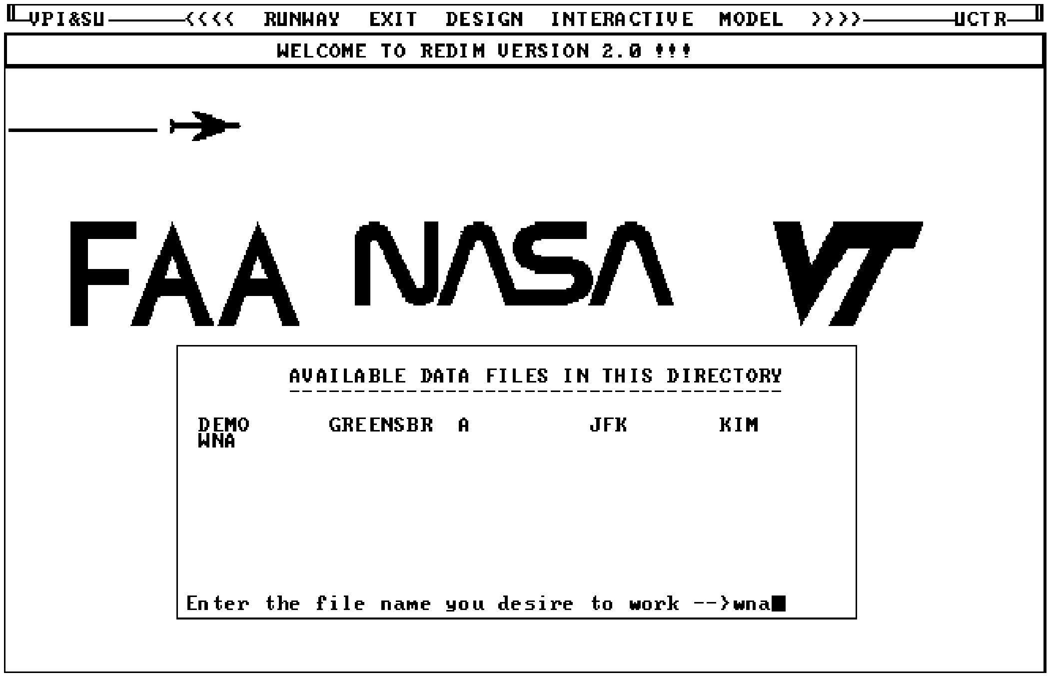


Figure 3.1 REDIM Title Screen.

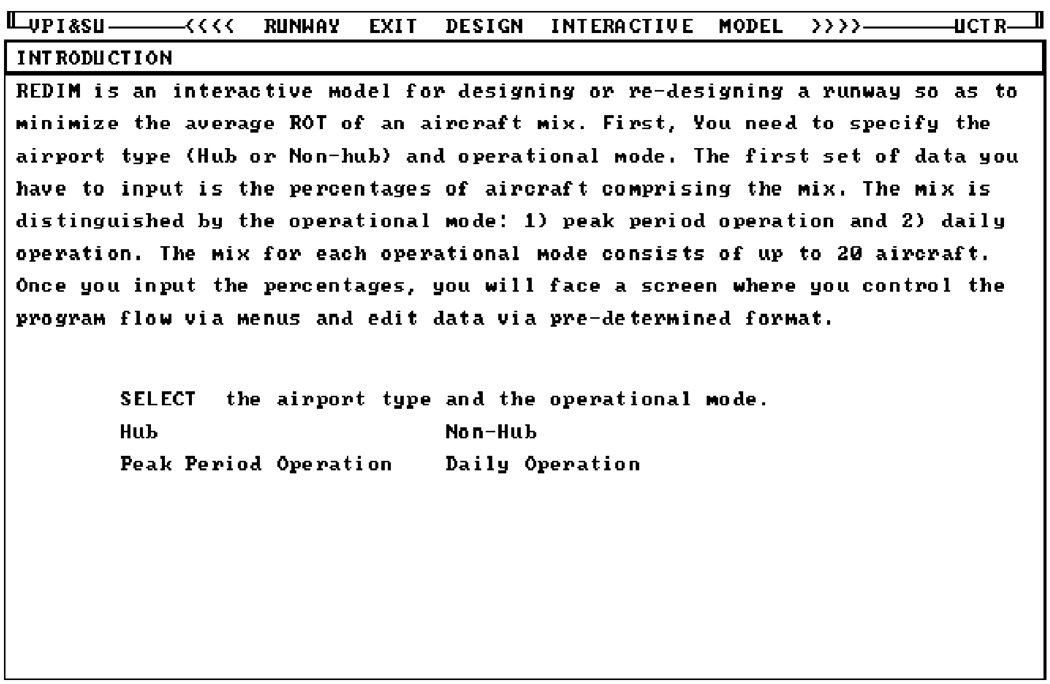


Figure 3.2 Introduction Screen.

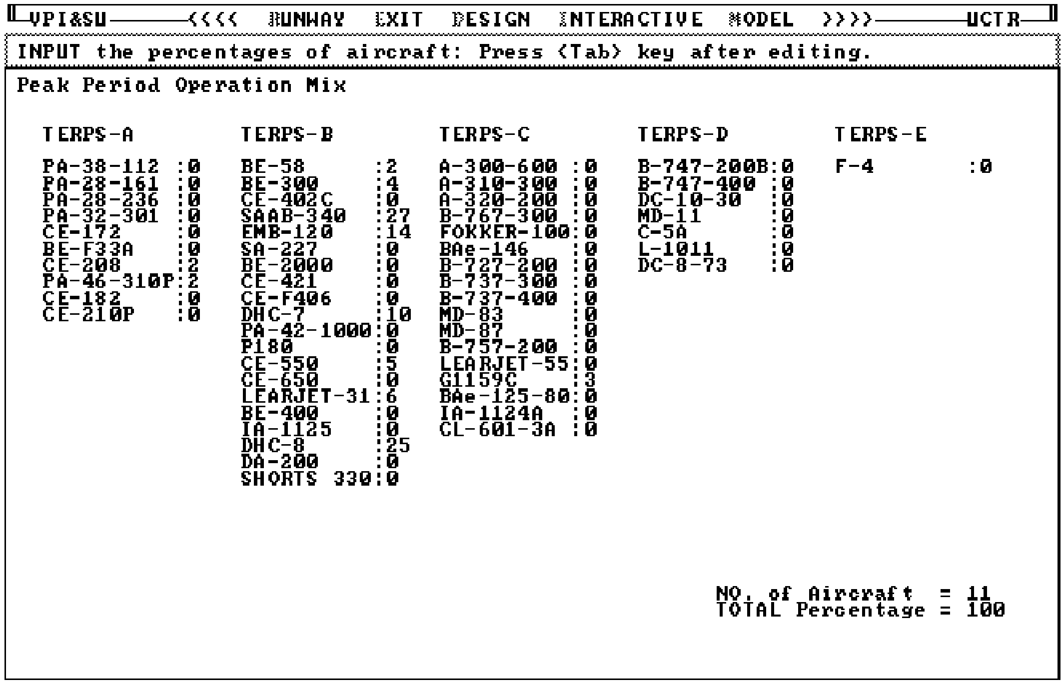


Figure 3.3 Aircraft Mix Screen.

menu choice. The sub menu which belongs to the current choice is shown in the upper left box in **white** color with a brief explanation in left. Users may change the current choice using the arrow-key. Press the 'enter-key,' when 'Edit' is **red** colored. Then, 'Edit' becomes **yellow** colored showing the path from the Main Menu to the current level in menu system and a sub menu is activated. The sub menu in 'Edit' has two choices: 'Working Data File' and "Master Data File.' The **red** colored item is the current choice, as is in Main Menu. The coloring convention remains the same throughout the menu system. That is, the red colored item is the current choice and the yellow colored item shows users' previous choices presenting the path from the Main Menu to the current menu. The 'enter-key' is used to make decision among choices, getting down to a lower level in menu system. The 'escape-key' is used to get back to a upper level whereas the arrow-keys are used to change the current selection.

In order to edit a working data file, users have to select 'Working Data File.' This activates a sub-sub menu at the bottom left box. The sub-sub menu shows the classification of type-independent data explained in Section 2.1. The selection of a class in the sub-sub menu shows data belonging to that class in the right box, while moving the cursor to the right. At this point, users are able to edit data. The convention for numerical data editing is the same as in the aircraft mix screen throughout REDIM. That is, the 'backspace-key' erases existing numbers, 'number-keys' are used to input new numbers and 'enter-key' and 'arrow-keys' moves the cursor. The **gray** colored number indicates the current position of the cursor. Figure 3.4 illustrates the screen to edit Airport Environmental Data. Users may edit type-dependent data after selecting the type of analysis to be executed.

To edit the master data file, users select 'Master Data File' from the edit menu. This will be necessary only when an aircraft of interest is not contained in the master file. The master data file can store up to 20 types of aircraft in each in trail separation category. Hence, if the aircraft type which should be added belongs to category B, the characteristics of the aircraft type should be written over an existing aircraft data set, because the data field for category B is already full. The sub-sub menu for 'Master Data File' includes 'Add an Aircraft Type' and 'Change a Specific Data' to add a complete data set for a new aircraft type or to partially change an existing aircraft data, respectively. Editing the master data file is accomplished in the following order:

1. Select an aircraft category from five aircraft categories provided on right hand side.
2. Choose an aircraft type (if changing specific data) or enter the aircraft type (if adding a new aircraft type).
3. Edit or enter the characteristics data as needed.

Figure 3.5 shows the screen for changing aircraft specific data.

3.3 Executing Analyses

In order to start the analysis process, select 'Analysis' in the Main Menu. The sub menu appearing in the upper left box shows four types of analyses: 'Design,' 'Improve,' Evaluate' and 'Individual'. After selecting a type of analysis, users may edit type-dependent data appearing at the right hand side box or initiate the analysis. The sub-sub menu in the lower left box shows the classification of the type-dependent data. For purpose of editing, select the class which should be edited from the sub-sub menu. Then, the cursor moves to the corresponding data field. The data can be edited following the numerical data editing conventions explained earlier. To initiate the analysis, choose the 'Save & Begin Analysis,'

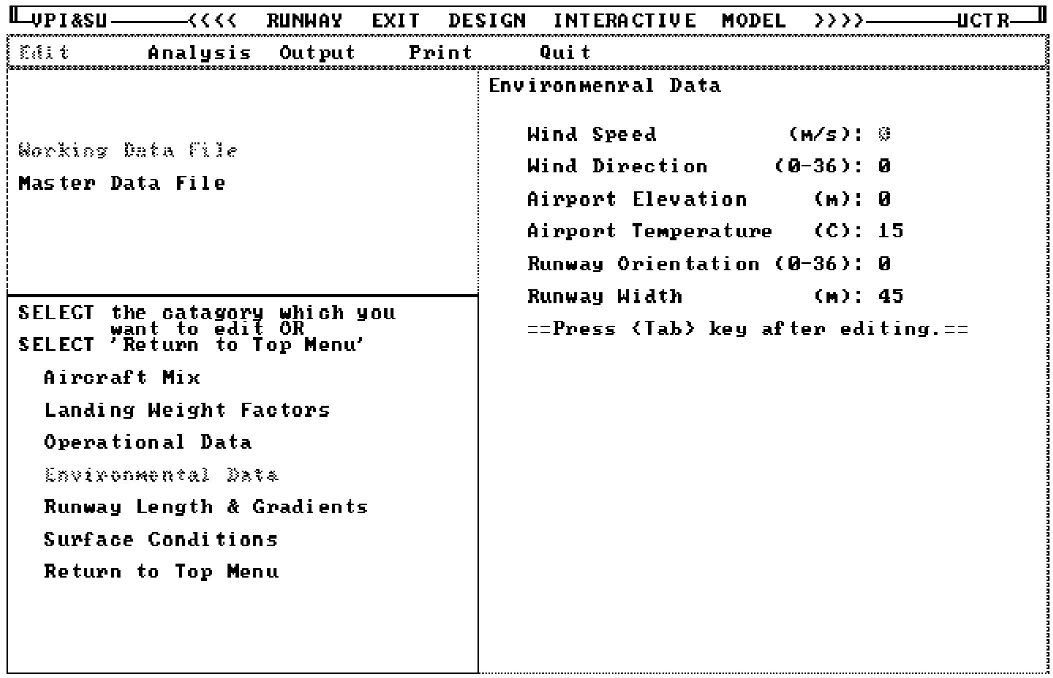


Figure 3.4 Working Data Editing Screen.

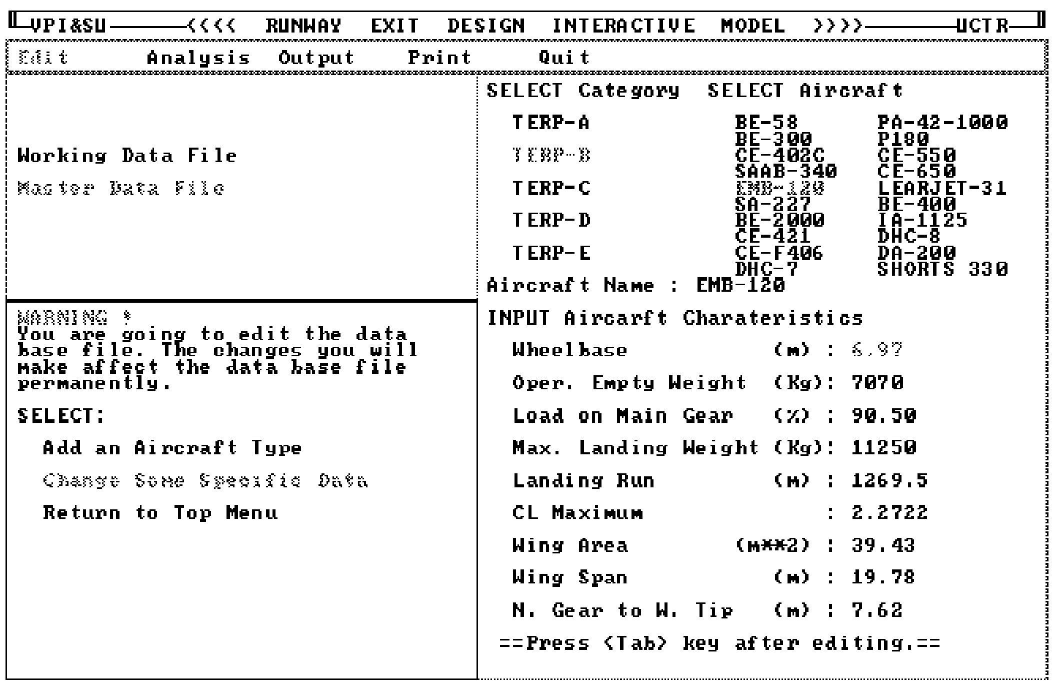


Figure 3.5 Master Data File Editing Screen.

which saves changes in type-dependent data in the working data file and asks users to enter an initial seed number. The initial seed number is required, since REDIM utilizes the

Monte Carlo technique to predict the probabilistic aircraft landing performance. Figure 3.6 shows the sub-sub menu and the type-dependent data pertinent to the 'Design' analysis. Figure 3.7 shows the prompt for initial seed number input. Figures 3.8, 3.9 and 3.10 show similar screens for 'Improve,' 'Evaluate,' and 'Individual' analyses.

blank space

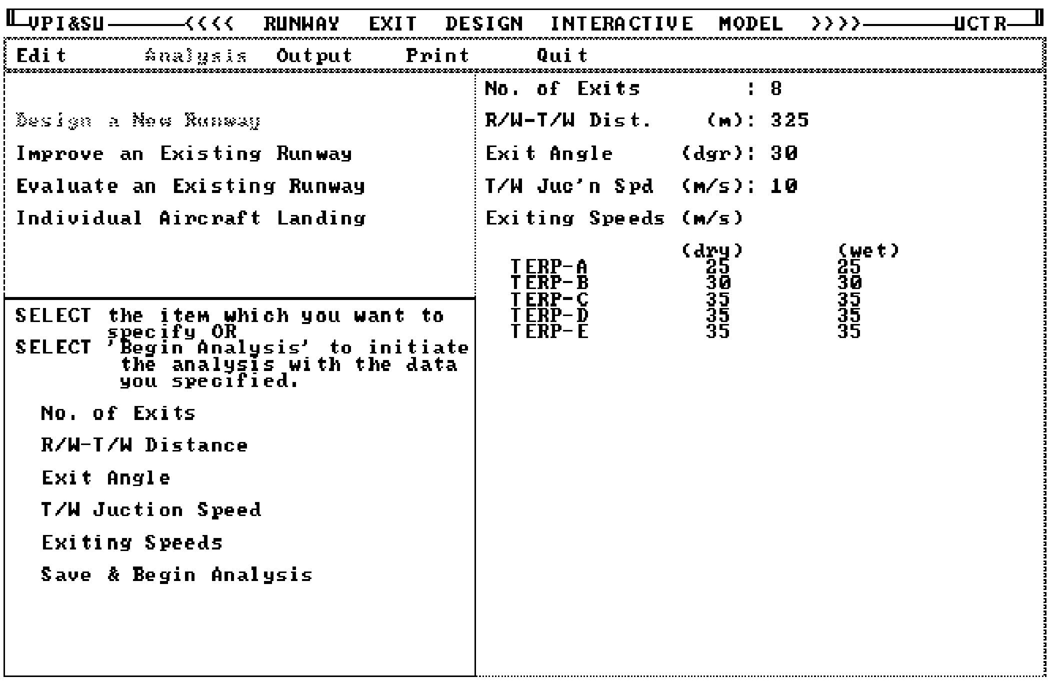


Figure 3.6 Type-dependent Data of 'Design' Analysis.

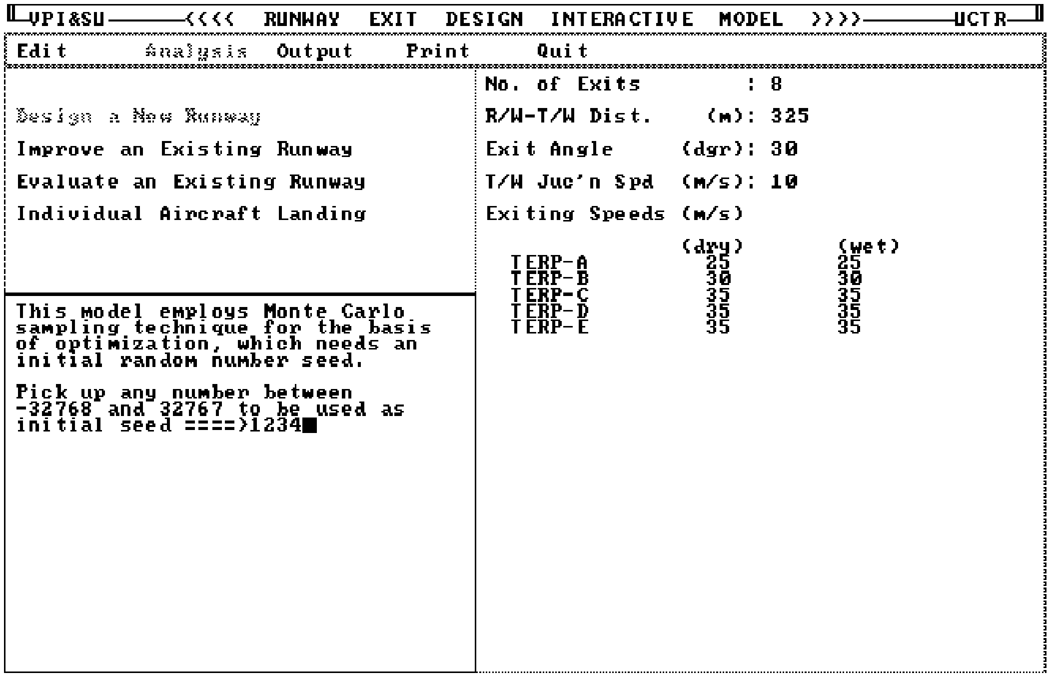


Figure 3.7 Screen for Initial Seed Number.

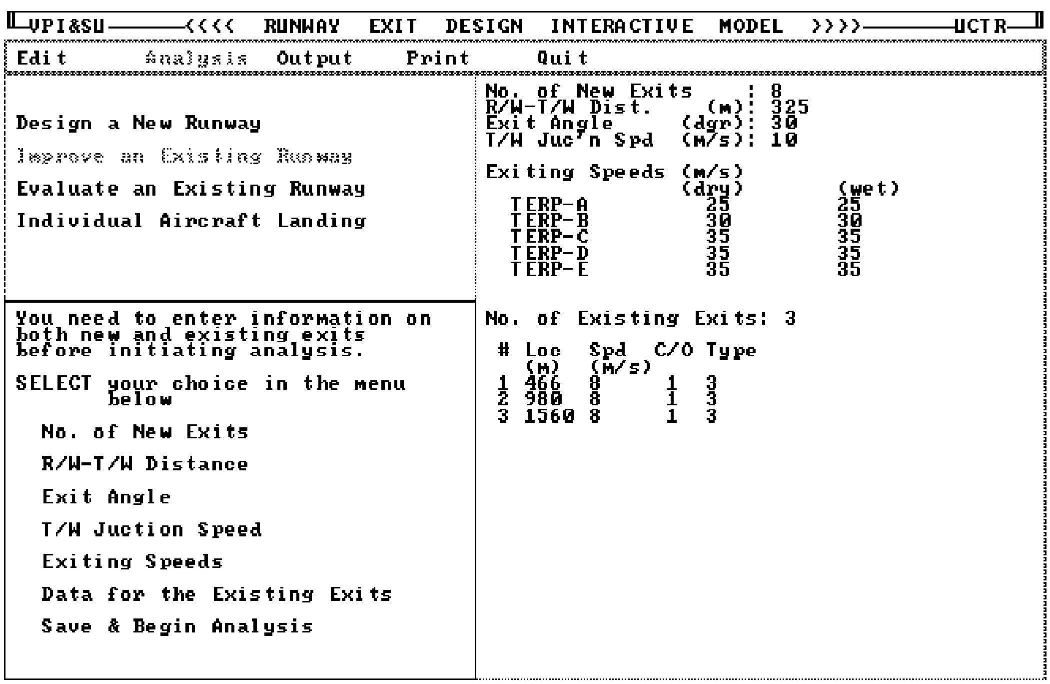


Figure 3.8 Type-dependent Data of 'Improve' Analysis.

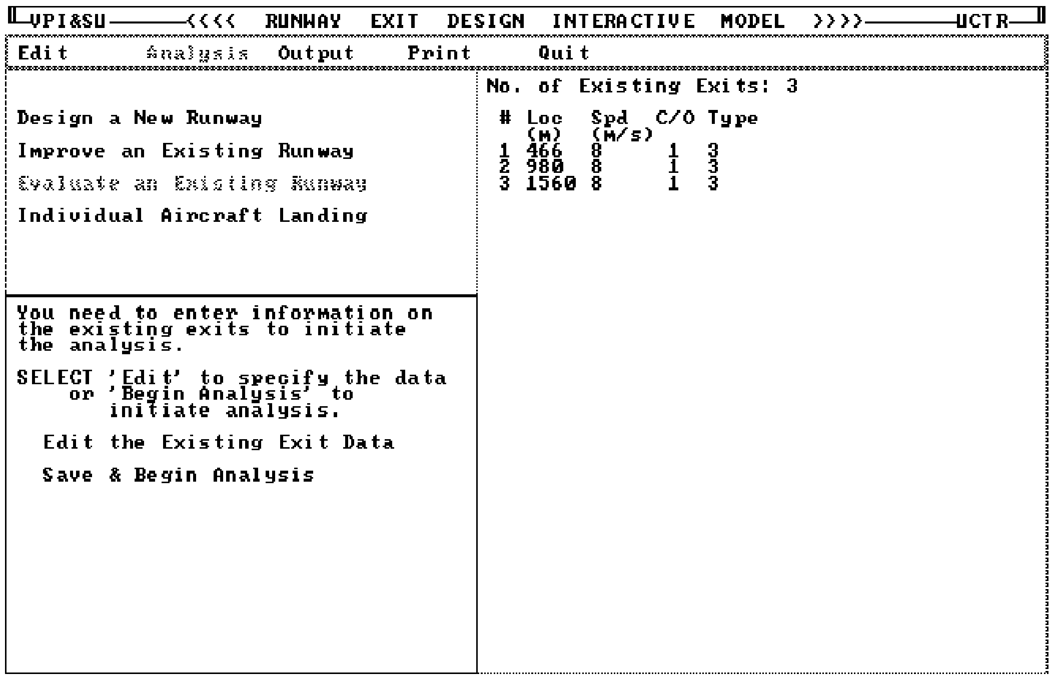


Figure 3.9 Type-dependent Data of 'Evaluate' Analysis.

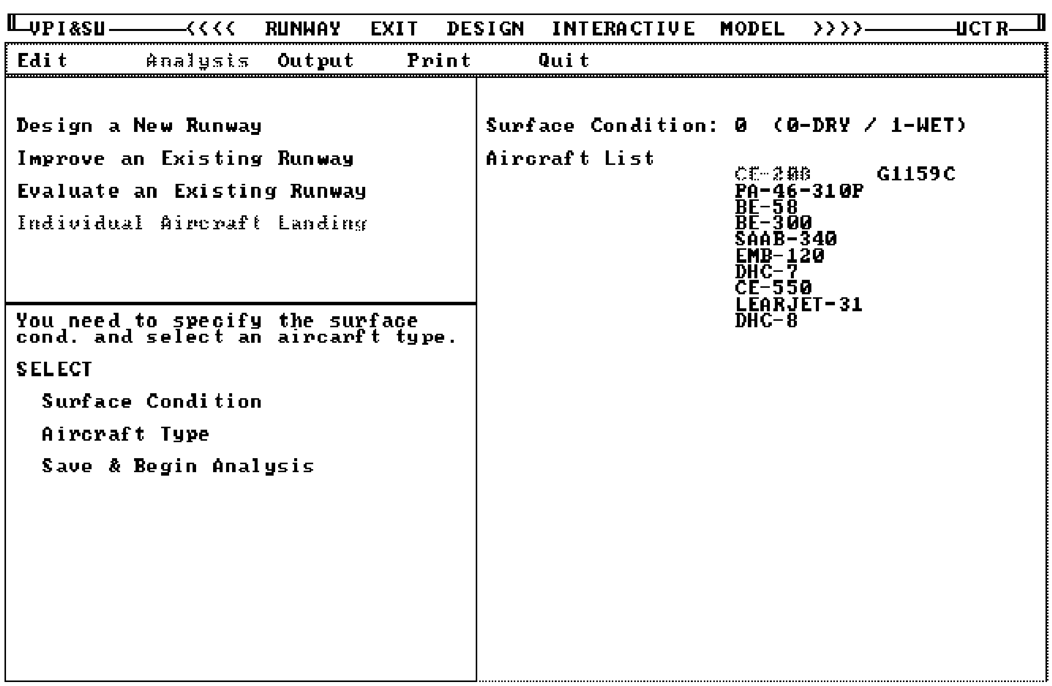


Figure 3.10 Type-dependent Data of 'Individual' Analysis.

3.4 Interpreting Output

REDIM creates an output file containing all the results of the analysis. Users may view the output just after a runway analysis or later if the output file is saved. Among the four types of analyses, the first three have the same output format. Figure 3.11 shows the Output Menu for these three analysis types. The first option in the Output Menu is the so-called ROT/Assignment table as illustrated in Figure 3.12. From this table users can extract the following information:

1. The location, type and status of both existing and new exits
2. The aircraft type and its proportion in the mix differentiated by the dry and wet surface conditions
3. Usage of exits by each aircraft type and the resultant average ROT of an aircraft type
4. The weighted average ROT (WAROT) of the mix

For example, Figure 3.12 is the ROT/Assignment table for an imaginary scenario where the 'Improvement' analysis was selected to add two new exits on a runway with three existing 90^{o} angled exits. First, it can be seen that REDIM suggests two additional exits located at 700m and 1225m from the active runway threshold. Note that lower and upper bounds are provided because of the range solution policy explained in Section 1.2. REDIM repeats the analysis process, landing data generation via simulation and optimization, five times obtaining five solutions for each exit location. Among these five solutions, take the second highest and the second lowest values as the upper and the lower bounds, respectively, to increase the robustness of the solution. The magnitude of this upper and lower bound interval ranges usually between 0 m to 100m. This approach provides users flexibility in deciding actual exit locations with similar WAROT performance. The type of exit also appears in the ROT/Assignment table as the fifth element of the table heading. REDIM accepts 5 types of standard runway exits: 90^{o}, 45^{o}, 30^{o}, modified 30^{o} with a 427 m spiral and the so-called wide throat exit. In addition, users may define a geometry using two radii of curvature, R_1, R_2, and the length of the entrance arc, L_1. High speed exit geometries generated by REDIM are designated as a variable type, 'Var.'

In Figure 3.12, the first aircraft labeled CE (Cessna Caravan) 208 uses exits 1 and 2. The probability for this aircraft to take exit 1 is 74% taking 25.3 seconds on the average under dry pavement conditions. The average ROT for the entire aircraft population mix is expected to be 46.8 seconds.

Figure 3.13 shows a typical exit location map depicting runway and taxiway configuration. Figure 3.14 shows a bar chart of ROT values for each aircraft type. Figure 3.15 plots various exit centerline geometries for comparison. Figures 3.16 and 3.17 show details of specific exits. To view these graphical outputs, users have to select 'Exit Loc'ns,' 'Turnoff CL' or 'Exit Geo.' from output menu, respectively.

Unlike other analysis types, the 'Individual' analysis has only one style of output as shown in Figure 3.18. Each curve represents a same percentile value of the aircraft landing distance and the corresponding ROT for various exit speeds. From the lower plot, it can be read that the aircraft generating the plot (EMB-120 in this case) can decelerate to 25m/s consuming less than 1127m in 90 cases out of 100 landings. In other words, if an exit suitable for 25m/s is built at 1127m, it will be able to serve 90% of this aircraft's landings.

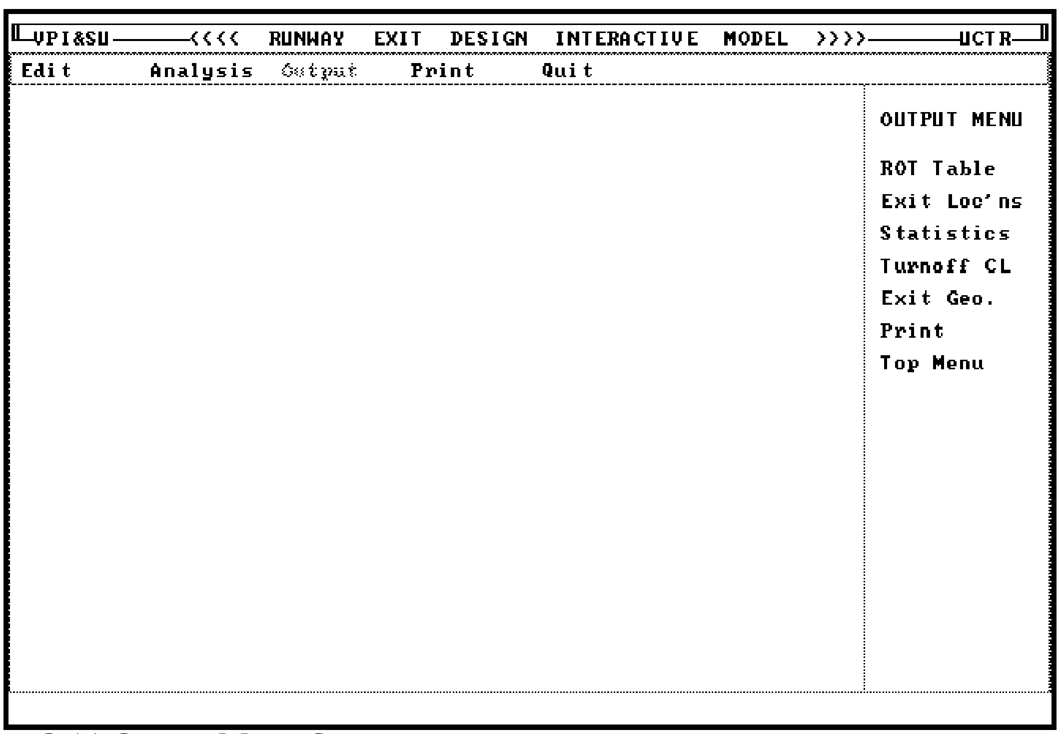
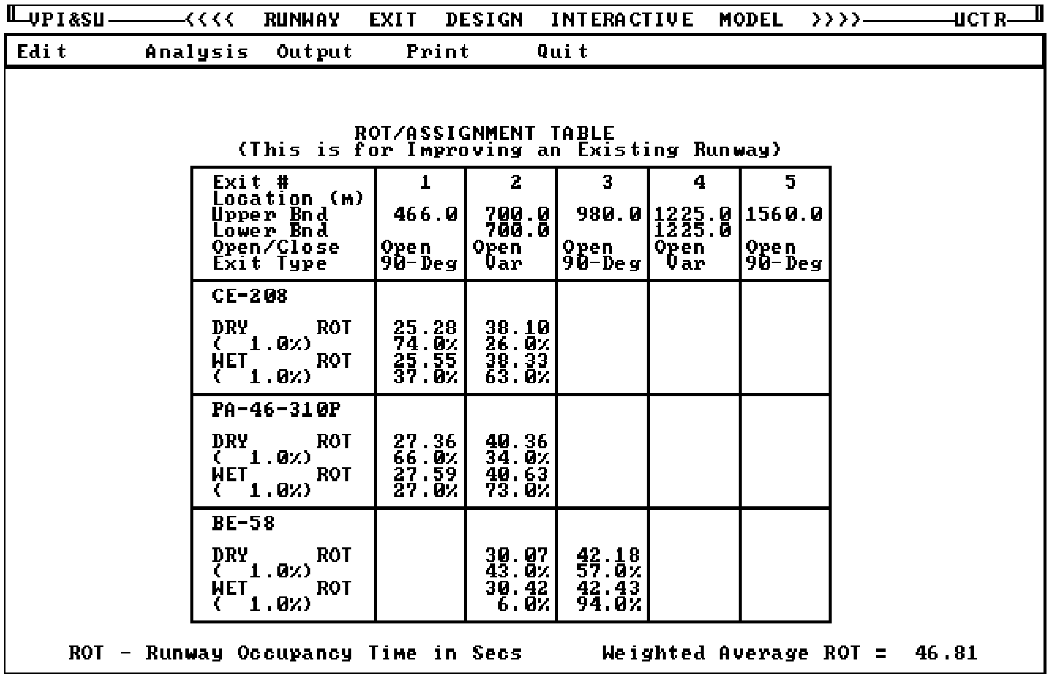
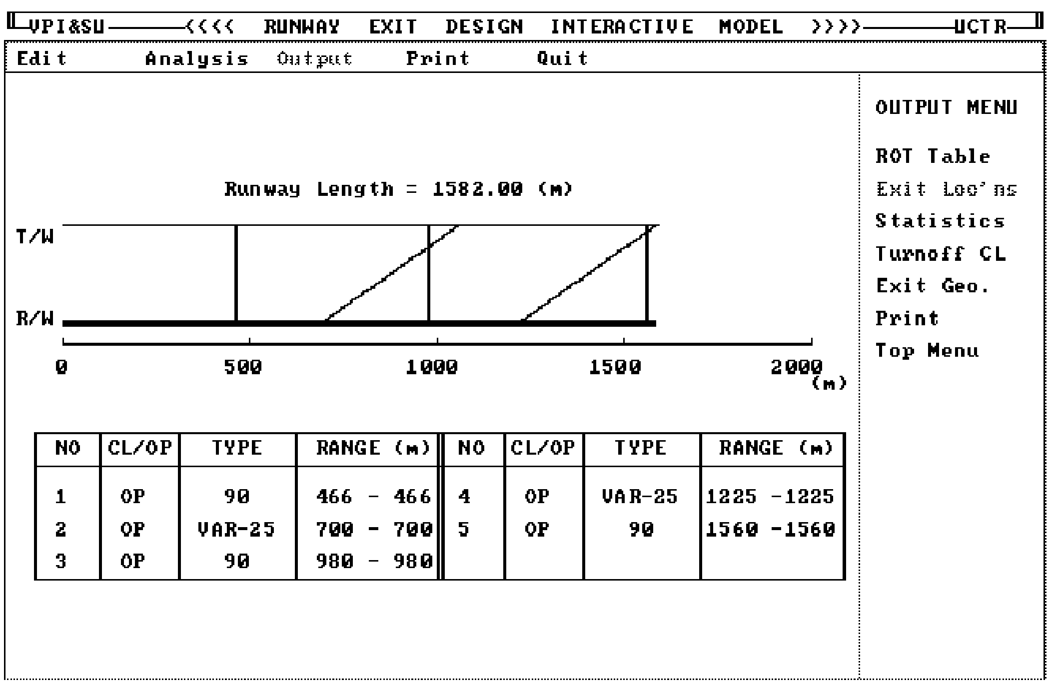


Figure 3.11 Output Menu Screen.



Exit #	1	2	3	4	5
Location (m)					
Upper Bnd	466.0	700.0	980.0	1225.0	1560.0
Lower Bnd		700.0		1225.0	
Open/Close	Open	Open	Open	Open	Open
Exit Type	90-Deg	Var	90-Deg	Var	90-Deg
CE-208					
DRY ROT	25.28	38.10			
(1.0%)	74.0%	26.0%			
WET ROT	25.55	38.33			
(1.0%)	37.0%	63.0%			
PA-46-310P					
DRY ROT	27.36	40.36			
(1.0%)	66.0%	34.0%			
WET ROT	27.59	40.63			
(1.0%)	27.0%	73.0%			
BE-58					
DRY ROT		30.07	42.18		
(1.0%)		43.0%	57.0%		
WET ROT		30.42	42.43		
(1.0%)		6.0%	94.0%		

Figure 3.12 ROT/Assignment Table.



NO	CL/OP	TYPE	RANGE (m)	NO	CL/OP	TYPE	RANGE (m)
1	OP	90	466 - 466	4	OP	VAR-25	1225 -1225
2	OP	VAR-25	700 - 700	5	OP	90	1560 -1560
3	OP	90	980 - 980				

Figure 3.13 Exit Location Map.

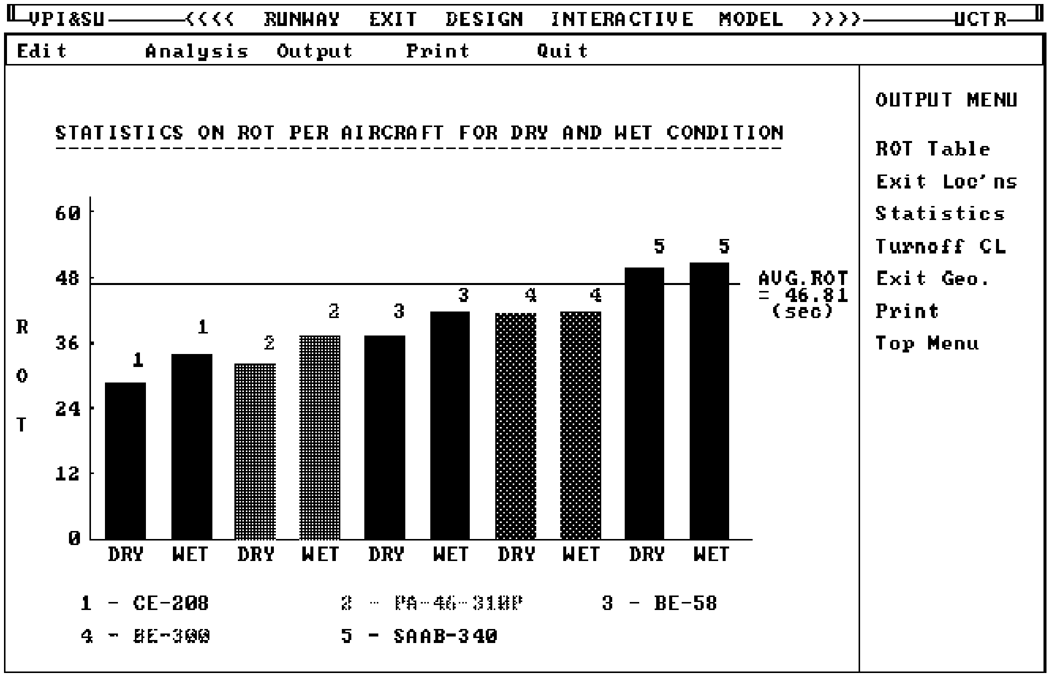


Figure 3.14 Expected Individual Aircraft ROT Value Statistics.

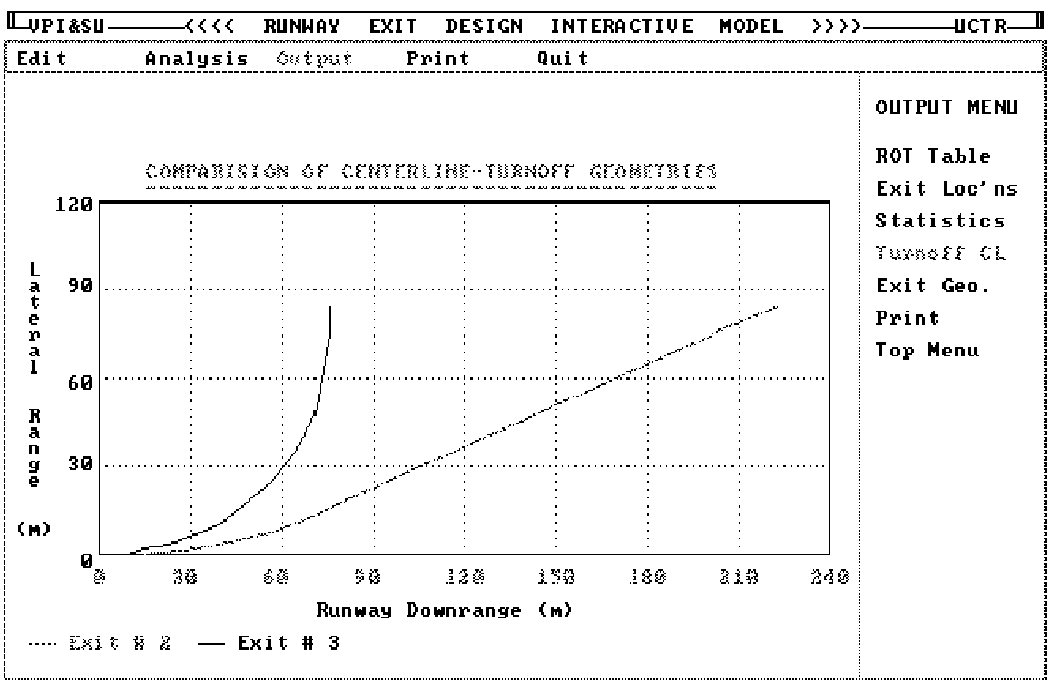


Figure 3.15 Turnoff Centerline Comparison.

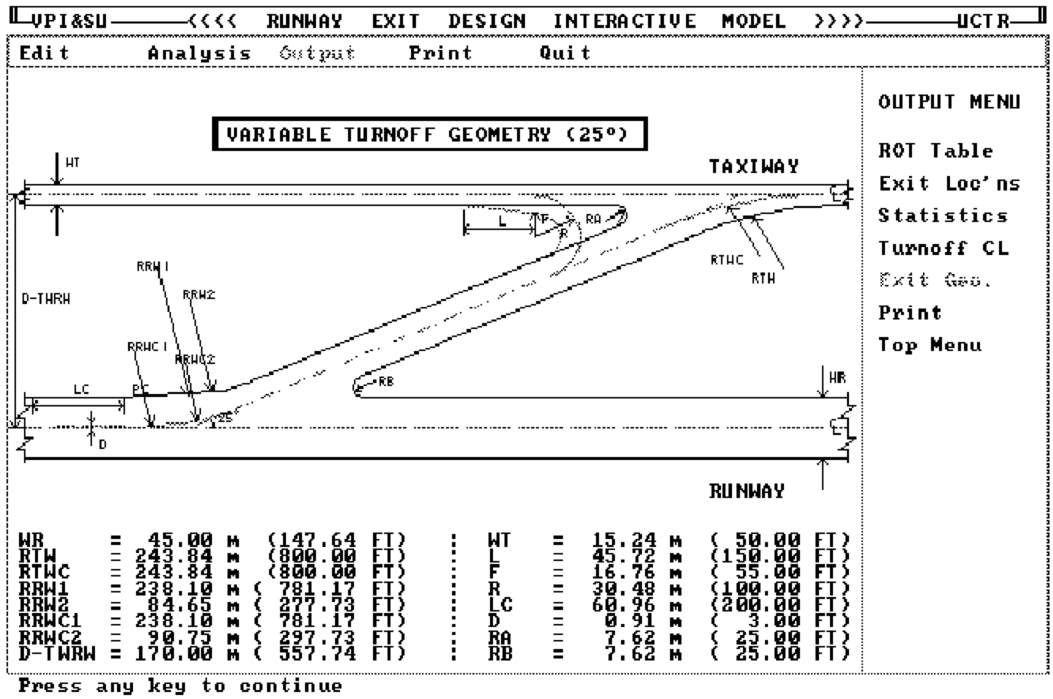


Figure 3.16 REDIM Generated Exit.

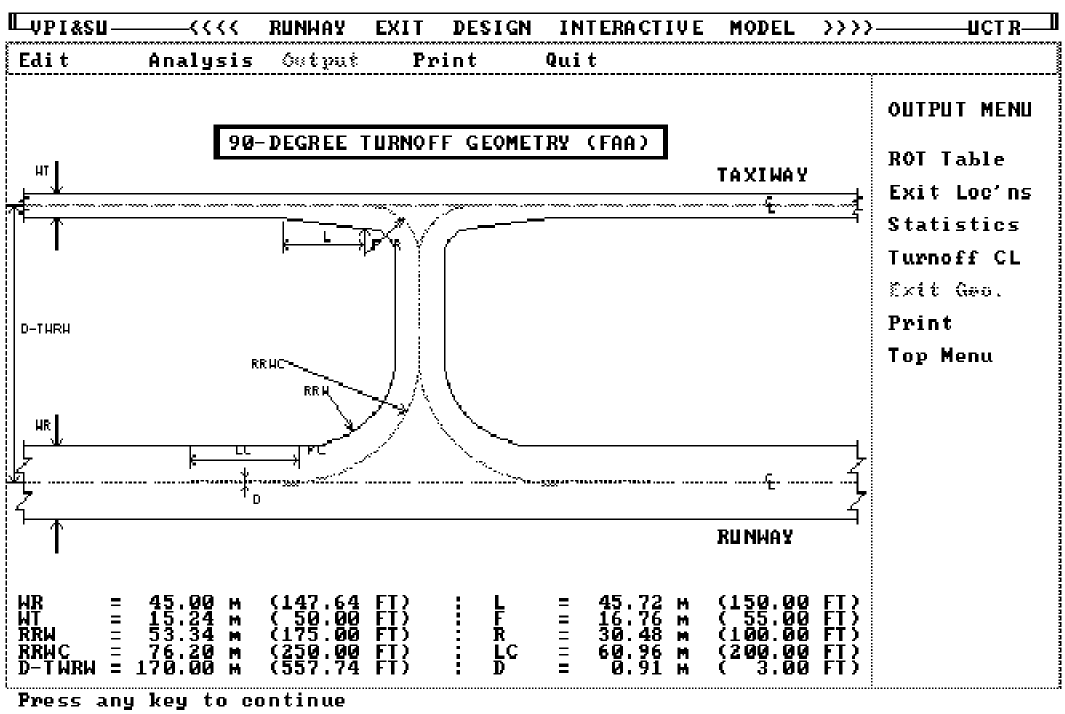


Figure 3.17 FAA Standard 90-Degree Exit.

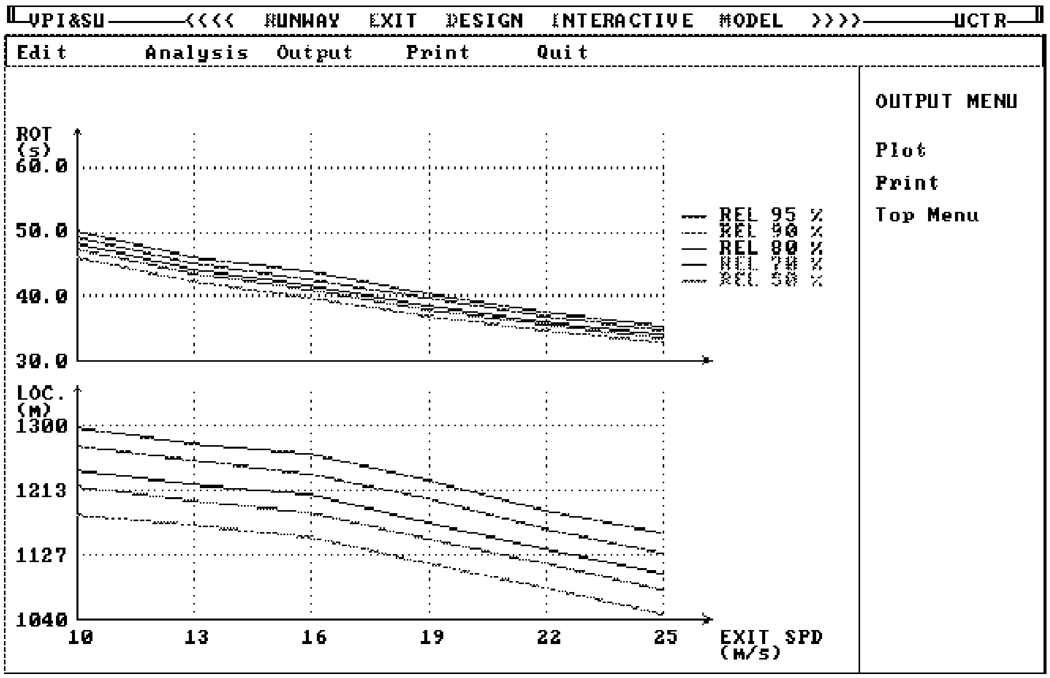


Figure 3.18 Landing Distance Distribution Plot.

IV. EXAMPLES

In this chapter, several analysis examples are presented to illustrate the application of the model. Raleigh Durham (RDU), Charlotte (CLT), Atlanta (ATL), Baltimore/Washington (BWI) and new Denver (DVX) airport were selected for illustrative purposes. For all examples, the following assumptions are made:

1. The mean and the standard deviation of landing weight factors are assumed to be 0.5 and 0.2, respectively. Empirical studies on the variations of landing weight factors reported in literature support this assumption [Credeur, 1989].
2. The first and the second free roll times are set to 3 seconds and 2 seconds, respectively. If users want more slack time, they may use larger values.
3. The safety factor for turnoff geometry design is set to 50%.
4. The wind speed is assumed 2.5 m/s (5 knots) to represent a mild headwind condition.
5. The frequencies of dry pavement and wet pavement are assumed to be same at 50% each.

4.1 RDU Airport

For RDU airport, suppose we are only interested in the performance of runway 5L-23R (refer to Figure 4.1). The first data set necessary for REDIM is the aircraft mix. FAA annually publishes 'Airport Activity Statistics' which contains the aircraft mix data for every airport serving airlines across the US [FAA, 1990]. From this book, the aircraft mix for RDU airport is found to be C-208 (1.5%), EMB-120 (2.5%), F-28 (1.5%), B-727 (47.0%), B-737 (10.0%), DC-9 (36.0%) and DC-10 (1.5%) ignoring the aircraft types comprising less than 1% of the total population.

The average elevation of the airfield is 122 m above mean sea level. The temperature is set to 30^{o}C to represent a summer day requiring higher approach speeds. Runway 5L-23R is 3050 m (10,000 ft) long and 45 m (150 ft) wide with a 0.4% uphill gradient from 5L threshold to 23R threshold. Seven exits are available for arrivals to runway 5L, located at 520 m (B3), 820 m (B4), 1290 m (B5), 1755 m (B6), 2060 m (B7), 2365 m (B8) and 2925 m (B9). Among these exits, B5, B6, B7 and B8 are constructed as a 'pseudo' wide-throat design allowing the aircraft to execute turnoffs up to 18 m/s (40 mph). Other exits are standard 90^{o} exits with an average exit speed of 8 m/s. Arrivals to runway 23R use seven exits labeled B8 to B2. The locations and types of these exits are: B8 (580 m, 90^{o}), B7 (880 m, 90^{o}), B6 (1190 m, 90^{o}), B5 (1600 m, wide-throat), B4 (2115 m, wide-throat), B3 (2420 m, wide-throat) and B2 (2965 m, 90^{o}).

A data file can be made with the data specified above. Notice that, for the aircraft mix, the Fokker F-28 and the Douglas DC-9 are substituted by F-100 and MD-83, whose characteristics are somewhat similar, respectively. If users, of course, have the complete data for those aircraft, they may edit the master data file to include more specific data. The evaluation results with initial seed number '1234' are shown in Tables 4.1 and 4.2 including the aircraft exit assignment and resultant ROT values. The difference in exit location and gradient produce a small difference in average ROT for the same aircraft mix (52.5 seconds for runway 5L and 54.0 seconds for runway 23R). Users, however, should notice that the result may be slightly different with different initial seed numbers due to the nature of the Monte Carlo simulation.

Table 4.1 Exit Utilization and ROT (RDU Runway 5L)

ROT in sec.(Usage in %)

Exit # Location Type	1 520 m 90^{o}	2 820 m 90^{o}	3 1290 m W-T	4 1755 m W-T	5 2060 m W-T	6 2365 m W-T	7 2925 m 90^{o}
C-208 D	28.6 (100%)						
C-208 W	28.6 (100%)						
EMB120 D			54.0 (99%)	66.1 (1%)			
EMB120 W			53.2 (99%)	66.1 (1%)			
F-100 D		36.4 (1%)	48.8 (99%)				
F-100 W			49.1 (96%)	59.9 (4%)			
B-727 D			49.1 (81%)	60.6 (19%)			
B-727 W			50.1 (41%)	60.6(59%)			
B-737 D			48.8 (99%)	59.1 (1%)			
B-737 W			48.9 (95%)	59.8(5%)			
MD-83 D			49.4 (86%)	59.5 (14%)			
MD-83 W			50.0 (56%)	60.6 (44%)			
DC-10 D			49.9 (73%)	60.9 (27%)			
DC-10 W			50.4 (14%)	61.4 (86%)			
Average ROT = 52.5 Seconds							

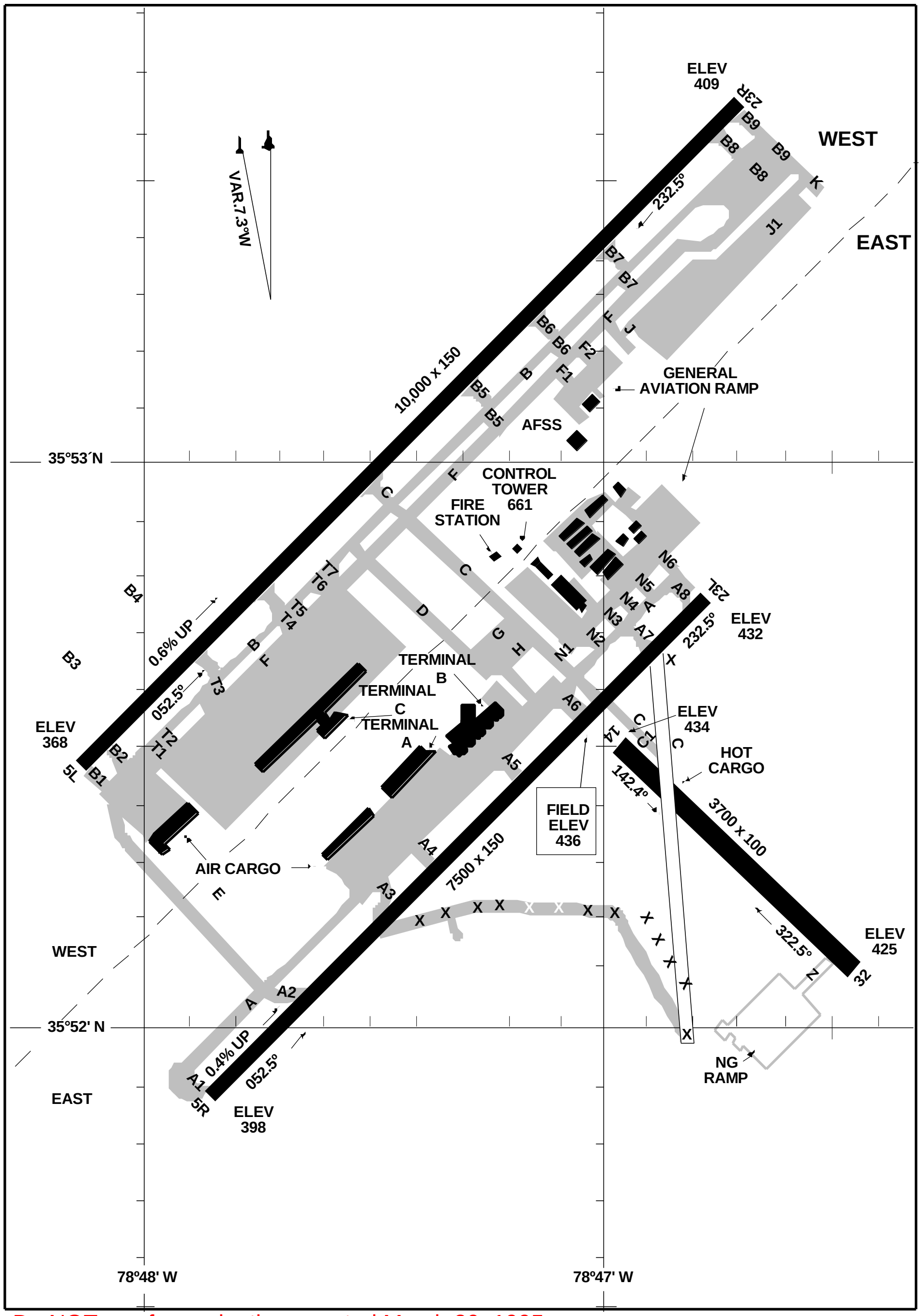


Figure 4.1 Airport Diagram of Raleigh Durham Airport (Adopted from FAA, 1989)

Table 4.2 Exit Utilization and ROT (RDU Runway 23R)

ROT in sec.(Usage in %)

Exit # Location Type	1 580 m 90º	2 880 m 90º	3 1190 m W-T	4 1600 m W-T	5 2115 m W-T	6 2420 m W-T	7 2925 m 90º
C-208 D	31.1 (100%)						
C-208 W	31.1 (100%)						
EMB120 D		40.9 (2%)	49.7 (93%)	61.9 (5%)			
EMB120 W			50.4 (57%)	63.3 (43%)			
F-100 D		38.3 (3%)	44.7 (89%)	55.8 (8%)			
F-100 W			46.1 (63%)	56.5 (37%)			
B-727 D			46.4 (27%)	57.0 (73%)			
B-727 W			48.0 (5%)	57.2 (94%)	68.2 (1%)		
B-737 D			44.9 (89%)	55.6 (11%)			
B-737 W			46.2 (42%)	56.6(58%)			
MD-83 D			46.4 (41%)	56.7 (59%)			
MD-83 W			48.2 (10%)	57.4 (88%)	68.9 (2%)		
DC-10 D			48.1 (16%)	57.7 (84%)			
DC-10 W				57.4 (94%)	69.4 (6%)		
	Average	ROT =	54.0	Seconds			

4.2 CLT Airport

Here, we analyze runway 23 at Charlotte Douglas International airport. The aircraft mix for CLT airport was found to be B-727 (16.5%), B737 (43%), B767 (1%), DC-9 (19%) and F-28 (20.5). The average airfield elevation is 220 m. Runway 23 is 2300 m long with a 0.5% down gradient and has three 90 degree angled exits located at 900 m, 1490 m and 2230m. Other input data are assumed to be the same as those of RDU airport. Table 4.3 shows the evaluation results for CLT runway 23 with baseline value of WAROT of 53.5 seconds.

For the same aircraft mix, the average ROT will be reduced to 48.7 seconds if two high speed exits are added to the runway at [1175 m - 1250m] and 1700 m as shown in Table 4.4. The exit speed for new exits are set to 20 m/s since the available space parallel to the runway is only 122 m.

Table 4.3 Exit Utilization and ROT (CLT Runway 23)
ROT in sec.(Usage in %)

Exit # Location Type	1 900 m 90^{o}	2 1490 m 90^{o}	3 2230 m 90^{o}
F-100 D	38.5 (2%)	52.2 (98%)	
F-100 W		52.9 (99%)	70.9 (1%)
B-727 D		53.0 (100%)	
B-727 W		54.3 (82%)	71.6 (18%)
B-737 D	39.3 (2%)	52.1 (98%)	
B-737 W		52.9 (99%)	69.9 (1%)
B-767 D		54.2 (94%)	71.4 (6%)
B-767 W		55.5 (44%)	72.7 (52%)
MD-83 D		53.0 (98%)	69.6 (2%)
MD-83 W		54.1 (84%)	71.2 (16%)
Average	ROT =	53.5	seconds

Table 4.4 Exit Utilization and ROT (CLT Runway 23, Improvement Scenario)
ROT in sec.(Usage in %)

Exit # Location Type	1 900 m 90^{o}	2 1200 m Var.	3 1490 m 90^{o}	4 1700 m Var.	5 2230 m 90^{o}
F-100 D	38.6 (1%)	47.2 (97%)	51.1 (2%)		
F-100 W		47.1 (91%)	51.7 (9%)		
B-727 D		47.7 (69%)	52.4 (30%)	58.1 (1%)	
B-727 W		48.3 (33%)	53.6 (41%)	58.6 (26%)	
B-737 D	39.5 (3%)	47.1 (94%)	51.2 (3%)		
B-737 W		47.0 (84%)	51.8 (16%)		
B-767 D		48.8 (46%)	53.9 (45%)	59.7 (9%)	
B-767 W		49.5 (7%)	55.7 (43%)	59.4 (46%)	72.5 (4%)
MD-83 D		47.4 (78%)	51.7 (21%)	56.4 (1%)	
MD-83 W		48.3 (31%)	53.4 (48%)	57.6 (20%)	70.2 (1%)
	Average	ROT =	48.7	seconds	

4.3 ATL Airport

Runway 8L of ATL airport has three exits located at 1435 m, 1880 m and 2600 m. The first and second exits are 30^{o} angled and the last one is a 90^{o} angled exit. The standard 30^{o} angled exit geometry is designed to accommodate aircraft exiting up to 26.7 m/s. However, for this analysis 25 m/s is considered as the maximum exit speed for the exits to account the lateral distance to the parallel taxiway, 152 m (500 ft). The aircraft mix for ATL airport consists of B-727 (23.5%), B-737 (7%), B-757 (10.5%), B-767 (5%), DC-9 (48.5%), L-1011 (4%) and A-300 (1.5). The average elevation of airfield is 305 m above mean sea level. Other data are set to be same as RDU airport. Table 4.5 shows the baseline evaluation results and Table 4.6 shows the improved ROT with one additional exit designed for 25 m/s. For the same aircraft mix in ATL airport, the average ROT will be reduced to 42.4 seconds if a high speed exit is added to the runway at any location between 1175 m and 1225 m.

Table 4.5 Exit Utilization and ROT (ATL Runway 8L)
ROT in sec.(Usage in %)

Exit # Location Type	1 1435 m 30º	2 1880 m 30º	3 2600 m 90º
B-727 D	45.5 (100%)		
B-727 W	45.7 (94%)	55.3 (6%)	
B-737 D	45.7 (100%)		
B-737 W	45.5 (99%)	54.3 (1%)	
B-757 D	46.4 (100%)		
B-757 W	46.2 (100%)		
B-767 D	46.0 (96%)	54.7 (4%)	
B-767 W	45.9 (75%)	56.0 (25%)	
MD-83 D	45.9 (99%)	54.6 (1%)	
MD-83 W	45.8 (96%)	54.7 (4%)	
L-1011 D	45.0 (97%)	54.1 (3%)	
L-1011 W	44.6 (61%)	54.7 (39%)	
A-300 D	46.1 (100%)		
A-300 W	45.9 (93%)	55.7(7%)	
Average	ROT =	46.1	seconds

Table 4.6 Exit Utilization and ROT (ATL Runway 8L, Improvement Scenario)
ROT in sec.(Usage in %)

Exit # Location Type	1 1200 m Var.	2 1435 m 30º	3 1880 m 30º	4 2600 m 90º
B-727 D	39.9 (79%)	44.7 (21%)		
B-727 W	40.4 (27%)	44.9 (67%)	55.1 (6%)	
B-737 D	39.8 (99%)	43.8 (1%)		
B-737 W	39.9 (84%)	43.4 (16%)		
B-757 D	40.6 (97%)	44.5 (3%)		
B-757 W	40.8 (67%)	44.9 (27%)	55.1 (6%)	
B-767 D	40.6 (52%)	44.9 (45%)	55.3 (3%)	
B-767 W	41.7 (15%)	45.6 (61%)	55.7 (24%)	
MD-83 D	40.0 (79%)	44.0 (21%)		
MD-83 W	40.8 (44%)	44.7 (48%)	54.3 (8%)	
L-1011 D	39.6 (40%)	44.2 (56%)	54.3 (4%)	
L-1011 W	39.9 (12%)	44.6 (59%)	54.9 (29%)	
A-300 D	40.4 (81%)	44.7 (18%)	55.3 (1%)	
A-300 W	41.0 (37%)	45.4 (52%)	55.8(11%)	
	Average	ROT =	42.4	seconds

The difference in the average ROT in ATL airport and CLT airport is mostly attributed to the exit types and their exit speeds as aircraft have to stay longer on the runway to decelerate to appropriate speed to negotiate 90° angled exits.

4.4 BWI Airport

Runway 28 of BWI airport has five exits located at 950 m, 1220 m, 1440 m, 2230 m and 2735 m, among which the first and the third are crossing runways used as exits for arrivals to runway 28 (refer to Fig. 4.3 to see the complete airport configuration). The third exit resembles a 45° angled exit whose design exit speed is set to 20 m/s and the others are similar to 90° exit whose design exit speed is 8 m/s. The aircraft mix for BWI airport consists of B-727 (17%), B-737 (36.5%), B-757 (1%), B-767 (1.5%), DC-9 (31%) and Fokker 100 (13%). The average elevation of airfield is 40 m above sea level. The remaining data are set to as those of RDU airport.

Table 4.7 shows the baseline evaluation results. Readers may wonder why ROT values for the second exit are greater than the third exit located at further downrange for every aircraft type. The reasons are: 1) Aircraft using the second exit have to decelerate to 8 m/s while the others have to decelerate to only 20 m/s, which implies the average ground speed for second exit is lower than that for the third. 2) Turnoff time for 90° angled exit is greater than that for 45° angled exit. For example, the average landing run time of B-727 using the second exit is 34.2 seconds and turnoff time for the exit is 12.8 seconds; the resultant ROT is 47.0 seconds, while the average landing run time using the third exit is 35.7 seconds and turnoff time for the exit is 8.6 seconds; the resultant ROT is 44.3 seconds.

The conclusion is that the average ROT heavily depends on the design exit speed as well as the exit location. The intelligent use of high speed exits would yield some gain in WAROT.

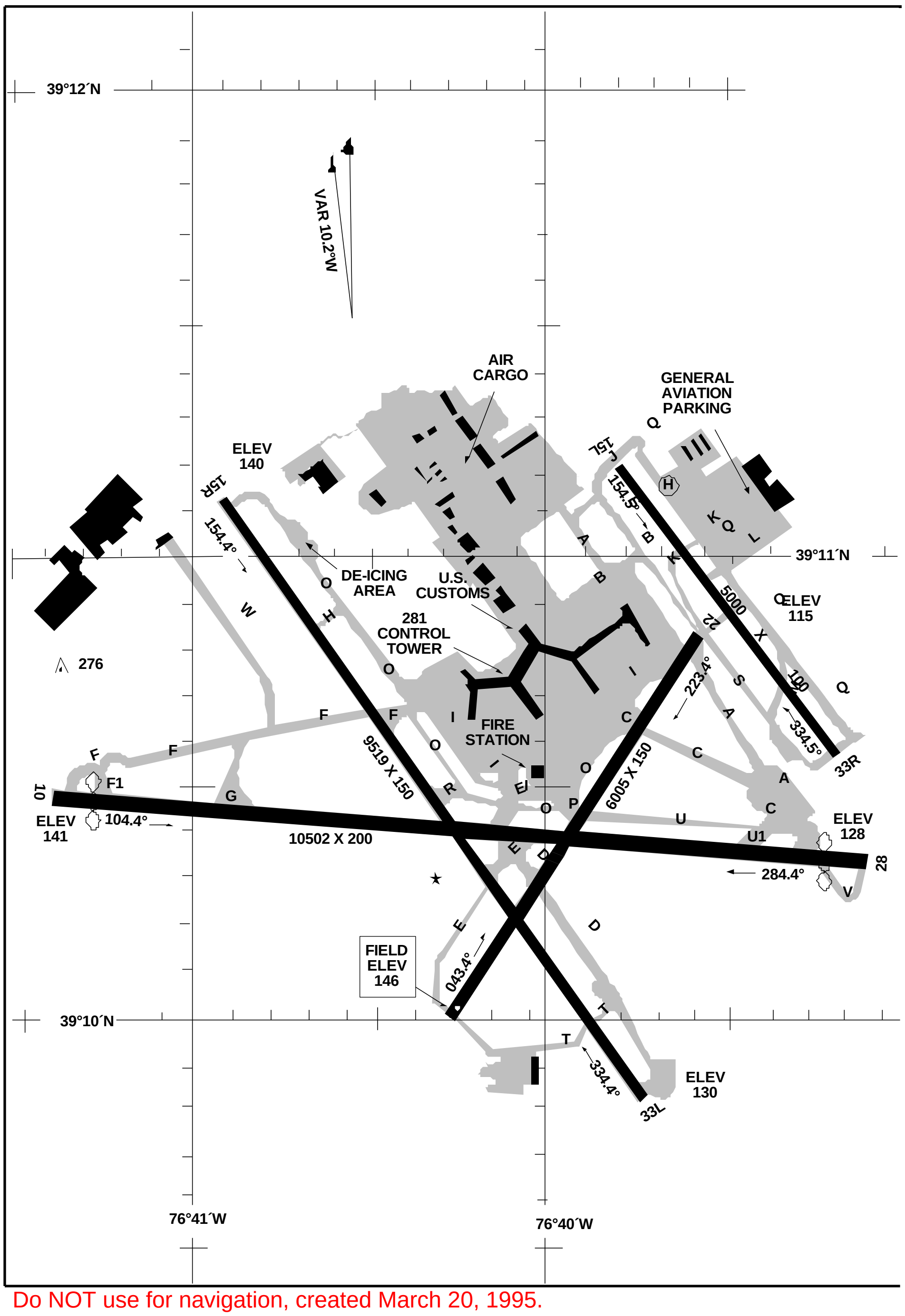


Figure 4.3 Airport Diagram of Baltimore Washington Airport (Adopted from FAA, 1989)

Table 4.7 Exit Utilization and ROT (BWI Runway 28)

ROT in sec.(Usage in %)

Exit # Location Type	1 950 m 90º	2 1220 m 90º	3 1440 m 45º	4 2230 m 90º	5 2735 m 90º
B-727 D		47.0 (40%)	44.3 (60%)		
B-727 W		48.6 (11%)	44.8 (81%)	71.6 (8%)	
B-737 D	40.0 (6%)	45.5 (86%)	43.8 (8%)		
B-737 W		46.8 (62%)	43.6 (37%)	70.1 (1%)	
B-757 D	40.9 (2%)	47.3 (78%)	44.2 (20%)		
B-757 W		48.6 (32%)	45.1 (67%)	72.2 (1%)	
B-767 D		48.5 (22%)	44.5 (73%)	71.3 (5%)	
B-767 W		49.7 (3%)	44.7 (63%)	72.8 (34.0)	
MD-83 D		47.1 (55%)	44.2 (44%)	70.1 (1%)	
MD-83 W	43.6 (1%)	48.9 (17%)	44.5 (76%)	71.1 (6%)	
F-100 D	39.8 (11%)	45.6 (85%)	42.9 (4%)		
F-100 W	41.1 (1%)	46.5 (68%)	44.5 (31%)		
	Average	ROT =	46.0	seconds	

Now, suppose we want to improve the performance of this runway. One way to do so is adding a new high speed exit as we did in previous examples. However, this is questionable in this example, because the new exit should be placed somewhere between the third and fourth exits (remind that there is a restriction on the distance between two neighboring exits: minimum 189 m). If an exit is built between the third and fourth exits, only some of aircraft currently using the fourth exit will get benefit by using the new exit. REDIM recommends 1700 m as the location of this exit lowering the average ROT to 45.5 seconds (a very small 0.5 second gain).

Another way to reduce ROT is to change the geometry of the second exit to accommodate higher exit speeds. This method seems plausible because the majority of the aircraft mix uses the second exit and some of existing pavement can be used for the new geometry. By making the second exit a 45º angled exit with 20 m/s exit speed, the average ROT decreases to 40.9 seconds. Table 4.8 shows the results of this design alteration.

Table 4.8 Exit Utilization and ROT (BWI Runway 28: Design Alteration)
ROT in sec.(Usage in %)

Exit # Location Type	1 950 m 90°	2 1220 m 45°	3 1440 m 45°	4 2230 m 90°	5 2735 m 90°
B-727 D		38.9 (71%)	43.5 (28%)	70.0 (1%)	
B-727 W		39.5 (32%)	44.0 (60%)	71.3 (8%)	
B-737 D	40.4 (9%)	38.7 (88%)	43.0 (3%)		
B-737 W		38.8 (78%)	43.0 (22%)		
B-757 D	41.8 (1%)	39.5 (84%)	43.9 (15%)		
B-757 W		39.8 (63%)	44.6 (37%)		
B-767 D		39.2 (49%)	43.7 (50%)	72.0 (1%)	
B-767 W		40.7 (8%)	44.8 (59%)	73.3 (33.0)	
MD-83 D		39.1 (73%)	43.5 (27%)		
MD-83 W		39.8 (42%)	44.2 (53%)	71.7 (5%)	
F-100 D	40.1 (12%)	39.2 (88%)			
F-100 W	41.4 (1%)	38.9 (89%)	43.5 (10%)		
	Average	ROT =	40.9	seconds	

4.5 New Denver (DVX) Airport

It is interesting to investigate how much ROT can be lowered with optimally located high speed exits. For this analysis, DVX airport, scheduled to be opened in November 1993, is selected. This airport will have six runways by September 1995. Each runway will be about 3500 m long. The aircraft mix is assumed to be the same as same as that of the existing DEN airport which consists of C-208 (1.5%), CV-580 (1.5%), BAe-146 (1.5%), B-727 (30.5%), B-737 (37%), B-757 (2.5%), B-767 (1%), DC-8 (2%), DC-9 (17.5%), DC-10 (4%) and A-300 (1%). CV-580 is substituted by a category B aircraft, EMB-120, representing commuter aircraft operating at this facility.

Suppose three high speed exits with 25 m/s design exit speed will be built on the runway in addition to a 90° angled exit at the end of the runway. REDIM recommends [1125 m - 1225 m], [1350 m - 1425 m] and [1675 m - 1800m] as the optimal ranges for the exits, resulting in WAROT of 42.8 seconds. Table 4.9 shows the exit utilization and individual aircraft ROT values with these optimally located exits. If four high speed exits are built, WAROT will be 41.8 seconds. By comparing WAROT values of three exit scenario and four exit scenario, it is found that adding more exits will not be paid off. Another way to reduce ROT further is to increase the design exit speed. With four high speed exits designed for 30 m/s exit speed, WAROT of 38.0 seconds is possible.

Table 4.9 Exit Utilization and ROT (DVX airport)

ROT in sec.(Usage in %)

Exit # Location Type	1 1200 m Var	2 1400 m Var	3 1750 m Var	4 3450 m 90^{o}
C-208 D	53.9 (100%)			
C-208 W	53.8 (100%)			
EMB120 D	41.0 (99%)	45.5 (1%)		
EMB120 W	41.1 (81%)	46.0 (19%)		
BAe146 D	41.8 (100%)			
BAe146 W	41.6 (100%)			
B-727 D	41.0 (74%)	44.5 (26%)		
B-727 W	41.4 (34%)	45.1 (53%)	53.3 (13%)	
B-737 D	40.2 (98%)	43.2 (2%)		
B-737 W	40.4 (76%)	43.6 (24%)		
B-757 D	41.3 (93%)	44.7 (7%)		
B-757 W	41.5 (56%)	45.1 (43%)	52.8 (1%)	
B-767 D	41.5 (40%)	45.2 (49%)	53.9 (2%)	
B-767 W	42.2 (8%)	46.2 (49%)	54.1 (43%)	
MD-83 D	41.1 (68%)	44.3 (31%)	52.7 (1%)	
MD-83 W	41.8 (44%)	45.0 (48%)	52.7 (8%)	
DC-10 D	41.8 (40%)	45.3 (59%)	53.8 (1%)	
DC-10 W	42.1 (11%)	45.9 (61%)	54.1 (28%)	
DC-8 D	43.5 (6%)	47.6 (50%)	56.5 (43%)	158 (1%)
DC-8 W		48.7 (10%)	56.8 (88%)	155 (2%)
A-300 D	41.4 (74%)	45.2 (24%)	53.2 (2%)	
A-300 W	41.9 (33%)	45.3 (55%)	53.7 (12%)	
	Average	ROT =	42.8	seconds