AN INVESTIGATION OF CAPACITY AND DELAY OF RUNWAY CONFIGURATIONS USING THE SIMMOD SIMULATION MODEL

by

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1.0 INTRODUCTION

1.1 Background

Aviation delays are on the rise as a consequence of disproportionate growth of the air transportation demand. According to the Federal Aviation Administration (FAA) in fiscal year 1987, U.S. commercial air carriers enplaned a total of 444.3 million passengers. Of this total, 415.0 million were counted as domestic enplanements and 29.3 million as international enplanements [FAA, 1988a]. Over the 12-year forecast period, domestic enplanements are forecast to increase by an average annual rate of 4.6 percent, totalling 713.7 million in 1999 as shown in Fig. 1.1 [FAA, 1988a]. Aviation Week & Space Technology [Aviation Week & Space Technology, 1989] estimated the air travel demands would built
FIG. 1.1 U.S. Commercial Air Carriers Scheduled Passenger Enplanements

Source: FAA 1988
up from 416 billion passengers revenue miles flown in 1988 to 
an 750 billion passenger revenue miles by 1999 with a 6% 
average growth rate. As these increases in air travel demand 
take place the level of delays seen today will correspondingly 
increase thus reducing the levels of service offered to the 
average passenger. The Federal Aviation Administration 
[FAA,1989f] concluded that 21 U.S. major airports had exceeded 
20,000 hours of airline flight delays in 1987. The FAA also 
forecasted that the number of airports which could exceed 
20,000 hours of annual aircraft delay would be projected to 
grow from 21 to 39, unless capacity improvements are made.

From the economical point of view, current statistics show 
that approximately three billion dollars are paid by air 
travelers due to the delay in U.S. alone[ Aviation Week & 
Space Technology, 1989]. Therefore, proper actions are 
required to identify and facilitate a reduction in flight 
delays and prevent their projected growth. According to the 
FAA these actions include [FAA,1989f]:

- Airport development
- Airspace development and new airspace procedures
- New technology
- Marketplace Solutions
1.2 Capacity, Demand and Delay

As demand approaches capacity, individual aircraft delay is increased. Successive hourly demands exceeding the hourly capacity result in unacceptable delays. When the hourly demand is less than the hourly capacity, aircraft delays will still occur if the demand within a portion of the time interval exceeds the capacity during that interval. Because the magnitude and scheduling of user demand is relatively unconstrained, reductions in aircraft delay can best achieved through airport improvements which increase capacity [FAA,1983].

Robert Horonjeff and Francis X. Mekelvey [Horonjeff and Mckelvey, 1983] pointed out several factors that affect hourly capacity of an airfield some being more significant than others. In general, capacity depends on the airfield configuration, the environment in which aircraft operate, the availability of aids to navigation and air traffic control facilities, and the airport landside characteristics. A more detailed list of specific factors is given in Table 1.1.
TABLE 1.1 Important Factors that Affect Hourly Capacity of Runway

Source: Adopted from Horonjeff and Mckelvey, 1983

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>1.</td>
<td>The configuration, number, spacing, and orientation of the runway system</td>
</tr>
<tr>
<td>2.</td>
<td>the configuration, size, and location of taxiways and runway exits</td>
</tr>
<tr>
<td>3.</td>
<td>The arrangement, size, and number of gates in the apron area</td>
</tr>
<tr>
<td>4.</td>
<td>The runway occupancy time for arriving and departing aircraft</td>
</tr>
<tr>
<td>5.</td>
<td>The size and mix of aircraft using the facilities</td>
</tr>
<tr>
<td>6.</td>
<td>Weather, particularly visibility and ceiling, since air traffic rules are different in good weather than in bad weather</td>
</tr>
<tr>
<td>7.</td>
<td>Wind conditions which may preclude the use of all available runways by all aircraft</td>
</tr>
<tr>
<td>8.</td>
<td>Noise abatement procedures which may limit the type and timing of operations on the available runways</td>
</tr>
<tr>
<td>9.</td>
<td>Within the constraints of wind and noise abatement, the strategy epoch the controllers choose to operate the runway system</td>
</tr>
<tr>
<td>10.</td>
<td>The number of arrivals relative to the number of departures</td>
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<tr>
<td>11.</td>
<td>The number and frequency of touch-and-go operations by general aviation aircraft</td>
</tr>
<tr>
<td>12.</td>
<td>The existence and frequency of occurrence of wake vortices which require greater separations when a light aircraft follows a heavy aircraft than when a heavy aircraft follows a light one</td>
</tr>
<tr>
<td>13.</td>
<td>The existence and nature of navigational aids</td>
</tr>
<tr>
<td>14.</td>
<td>The availability and structure of airspace for establishing arrival and departure routes</td>
</tr>
<tr>
<td>15.</td>
<td>The nature and extent of the air traffic control facilities</td>
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</table>
1.3 Project Scope

Among the factors previously mentioned some can be controlled and considered to improve the airport capacity with proper planning. One obvious solution to the problem of delay, is to increase the capacity of hub area either by adding new runways to an existing airport, or by building new reliever airports near the more congested terminal areas. Since these measures would require the airport sponsor to buy large tracts of land they usually represent expensive undertakings. Yet the former alternative is the most sound economically as some major airports have some room to expand. In fact the new airport capacity enhancement plan calls for 50 new runways to be added to the top 100 airports by the year 1996 [FAA, 1989f]. On the other hand even if the sponsoring airport authorities could purchase the necessary land to built new airport facilities there would undoubtedly be strong community objections to the potential environmental problems associated with the operation of the airport [Lucas, 1983]. Proof of this are the strict noise abatement procedures adopted at several airports in California. Thus new runway configurations are desired to ameliorate these problems.
1.4 Project Objectives and Approach

The primary objective of this project is to analyze the runway capacity and delay of a "Fanway" runway configuration developed by Mr. Ernest W. Millen while at NASA Langley Research Center [Millen, 1979]. The performance of this novel runway configuration was compared to that of "dual-lane" and single runway using the SIMMOD computer simulation model.

The Fanway concept consists of two or three intersecting, diverging runways with a single touchdown zone as an intersection point. This configuration was evaluated by William E. Lucas, III in 1983 using the Delay Simulation Model (DSM), a first generation airport delay prediction model. According to Lucas' conclusions the fanway configuration compared favorably with a conventional parallel runway configuration at Denver's Stapleton Airport and, in fact, achieved greater service rates than their conventional counter parts (i.e. single and dual configurations) for both VFR and IFR scenarios [Lucas, 1983].

Several deficiencies of the ADSIM model have been addressed with the introduction of a more sophisticated airport and
airspace simulation model "SIMMOD" developed by CACI Products Inc. and the office of operations research at the Federal Aviation Administration and the intend of this project is to evaluate this promising configuration using SIMMOD and point out some of the air traffic control (ATC) and pilot operational constraints of the Fanway concept neglected in the previous study. This new computer simulation model has received strong support by FAA, local airport planning and private industry. Several capacity analysis efforts have been undertaken successfully with the model. Several reports including the California Air Traffic Project have shown that the SIMMOD model is a valuable tool for use in identifying, evaluating, and analyzing operational alternatives for increasing capacity and reducing delay in the National Airspace System [FAA, 1988b].

Thus the final goals of this project are as follows:
1. Airport capacity and aircraft delay comparison analysis of three different type runway configurations (Fanway, parallel and single) by using the newly developed computer simulation model "SIMMOD".
2. To see the advantages and disadvantages of Fanway runway concepts.
3. Each runway configuration sensitivity analysis is based on the different aircraft approach diagonal separation distance
between 2.0 NM and 1.5 NM.

4. Evaluate the merit of SIMMOD model as a tool for airport capacity and delay analysis model.

5. Comparison of the analysis results between the values obtained with by SIMMOD model and hand calculations.

Horonjeff and Mckelvey [Horonjeff and Mckelvey, 1983] point out that "the analysis of capacity and delay by computer simulation models are extremely useful for studying complex systems which cannot be represented by equations. But an important point to remember is that the prime justification for using computer simulation is to reduced the differences between the real world and the abstract world of the model. If the input data required for the model are not very detailed, the results may not be any better than the results obtained from an analytical model of lesser complexity". Thus in order to reduce the gap between the real world and SIMMOD simulation model condition, first an understanding of the simulation model itself is required.

Because this project focused in the capacity and delay comparison of three different types of runway configurations, the same airspace and airport conditions were required and only the airfield configurations module needed modifications to explore general results influence by different main taxiway
length and number or terminal gate number and location, the main taxiway and gate conditions require the same conditions. Thus the Fanway configuration was used as baseline scenario and then modified parallel taxiways and make one gate for large amount of aircraft. Next, the parallel runway and single runway can be created by modifying the existing Fanway configuration slightly.

The comparison of each runway configuration was made possible by overlaying the average delay vs. number of operations in a single graph. At least four data points were obtained to determine the shape of the delay curves modifying the number of aircraft operations for two diagonal separation scenarios (Diagonal separation here is interpreted as the physical separation in the air between two consecutive arrivals). For this purpose five simulation scenarios were considered as shown:

1. Fanway 2.0 NM separation: 6 cases
2. Fanway 1.5 NM separation: 6 cases
3. Parallel runway 2.0 NM separation: 6 cases
4. parallel runway 1.5 NM separation: 6 cases
5. Single runway : 4 cases (No diagonal separation)
2.0 FANWAY CONCEPT

2.1 Background of Fanway

According to the NASA's disclosure of invention document, the Fanway concept was developed by Mr. Ernest W. Millen in 1979 when he was employee of National Aeronautics and Space Administration (NASA) as an aerospace engineer [Millen, 1979].

The conceptual development of the Fanway configuration was based primarily on the performance of the Microwave Landing System (MLS), which allows curved approach paths and an improvement in navigational accuracy. Even though the
Instrument Landing System (ILS) is still the standard navigational aid used, the new Microwave Landing System is considered to provide many advantages to the pilots and operators. The main difference between the MLS and ILS is the type of transmitting signal. The ILS system uses a fixed beam signal that requires the aircraft to approach the runway with following the single alignment, but the MLS system uses the scanning beam that provides guidance over a much larger spectrum of airspace. The scanning beam not only provides continuous distance measurements, but also let the aircraft to approach the runway in varying approach angles [Lucas, 1983].

Besides the MLS, there are other considerations that influenced the development of the Fanway concept. One of these considerations was based on the fact that NASA's Terminal Configured Vehicle (TCV) program has set 40 second inter-arrival time, which in effect is 90 landings per hour per runway, could result in runway occupancy times becoming a constraint to the overall airport system [Lucas, 1983].

The other consideration is the limitation and disadvantage of high level braking and high speed exit. The high level braking decelerations after touchdown could be used to enable aircraft to quickly exit the runway using existing turnoffs, but brake wear and brake replacement costs would then increase.
by significant levels. The high speed exits that have large turning radii and small angles was considered as an alternative to high braking decelerations, but these high speed exits have not proved to be popular with either pilots and the airline passengers [Lucas, 1983].

Thus the Fanway configuration was proposed as an alternate means of improving airport capacity that would be safe and more cost efficient [Lucas, 1983].

2.2 Fanway Geometric Design

There are three different types of Fanways can be considered for the Fanway geometric design as below [Millen, 1979]:

1. Basic Fanway: One-way single Fanway, Two-way Fanway
2. Two-Fan modules Fanway
3. Simplex Fanway airport system

The One-way single Fanway as shown in Figure 2.1 is the basic design configuration of Fanway. The single Fanway consists of three runways that are aligned with the prevailing wind
Fig. 2.1 One-way Single Fanway

Source: Millen, 1979
Fig. 2.2 Two-Fan Modules Fanway

Source: Millen, 1979
direction and intersect at near the landing touchdown zone. As shown in Figure 2.2, addition of another Fanway module that is oriented with a reciprocal image of the first module will increase the number of airport operations whenever the wind is approximately 180 degrees opposite the normal prevailing wind direction [Lucas, 1983]. If more runways are desired, the basic two-way Fanway module may be modified through the addition of one or two runways to the right or left side of the basic configuration depending on the airport land availability.

2.3 Evaluation of Fanway

Lucas [Lucas, 1983] points out the advantages and weaknesses of the Fanway concept as follows:

1. Advantages
   - Runway occupancy times will not become a constraint on practical minimum arrival times
   - Landing capacity will be increased and delays reduced if 30 to 40 second inter-arrival times are attained
   - Simple, straight rollouts enable aircraft to decelerate
safely without requiring high speed turns. These rollouts can be utilized under all runway and visibility conditions.

- Environmental (noise) and wake vortex problems could be reduced
- Airport real estate requirements are diminished
- Aircraft maintenance costs (e.g., brakes) are reduced
- Pilot work loads are simplified by providing dedicated taxi routes which require reduced controller to pilot communication.

2. Weakness points

- A thorough and comprehensive inquiry must be conducted on all aspects that relate to aircraft safety (both airside and groundside)
- Economic studies should be conducted to determine the benefits and costs that would be associated with modifying existing airports into simplex airports
- A cost analysis should be conducted to determine the tradeoff between the Fanway's saving of overall airport real estate and its higher runway pavement requirements
- The Fanway concept will be controversial because aircraft owners, airport operators, passengers, and traffic controllers will be unfamiliar with its premises
- The continued delay of MLS installation and operation will cause uncertainty about usage of curved approach patterns at major airports.
3.0 REVIEW OF AIRPORT SIMULATION MODELS

3.1 Mathematical Models

Airport researchers, engineers and planners have developed and used various mathematical models to represent and analyze several components of the National Airspace System. An analytical model solution is based on sets of mathematical relationships, while a fast-time, computer is required for simulation models [Lucas, 1983]. Horonjeff and Mckelvey (Horonjeff and Mckelvey, 1983) also described that "models is confined to the airfield which is composed of the runways,
taxiways, and apron areas are also used to analyze "Capacity and delay have been used extensively. These models are often referred to as mathematical models. The mathematical models of airport operations are tools for understanding the important parameters that influence the operation of systems and for investigating specific interactions in systems that are of particular interest. Depending upon the complexity of the system, a large number of conditions may be studied, perhaps more cheaply and quickly than by other methods. To make the mathematics tractable for a complex system, many simplifying assumptions must often be made, which may result in unrealistic answers. In such a case one can resort to a computer simulation model or some other technique. Thus it is necessary, when contemplating the formulation and application of a mathematical model, to examine critically the correspondence between the real world being studied and the abstract world of the model, and to determine the effect of their differences on the decisions to be made."

In 1948 Bowen and Pearcey [Bowen and Pearcey, 1948] made an empirical study of aircraft arriving at the Kingsford-Smith Airport in Sydney Australia and found that arrivals could be satisfactorily described by the Poisson probability distribution. Since flights on civil airlines are scheduled, one would intuitively suspect that aircraft arrivals are
regular; however it was found that the difference between the expected and actual times of arrival was large and that the process was more random than regular [Bowen and Pearcey, 1948]. Assuming Poisson arrivals and constant service times, Bowen and Pearcey derived an equation for average (steady state) landing delay:

$$\bar{w} = \frac{\rho}{2\mu(1-\rho)}$$

(1)

where $\rho = \text{the load factor} = \frac{\lambda}{\mu}$

$\lambda = \text{arrival rate (aircraft/unit time)}$

$\mu = \text{service rate (aircraft/unit time)} = \frac{1}{b}$

$b = \text{mean service time}$

In a more general form, this equation is known as the Pollaczek Khinchin formula [Ashford and Wright 1979]:

$$\bar{w} = \frac{\rho(1 + C_b^2)}{2\mu(1 - \rho)}$$

(2)

where $C_b = \text{coefficient of variation of service time} = \frac{\sigma_b}{b}$

$\sigma_b = \text{standard deviation of service time}$

These equations can also be applied to runways serving departures only. A more complicated formula has been developed
to calculate the average delay to departures in mixed operations. Although analytical equations such as these help us to understand delay-capacity relationships, they do not provide accurate estimates of average delay, except for extremely simple situations. The equations have at least two major shortcomings:

1. They account for the effects of only a few of the many factors known to influence runway capacity and delays.
2. They give "steady state" solutions.

In 1960 the FAA contracted the Airborne Instruments Laboratory to develop mathematical models for estimating the runway capacity [FAA, 1963]. These models rely on steady-state queuing theory. Essentially there are two type models, one for runways serving either arrivals or departures and the other for runways serving mixed operations. For runways used exclusively for arrivals or departures the model is that of a simple Poisson-type queue with a first-come, first-served discipline. In the mixed operations arrival have priority over departures for the use of the runways. The takeoff demand process is assumed to follow a Poisson distribution; however, the landing process at the end of the runway is not Poisson but more like the output of an airborne queuing system. It was recognized that steady-state conditions are rarely achieved at
airports. However, it was argued that time-dependent solutions, although possible, were quite complex and were out of the question for the large number of situations required for a capacity handbook. Additional support for the use of situations came from observations which showed that average delay times yielded by the models were in general agreement with measured delays under a wide variety of operating conditions [Horonjeff and Mckelvey, 1983].

Horonjeff and Mckelvey [Horonjeff and Mckelvey, 1983] introduced a mathematical formulation for delay-related capacity. The calculation of delay for runway used exclusively by arrivals may be computed from the following equation:

\[ W_a = \frac{\lambda_a (\sigma_a^2 1/\mu_a^2)}{2 (1 - \lambda_a / \mu_a)} \]  

(3)

where  
\( W_a = \) mean delay to arriving aircraft, time units  
\( \lambda_a = \) mean arrival rate, aircraft per unit of time  
\( \mu_a = \) mean service rate for arrivals, aircraft per unit of time, or reciprocal of mean service time  
\( \sigma_a = \) standard deviation of mean service time of arriving aircraft

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They also pointed out that "the mean service time may be the runway occupancy time or the time separation in the air immediately adjacent to the runway, whichever value is the largest. The model for departures is identical to that for arrivals, except for a change in subscripts." The following equation is therefore used for the departure delay:

\[ W_d = \frac{\lambda_d (\sigma_d^2 + 1/\mu_d^2)}{2(1 - \lambda_d/\mu_d)} \]  

(4)

where \( W_d \) = mean delay to departing aircraft, time units
\( \lambda_d \) = mean departure rate, aircraft per unit of time
\( \mu_d \) = mean service rate for departures, aircraft per unit of time, or reciprocal of mean service time
\( \sigma_d \) = standard deviation of mean service time of departing aircraft

For mixed operations, arriving aircraft are given priority, and the delay to these aircraft is given by the arrivals equation, Eq.(3). However, the average delay to departures can be found from the following equation:

\[ W_d = \frac{\lambda_d (\sigma_j^2 + j^2)}{2(1 - \lambda_d j)} + \frac{g(\sigma_f^2 + f^2)}{2(1 - \lambda_a f)} \]  

(5)
where

\[ W_d = \text{mean delay to departing aircraft, time units} \]

\[ \lambda_a = \text{mean arrival rate, aircraft per unit of time} \]

\[ \lambda_d = \text{mean departure rate, aircraft per unit of time} \]

\[ j = \text{mean interval of time between two successive departures} \]

\[ \sigma_j = \text{standard deviation of mean interval of time between two successive departures} \]

\[ g = \text{mean rate at which gaps between successive arrivals occur} \]

\[ f = \text{mean interval of time in which no departure can be released} \]

\[ \sigma_f = \text{standard deviation of mean interval of time in which no departure can be released} \]
3.2 Application of Mathematical Models

In 1968 and 1969 the FAA published Advisory Circular AC 150/5060-1A and AC 150/5060-3A summarizing the application of the mathematical models to a variety of runway configurations in graphical form [FAA, 1968 and 1969]. But in 1983 these two Advisory Circulars were updated by AC 150/5060-5 entitled "Airport Capacity and Delay" [FAA, 1983]. This Advisory Circular explains how to compute airport capacity and aircraft delay for airport planning and design. As it stands, the airport capacity and delay calculation methods outlined in AC 150/5060-5 are very popular and used throughout the world. For the purpose of this project a comparison of the analysis results between the SIMMOD model and the hand calculations summarized in AC 150/5060-5 were made. The major procedures in this Advisory Circular are explained in the next section.

3.2.1 Calculations for Long Range Planning

The computations for determining hourly airport capacity,
annual service volume and aircraft delay for long-range airport planning are detailed in Chapter 2 of Advisory Circular AC 150/5060-5. When more precise results are required or if the conditions differ significantly from the assumptions described alternate calculations are found in another chapter of AC 150/5060-5 [FAA, 1983].

An example calculation of the hourly VFR and IFR capacities for various single and multiple runway configurations are shown in Fig. 3.1. These are based on runway utilization which produce the highest sustainable capacity consistent with current air traffic control rules and practices. The values are representative of typical U.S. airports having similar runway-use configurations. The capacity and annual service volume in Fig. 2-1 of AC 150/5060-5 are based on some assumptions such as equal departures and arrivals, and IFR weather conditions occur roughly 10 percent of the time and. The percentage of aircraft classes C and D using or expected to use the facility are required to calculate the approximate hourly capacities and annual service volume based upon an equivalent aircraft mix index. For aircraft terminal operations and procedures (TERPS) the FAA has classified all aircraft in the categories shown in Table 3.1 [FAA, 1983].
FIG. 3.1 Capacity and ASV for Long Range Planning (Partial View)

Source: FAA 1983
**TABLE 3.1 Aircraft Classification**

Source: FAA 1983

<table>
<thead>
<tr>
<th>Aircraft Class</th>
<th>Max. Cert. T.O. Weight (lbs)</th>
<th>Number Engines</th>
<th>Wake Turbulence Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12,500 or less</td>
<td>Single</td>
<td>Small (S)</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>Multi</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>12,500 - 300,000</td>
<td>Multi</td>
<td>Large (L)</td>
</tr>
<tr>
<td>D</td>
<td>Over 300,000</td>
<td>Multi</td>
<td>Heavy (H)</td>
</tr>
</tbody>
</table>
The average aircraft delay for long range planning is calculated as follows [FAA, 1983]:

1. Estimate annual demand using current or historical information or projections of future traffic.
2. Calculate the ratio of annual demand to annual service volume.
3. Obtain average delay per aircraft from chart.
4. Calculate total annual aircraft delay as the average delay multiplied by the annual demand.

3.2.2 Calculations for Short Range Planning

The FAA AC 150/5060-5 also contains a procedure to estimate the airport short range capacity and delay calculation as follows [FAA, 1983]:

1. Capacity Calculations
   a. Hourly capacity of the runway component
   b. Hourly capacity of the taxiway component
   c. Hourly capacity of gate group components
   d. Airport hourly capacity
   e. Annual service volume
2. Delay Calculations
a. Hourly delay
b. Daily delay
c. Annual delay

Table 3.2 provides a checklist of the data required for these calculations.

Among the above eight calculations, the calculation procedures for the hourly capacity and hourly delay of the runway are introduced here. First, the calculation of the runway component hourly capacity is developed as follows [FAA 1983]:

1. Select the runway-use configuration in Fig. 3.2 which best represents the use of the airport during the hour of interest and identify from Fig. 3.2 the figure number for capacity (for $C^*$, $T$, and $E$), example is shown in Fig. 3.3.

2. Determine the percentage of class C and D aircraft operation mix index.

3. Determine percent arrivals (PA), hourly capacity base ($C^*$), the percentage of touch and go operations during VFR operations and determine the touch and go factor ($T$) and the location of exit taxiway ($E$).

4. Calculate the hourly capacity by following equation:
   Hourly capacity of the runway component = $C^*T^*E$
Table 3.2 Information Required for Capacity and Delay Calculations

**Source:** FAA 1983

<table>
<thead>
<tr>
<th>Output</th>
<th>Input Needed</th>
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| 1. Hourly capacity of runway component | a. Ceiling and visibility (VFR, IFR, or PVC)  
See: paragraph 3-2  
appendix 2 (figure A2-1) | b. Runway-use configuration  
c. Aircraft mix  
d. Percent arrivals  
e. Percent touch and go  
f. Exit taxiway locations |
| 2. Hourly capacity of taxiway component | a. Intersecting taxiway location  
See: paragraph 3-3  
appendix 2 (figure A2-2) | b. Runway operations rate  
c. Aircraft mix on runway being crossed |
| 3. Hourly capacity of gate group components | a. Number and type of gates in each gate group  
See: paragraph 3-4  
appendix 2 (figure A2-3) | b. Gate mix  
c. Gate occupancy times |
| 4. Airport hourly capacity | Capacity outputs from 1, 2, and 3 above  
See: paragraph 3-5  
appendix 2 (figure A2-4) |
| 5. Annual service volume | a. Hourly capacities of runway component  
See: paragraph 3-6  
appendix 2 (figure A2-5) | b. Occurrence of operating conditions |
| 6. Hourly delay to aircraft on runway component | a. Hourly demand  
See: paragraph 3-7  
appendix 2 (figure A2-6) | b. Hourly capacity of the runway component  
c. Demand profile factor |
| 7. Daily delay to aircraft on runway component | a. Hourly delay  
See: paragraphs 3-8 and 3-9  
appendix 2 (figures A2-7, and A2-8) | b. Hourly demand  
c. Hourly capacity |
| 8. Annual delay to aircraft on runway component | a. Annual demand  
See: paragraph 3-10  
appendix 2 (figure A2-9) | b. Daily delay  
c. Hourly demand  
d. Hourly capacities  
e. Percent VFR/IFR conditions  
f. Runway-use configuration |
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<td>3-81</td>
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</table>

**LEGEND**

- Indicates that an arrival (landing) can occur on the runway indicated.
- Indicates that a departure (takeoff) can occur on the runway indicated.
- The lack of a symbol means that aircraft operations will not occur on the runway indicated.
- Indicates a variable runway spacing.
- Indicates a runway spacing of 700 to 2499 feet.

**FIG. 3.2 Runway-Use Diagram (Partial View)**

Source: FAA 1983
FIG. 3.3 Hourly Capacity of Runway-Use Diagram (1)

Source: FAA 1983
FIG. 3.3 Hourly Capacity of Runway-Use Diagram (2)

Source: FAA 1983
When the hourly demand does not exceed the calculation of hourly capacity to aircraft on the runway component is as follows [FAA, 1983]:

1. Calculate the hourly capacity of the runway component for the specific hour of interest and identify from Fig. 3.2 the Fig. number (example Fig. 3.5) for arrival delay index (ADI) and the departure delay index (DDI).

2. Identify the hourly demand (HD) and the peak 15 minute demand (Q) on the runway component.

3. Calculate the ratio of hourly demand to hourly capacity (D/C).

4. Calculate the arrival delay factor (ADF), departure delay factor (DDF) and demand profile factor (DPF).

5. Calculate the average delay for arriving aircraft (DAHA) and departing aircraft (DAHD) from Fig. 3.6.

6. Calculate hourly delay (DTH) by the following equation:

\[
DTH = HD \{ PA \times DAHA + (100 - PA) \times DAHD \} / 100
\]
ARRIVAL DELAY INDEX = 1.00

DEPARTURE DELAY INDEX

Figure 3-95. Delay indices for runway-use diagram nos.: 10,11,20,21,25,29,30,69-71 for IFR conditions.

FIG. 3.5 Delay Indices for Runway

Source: FAA 1983
FIG. 3.6 Average Aircraft Delay in an Hour

Source: FAA 1983
3.2.3 Computer Programs for Analytical Calculation

The FAA Advisory Circular 150/5060-5 Change 1 [FAA, 1984] identifies all the FAA computer models for determining airport capacity and aircraft delay. According to the FAA these the models may be used to study the sensitivity of proposed physical and/or operational changes to the airport. The models should be used whenever planning or design requirements for capacity and/or delay information exceed the computational capabilities presented in Chapter 3.2.2 of this project report [FAA, 1984]. The FAA computer models recommended in AC 150/5060- Change 1 are as follows [FAA, 1984].

1. Runway Capacity model

The upgraded FAA Airfield Capacity Model analytically calculates the hourly capacities for 52 different runway-use configurations and a range of operating conditions. The model uses built-in values for current ATC system and operating practices such as in-trail separations, aircraft approach speeds, time deviations, etc. This model is
available through the National Technical Information Service (NTIS).

2. Annual Delay Model

The Annual Delay Model analytically calculates total annual delay, average delay to an aircraft, and the distribution of aircraft delay over the course of the year. The model operates with built-in values or user supplied data.

3. Annual Service Volume Model

The Annual Service Volume Model analytically calculates annual service volumes from user supplied data.

3.3 Computer Simulation Models

Horonjeff and Mckelvey [Horonjeff and Mckelvey, 1983] pointed out that "the computer simulation models are extremely useful for studying complex systems which cannot be represented by equations. These have been used successfully for solving many problems in air transport, including airport planning. An important point to remember is that the prime justification for using computer simulation is to reduced the differences between the real world and the abstract world of the model.
If the input data required for the model are not very
detailed, the results may not be any better than the results
obtained from an analytical model of lesser complexity."

Odoni and Simpson (Odoni and Simpson, 1978) reviewed several
simulation models that are concerned with the airside
operations at an airport. The Airport Performance Model,
yield delay estimates which are sufficiently accurate to be
useful in airport investment analyses and in calculations of
energy consumption and pollution emissions. The weakness of
this model, however, is the deterministic nature of the delay
values it yields. A complete airport model was developed
specifically for the Dallas-Ft. Worth Airport. Other airport
models reviewed are large-scale simulations that are capable
of analyzing in detail arrivals and departures on runways,
taxiways, aprons, and gates. One of these models, the Delay
Simulation Model (DSM), introduced already in the previous
chapter , was developed for the Federal Aviation
Administration and was made available for public use. While
the DSM is a complex and costly model to operate, it has been
validated and reviewed in different airport situations by
independent observers. The final complete airport model, the
Ground Operations Simulation (GOSIM) model, was developed by
the Boeing Company. Whereas the model has several features
that are superior to corresponding features of the Delay
Simulation Model, the Boeing Company, however, has not allowed the GOSIM model to be used by outside researchers. Therefore, there are no outside reviews or critiques of this model.

In 1984 the FAA developed another computer simulation model, the Airfield Delay Simulation Model, is recommended in AC 150/5060- Change 1 as follows "The Airfield Delay Simulation Model is a discrete event simulation calculating travel times, delay, and flow rates. This model may be used to analyze the components of an airport, airport operations, and operations in the adjacent airspace. This program are written in FORTRAN IV and should be operable on any FORTRAN compatible computer having 560K bytes of core capacity" [FAA, 1984].

Currently the new computer simulation model receiving strong support is denoted SIMMOD. The Federal Aviation Administration (FAA) has sponsored a research program over the past 10 years (1978 - 1988) which has resulted in the development of the Airspace and Airport Simulation Model (SIMMOD). The FAA evaluated it as follows: "SIMMOD is an advanced, state-of-the-art, computer model that simulates both airport and airspace operations. It is a flexible tool, capable of calculating capacity and delay impacts of a wide variety of potential airport and airspace operating alternatives" [FAA, 1988b]. The SIMMOD Information Brief
[FAA, 1989a] introduced SIMMOD as "a comprehensive planning tool for airport designers and managers, air traffic planners, and airlines. This software system aids in the study and evaluation of en route air traffic, terminal area air traffic, and airport and airline ground operations. SIMMOD addresses both the design and procedural aspects of all air traffic operations and produces measures of airport capacity, aircraft travel time, aircraft delay, and aircraft fuel consumption. Once a standard scenario has been established (based on data from existing or proposed operations), users may change the input data to develop and evaluate new alternatives". Thus, because of the reasons mentioned above the SIMMOD computer simulation model was adopted for this runway configuration comparison project.
4.0 DESCRIPTION OF SIMMOD

4.1 History of SIMMOD

SIMMOD is the Federal Aviation Administration's Airport and Airspace Simulation Model [FAA, 1989b]. According to the FAA [FAA, 1990] SIMMOD's history can be summarized as follows:

1978 - 1979: Development of the Airport/Airspace Delay Model (ADM)

1980 - 1982: Development of SIMMOD by adding to ADM an airfield model and a fuel consumption model

1983 - date: Modification and enhancement of the SIMMOD
simulation and development of pre-and post-processors

1985 - date: Validation of the SIMMOD Simulation Model

1987 - date: Application of SIMMOD to address "real-world" capacity and delay problems (i.e., San Diego, New York, etc.)

4.2 The SIMMOD System

SIMMOD is a complete system for developing and analyzing airport and airspace models. The system is based upon the SIMSCRIPT II.5 simulation language. The most visible element of the SIMMOD system is the executive shell which provides the menu-driven interface and serves as the controller for all SIMMOD functions as shown in Fig. 4.1 [FAA, 1989c]. The SIMMOD system consists of five modules tied together with an executive shell program. These modules execute the following tasks [FAA, 1989a]:

- Aid in preparing the model input data.
- Perform the actual simulation (i.e., the calculations and
related data processing).
- Compute fuel consumption statistics.
- Generate animated graphic displays of the simulation module output.
- Format reports of the simulation and fuel burn output.

The other programs which make up the SIMMOD system handle vital support functions, including:
- Capturing and formatting input data
- Digitizing airport maps and airspace charts
- Re[resenting the input data set in visual displays
- Validating aircraft performance data
- Computing aircraft fuel consumption
- Analyzing simulation output
- Translating output into animated graphic displays
- Generating printed reports and graphical charts of simulation results
Fig. 4.1 SIMMOD Executive Shell and Menu Structure

Source: FAA, 1989c
4.3 Capabilities of SIMMOD

SIMMOD's modeling and simulation capabilities allow users to ask "What if...?" at any level of air traffic operations [FAA, 1989a]. SIMMOD is a fast-time, event-step, simulation model that simulates the real world processes by which aircraft fly through air traffic controlled en route and terminal airspace and arrive and depart one or more airports. SIMMOD traces the movement of individual aircraft as they travel through the gate/taxiway/runway/airspace system and detects potential violations of separations and operational procedures. It simulates the air traffic control actions required to resolve potential conflicts to insure that aircraft operate within procedural rules. Aircraft travel time, delay, and traffic statistics are computed and provided as model outputs.

There is no conceptual limit to the number of airport, expanse of terminal and/or en route airspace, or level of traffic that can be simulated by SIMMOD. The model properly captures the interactions between airspace and airport operations, including interactions among multiple neighboring airports. The model is capable of simulating future airport facilities, runway configurations, airspace route structures, airspace sectorization, separation standards, traffic management
techniques, and air traffic control procedures and policies [FAA, 1988b,1989a].

4.4 SIMMOD Program Logic

The SIMMOD program logic consists of three major components: airspace traffic logic, airport/airspace interface logic, and the airfield logic. These logic components are integrated to capture the interrelationships between airport and airspace operations [FAA, 1989b].

The airspace logic component simulates the movement of individual aircraft through the modeled airspace by considering three levels of control. Level I, tactical control, simulates the processes by which controllers maintain minute-by-minute separation between aircraft by speed control, vectoring, or holding. Level II, sequencing control, mimics the processes by which controllers coordinate their near-term separation service plans, and sequence and space aircraft for downstream merges. Level III, strategic control, simulates the processes by which controllers coordinate their multisector
procedural rules, such as in-trail spacing adjustments at facility boundaries. The airspace logic properly models separation and capacity constraints, including sector workload capacity constraints, route segment capacity constraints, pair airway safety separations by aircraft types, normal in-trail separations, route restrictions, departure flow restrictions, inter-arrival spacing constraints, and flow constraints at sector and facility boundaries [FAA,1989b].

The airport/airspace interface logic component simulates the interactions between airspace and airport operations, procedures and constraints. This logic includes simulating the processes by which controllers set-up and maintain separation along final approach, including IFR and VFR operations. The processes by which controllers interleave departures and arrivals, select runway use, and insure proper runway utilization, this logic component simulates the processes by which controllers insure proper departure/departure spacing, taking into account departure queuing considerations, airspace capacity constraints, departure flow restrictions, and runway occupancy times and rules.

The airfield logic component simulates airfields traffic movements, including gate, taxiway, and runway operations. This includes gate allocation logic for simulating the
processes by which departing and arriving aircraft are assigned and occupy gates. The taxipath planning logic simulates the processes by which aircraft are assigned taxipaths between runways and gate areas, which may be selected from predefined routings (i.e., minimum time routes) or from computed "best" routings. Taxiway control logic simulates the movements of aircraft along taxiways and the processes by which controllers insure proper separations, including holding aircraft at taxiway intersections and runway crossings. Departure queuing logic provides for simulating a variety of departure lineup strategies, including queuing by runway use, departure routing, aircraft type, etc. [FAA, 1989b].

4.5 User Inputs

In order to provide the flexibility for SIMMOD to simulate existing as well as a wide range of potential alternative operations, many air traffic operational parameters are controlled by the user. The inputs fall into three major categories: airfield-related input, airspace-related input, and simulation event input [FAA, 1989c].
The airfield-related input allows the user to specify the physical layouts of airports and operational parameters such as gate/ taxiway/ runway structure, gate utilization by airlines, taxiway routings between gates and runways, departure lineup strategies, and aircraft landing and takeoff characteristics. The airspace-related input allows a user to specify airspace routings, airspace sectorization, airspace separation standards, arrival and departure procedures and required separations, metering and flow constraints, and strategies for resolving potential conflicts. Simulation input events provide the user with the capability to specify the departure and arrival demand schedules and desired changes in operating conditions, including runway use configurations, terminal routing plans, flow and metering constraints, and wind conditions [FAA, 1989b].

Some inputs are optional, based on the operations being simulated by SIMMOD. For example, airport gate and taxiway inputs may not be needed if the user is simulating an airspace problem where the details of the airfield simulation are not of concern. This feature relieves the user of unnecessary input preparation [FAA, 1989b].
Since SIMMOD simulates the movement of each individual aircraft on the airfield and in the airspace, the model is capable of producing a wide variety of results at a detailed or aggregate level. The simulation produces some printed output reports as well as computer files of simulation results that can be used as input into other programs, including the SIMMOD Report Module. The Report Module, a subprogram within the SIMMOD system, provides many varied reports depending on the analysis needs of the user. Reports produced by SIMMOD include delay and travel time statistics, traffic activity statistics by route and sector, arrivals and departures by airport and runway, and airport gate use statistics. These results can be generated for the entire simulation or for specific time periods.

SIMMOD also has the capability for the user to obtain a simulation log describing the detailed activity of each flight simulated. The time period for which logs are output and the contents are controlled by the user. This provides
the capability to monitor the simulated movements of individual flights [FAA, 1989b].

4.7 Application of SIMMOD

SIMMOD is an extremely valuable tool for addressing many of the critical problems and issues facing the National Airspace System. SIMMOD can be used to identify and quantitatively evaluate the impacts on capacity and delay of potential airport and airspace improvements options aimed at increasing capacity, reducing delay, and improving the efficiency of the air traffic system. Table 4.1 is a partial list of SIMMOD analysis topics, arranged by subject category. SIMMOD is designed to "play out" operations within the computer and calculate the real-world results that would be obtained if potential alternatives were actually implemented. Thus, SIMMOD can be used to compute the impacts of proposed changes in airport and airspace facilities, traffic activities, and operational constraints and procedures prior to decisions regarding implementation [FAA, 1988b].
<table>
<thead>
<tr>
<th>TABLE 4.1</th>
<th>SIMMOD Analysis Topics</th>
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<td><strong>Source:</strong> FAA, 1989b</td>
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**Airport Facilities**
- Impact of new facilities.
- Expansion or relocation of existing terminal.
- Relocation of gates.

**Airfield design and procedures**
- Revision of terminal routing plan.
- Runway and taxiway configurations.
- New runway construction.
- High-speed runway exits.
- Runway and taxiway holding pads.
- Reduction of runway occupancy time.
- Parallel approaches.
- Converging approaches.
- Microwave Landing Systems (MLS).
- Location of navigational aids.
- Apron area operations.
- Queuing strategies and departure rules.

**Airspace design and procedures**
- Revision of separation rules.
- Speed and altitude restrictions.
- Controller tactics.
- Realignment of en route and terminal airspace.
- New profiles and tracks.
- Sector capacities.

**Operations**
- Aircraft performance.
- Hub and spoke operations.
- Traffic demand and fleet mix.
- Revised scheduling.
- Redistribution of departure schedules at peak hours.
- Revised ATC procedures.
- Separation of general aviation and air carrier traffic.
- Visual and instrument flight procedures (VFR & IFR).
- Interactions among multiple airports.

**Other**
- Noise abatement procedures.
- Wind conditions (speed, direction, ceiling and visibility).
The SIMMOD manual points out the typical SIMMOD applications as follows [FAA, 1989d]:

- Gate-taxi-runway management
- Runway spacing and alignment
- Airspace route planning
- Traffic demand and fleet mix evaluation
- Air carrier scheduling
- Hub and spoke operations
- Air traffic control separation rules
- Controller decision logic testing
- Airspace sectorization
- Airport expansion
- Location of navigational aids.
4.8 Computer Requirements

The SIMMOD simulation computer program is written in the simulation language SIMSCRIPT II.5 both being marketed by CACI Products Company. This simulation program is currently configured to run on an IBM mainframe computer and IBM PC or compatible computer [FAA, 1988b]. The Following hardware/software combination is recommended to successfully run SIMMOD model [FAA, 1989a].

Hardware: - IBM PC/AT or a 286 compatible personal computer
    - 20 MB hard disk drive
    - 1.2 MB floppy disk drive
    - 2 MB RAM (Minimum)
    - Mouse
    - 80287 math co-processor
    - EGA or VGA graphics board and monitor
    - Printer

Software: - DOS operating system (Version 3.1 or higher)
    - PC SIMSCRIPT RUNTIME LIBRARIES
    - Standard SIMMOD package
These hardware and software represent minimum equipment requirements. However, according to recent suggestions made by CACI a faster microprocessor such as the INTEL 30386 coupled with a 80387 math co-processor is a more realistic configuration. Also, the addition of a large color monitor (i.e., 16 inches) and a high quality output device are suggested for serious work. In order to expedite the digitization of complex airfield /airspace scenarios a digitizer is highly recommended. SIMMOD has also file exchange capabilities with popular CAD programs to ease the airfield/airspace node-link construction.
5.0 SCENARIO ANALYSIS

5.1 Scenario Selection

Many scenarios can be considered depending on the project purpose and project characteristics. As mentioned in Chapter 1 this project focus in the capacity and delay comparison of three different types of runway configurations: Fanway, A single runway, and a dual-lane, closely spaced runway system. Two of these different configurations comprise two cases corresponding to two in-trail, distance based criteria (i.e., 2 and 1.5 nautical miles of in-trail separation). The resulting scenarios are summarized as follows:

1. Scenario 1: - One-way single Fanway
   - Diagonal separation is 2 NM
<table>
<thead>
<tr>
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<th>Case</th>
<th>Runway Type</th>
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<td>1</td>
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<td>2.0 NM</td>
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<td>1-4</td>
<td>Fanway</td>
<td>2.0 NM</td>
<td>84/Hour</td>
</tr>
<tr>
<td></td>
<td>1-5</td>
<td>Fanway</td>
<td>2.0 NM</td>
<td>96/Hour</td>
</tr>
<tr>
<td></td>
<td>1-6</td>
<td>Fanway</td>
<td>2.0 NM</td>
<td>108/Hour</td>
</tr>
<tr>
<td>2</td>
<td>2-1</td>
<td>Fanway</td>
<td>1.5 NM</td>
<td>48/Hour</td>
</tr>
<tr>
<td></td>
<td>2-2</td>
<td>Fanway</td>
<td>1.5 NM</td>
<td>60/Hour</td>
</tr>
<tr>
<td></td>
<td>2-3</td>
<td>Fanway</td>
<td>1.5 NM</td>
<td>72/Hour</td>
</tr>
<tr>
<td></td>
<td>2-4</td>
<td>Fanway</td>
<td>1.5 NM</td>
<td>84/Hour</td>
</tr>
<tr>
<td></td>
<td>2-5</td>
<td>Fanway</td>
<td>1.5 NM</td>
<td>96/Hour</td>
</tr>
<tr>
<td></td>
<td>2-6</td>
<td>Fanway</td>
<td>1.5 NM</td>
<td>108/Hour</td>
</tr>
<tr>
<td>3</td>
<td>3-1</td>
<td>Parallel</td>
<td>2.0 NM</td>
<td>48/Hour</td>
</tr>
<tr>
<td></td>
<td>3-2</td>
<td>Parallel</td>
<td>2.0 NM</td>
<td>60/Hour</td>
</tr>
<tr>
<td></td>
<td>3-3</td>
<td>Parallel</td>
<td>2.0 NM</td>
<td>72/Hour</td>
</tr>
<tr>
<td></td>
<td>3-4</td>
<td>Parallel</td>
<td>2.0 NM</td>
<td>84/Hour</td>
</tr>
<tr>
<td></td>
<td>3-5</td>
<td>Parallel</td>
<td>2.0 NM</td>
<td>96/Hour</td>
</tr>
<tr>
<td></td>
<td>3-6</td>
<td>Parallel</td>
<td>2.0 NM</td>
<td>108/Hour</td>
</tr>
<tr>
<td>4</td>
<td>4-1</td>
<td>Parallel</td>
<td>1.5 NM</td>
<td>48/Hour</td>
</tr>
<tr>
<td></td>
<td>4-2</td>
<td>Parallel</td>
<td>1.5 NM</td>
<td>60/Hour</td>
</tr>
<tr>
<td></td>
<td>4-3</td>
<td>Parallel</td>
<td>1.5 NM</td>
<td>72/Hour</td>
</tr>
<tr>
<td></td>
<td>4-4</td>
<td>Parallel</td>
<td>1.5 NM</td>
<td>84/Hour</td>
</tr>
<tr>
<td></td>
<td>4-5</td>
<td>Parallel</td>
<td>1.5 NM</td>
<td>96/Hour</td>
</tr>
<tr>
<td></td>
<td>4-6</td>
<td>Parallel</td>
<td>1.5 NM</td>
<td>108/Hour</td>
</tr>
<tr>
<td>5</td>
<td>5-1</td>
<td>Single</td>
<td></td>
<td>48/Hour</td>
</tr>
<tr>
<td></td>
<td>5-2</td>
<td>Single</td>
<td></td>
<td>60/Hour</td>
</tr>
<tr>
<td></td>
<td>5-3</td>
<td>Single</td>
<td></td>
<td>72/Hour</td>
</tr>
<tr>
<td></td>
<td>5-4</td>
<td>Single</td>
<td></td>
<td>84/Hour</td>
</tr>
</tbody>
</table>

Total 28 cases

Note: 1. All scenarios are under IFR condition
2. Fanway and Parallel runway fall into dependent operation
2. Scenario 2: - One-way single Fanway
   - Diagonal separation is 1.5 NM
3. Scenario 3: - Two parallel runway
   - Diagonal separation is 2 NM
4. Scenario 4: - Two parallel runway
   - Diagonal separation is 1.5 NM
5. Scenario 5: - One single runway

Every scenario considered was modelled under various demand conditions to estimate the practical hourly capacity. The number of aircraft hourly operations for every case are shown in Table 5.1. Moreover, due to the stochasticity under which SIMMOD operates each case was replicated five times in order to obtain average results.

5.2 Airfield Features of Scenarios

5.2.1 Runway Configurations

The runway configuration for scenarios 1 and 2 corresponds to
a single Fanway consisting of three straight runways intersecting at an angle of 10 degrees as shown in Fig. 5.1. Scenarios 3 and 4 use one parallel runways which is modified partially from the one-way single Fanway of scenarios 1 and 2. As shown in Fig 5.2, the separation distance between the parallel runways is 3,300 ft. Equivalent to the Fanway's lateral spacing requirements shown in Fig. 5.2. As the reader is aware, this lateral separation does not offer independent simultaneous approaches under IFR conditions. It was, however, considered important to keep the lateral dimension constant to compare all the scenarios under the same land use availability constraints. According to the FAA's Advisory Circular AC 150/5300-13 this parallel runway separation could allow simultaneous radar departures under IFR conditions [FAA, 1989e]. Thus the parallel runway and Fanway configuration partially derived from the one-way single Fanway as shown in Fig. 5.3. Note that these assumptions apply to Precision Instrument Runways. Thus requiring the largest separation standards available.
Fig. 5.1 Fanway Configuration
Remark: Link and node numbers shown according to SIMMOD diagram.

FIG. 5.2 Parallel Runway Configuration
Remark: Link and node numbers shown according to SIMMOD diagram.

Fig. 5.3 Single Runway Configuration
5.2.2 Runway Length

The length of the runways used for this study was selected to be 10,000 ft following the original sketches done by Millen [Millen, 1979]. This runway length seems to offer good functional qualities such as large crossing taxiway segments at the end of the inactive threshold allowing one or two aircraft to hold prior to crossing an active runway. Generally speaking, except few aircraft the length of 10,000 ft is considered enough for landing and takeoff. Also this runway length is capable of serving a large variety of aircraft ranging from small general aviation aircraft to heavy transports as seen in Table 5.2. The width and type of runway pavements are not considered in this project because SIMMOD does not have these functions to affect aircraft performance appreciably.
<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Manufacturer</th>
<th>Maximum Payload Passenger</th>
<th>Runway Length (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-10-10</td>
<td>McDonnell-Douglas</td>
<td>275-345</td>
<td>9,000</td>
</tr>
<tr>
<td>DC-10-30</td>
<td>McDonnell-Douglas</td>
<td>275-345</td>
<td>11,000</td>
</tr>
<tr>
<td>B-727-200</td>
<td>Boeing</td>
<td>86-125</td>
<td>5,600</td>
</tr>
<tr>
<td>B-727-200</td>
<td>Boeing</td>
<td>134-125</td>
<td>8,600</td>
</tr>
<tr>
<td>B-757-200</td>
<td>Boeing</td>
<td>86-125</td>
<td>6,900</td>
</tr>
<tr>
<td>B-767-200</td>
<td>Boeing</td>
<td>134-125</td>
<td>6,700</td>
</tr>
<tr>
<td>B-747-B</td>
<td>Boeing</td>
<td>362-490</td>
<td>11,000</td>
</tr>
<tr>
<td>B-747-SP</td>
<td>Boeing</td>
<td>288-364</td>
<td>8,000</td>
</tr>
<tr>
<td>L-1011-500</td>
<td>Lockheed</td>
<td>246-400</td>
<td>9,300</td>
</tr>
<tr>
<td>A-300</td>
<td>Airbus Industrie</td>
<td>225-345</td>
<td>6,500</td>
</tr>
<tr>
<td>Concorde</td>
<td>British Aircraft-Aerospatial</td>
<td>108-128</td>
<td>11,300</td>
</tr>
<tr>
<td>Ilyushine-86</td>
<td>U.S.S.R</td>
<td>350</td>
<td>8,600</td>
</tr>
</tbody>
</table>

* At sea level, standard day, no wind, level runway
5.2.3 **Taxiway System**

The taxiway subsystem for all configurations investigated the design of this project followed the taxiway design principles of FAA Advisory Circular 150/5300-13 [FAA,1989e]. On the base of the design principles, every runway configurations of each scenario is provided with taxiway and parallel taxiway system as shown in Figs. 5.1 through Fig. 5.3. Another important reason in providing a parallel taxiway is to avoid excessive taxiway congestion. Since this project is focused to only runway capacity and delay among the airfield components, other components are required "unlimited" capacity except some taxiways which are located between runway of Fanway and two parallel runways.

Thus the length, separation and location of the parallel taxiway followed the same guidelines throughout all the configurations. All of the following design dimensions are based on the assumptions of Precision Instrument Runways and airport elevations below 1,345 ft. Other relevant design criteria are:
1. Based airplane design group for airport design: Group Five
   (Wing span 171 ft up to but not including 214 ft) [FAA, 1989e]
2. Taxiway and parallel taxiway length: 10,000 ft
3. Separation distance from precision runway centerline to taxiway centerline: 400 ft
4. Separation distance from taxiway centerline to parallel taxiway centerline: 267 ft

The Fanway is provided with just two exit taxiways compared to four the corresponding parallel runway (see Fig. 5.1, 5.2). This is due to the gradual separation of runways comprising the Fanway configuration. If the separation distance between runways does not allow aircraft to hold between runways the corresponding turnoff should not be considered. The minimum separation distance requirement between two runways allowing waiting aircraft to hold can be calculated as follows:

- The separation distance from Precision Instrument Runway to taxiway is 400 ft.
- For both directions: 400 ft \* 2 = 800 ft
- Aircraft length (assume Boeing 747-400): 231.8 ft [FAA, 1989e]
- If assume allow two aircraft simultaneously:
  \[231.8 \text{ ft} \times 2 = 463.6 \text{ ft}\]
- Safety margin for two aircraft separation [FAA, 1989e]:
  \[231.8 \text{ ft} \times 0.7 + 10 \text{ ft} = 242.5 \text{ ft}\]
- The minimum separation:
  \[800 \text{ ft} + 463.6 \text{ ft} + 242.5 \text{ ft} = 1,506.1 \text{ ft}\]

Thus only the last two exit taxiways can satisfy the separation distance requirements.

### 5.2.4 Gate System

Generally considered a subsystem on its own has an important role in determining airside capacity. SIMMOD requires a detailed gate system definition as aircraft leave the simulation after gate waiting in case of arrivals and all aircraft begin their journeys after stochastically defined gate waiting times [FAA, 1990]. Thus all runway configurations require a gate subsystem providing enough gate capacity to minimize the effects of gate delays. A single high-capacity node-gate subsystem was provided in all configurations. This subsystem was modeled as capable of serving 100 widebody aircraft simultaneously. Notice that all the gates are represented at a single node as shown in Figs. 5.1 through 5.3.
5.2.5 Departure Queues

The SIMMOD simulation model requires departing aircraft to enter a queue in the taxipath subsystem [FAA, 1989b]. The departure queues are usually located at end of runway in SIMMOD, thus all runways in this project were provided with departure queues at the end of all active runways in a node form. Between two departure queue strategy options this project adopted the first in first out (FIFO) queue method.

5.3 Airspace Features of Scenarios

5.3.1 Airspace Networks and Routes

In this project only a limited airspace network is considered as part of the analysis. As SIMMOD requires every arriving aircraft to start its movement from a designated airspace node and departing aircraft leave the simulation at either an
Fig. 5.5 Parallel Runway Airspace Routes for Scenario 3 and 4
Fig. 5.6 Single Runway Airspace Route for Scenario 5
airspace or airfield node, each airport scenario is provided with an airspace structure route as shown in Figs. 5.4 through Fig. 5.6. The airspace network of two parallel runways and single runway scenarios use the same routes that of the Fanway with minor modifications. The air route length of approach side is extended to 30 nautical miles to provide enough spacing to model terminal airspace separations. The profiles of the air routes are based on the separation distance between runway threshold and each airspace route node location. The profile elevation value can be obtained by profile function of SIMMOD model dependent upon aircraft type, but all profile values along the routes are simply calculated under the assumption that all angles for approach and departure are conform to a 3 degree standard.

5.3.2 Wake Vortex Separations

Every aircraft has its own characteristics but many different models of aircraft have roughly equivalent characteristics when airborne. For the purpose of wake vortex separation (the in-trail separation requirements for each aircraft of a given group followed by another group) the SIMMOD model requires every aircraft must be classified into groups. The SIMMOD
TABLE 5.3 In-trail Separation
Source: FAA, 1989f

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Separation in Nautical Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Followed by</td>
</tr>
<tr>
<td></td>
<td>Small</td>
</tr>
<tr>
<td>Small</td>
<td>2.5</td>
</tr>
<tr>
<td>Large</td>
<td>2.5</td>
</tr>
<tr>
<td>Heavy</td>
<td>6.0</td>
</tr>
</tbody>
</table>
model classifies all aircraft into one of 4 groups according to the Integrated Noise Model (INM) Version 3.9 database. These are: Heavy, Large, Small and General Aviation [FAA, 1989b]. For the purpose of this project the wake vortex separation criteria used is also based upon recent FAA recommendations as shown in Table 5.1 [FAA, 1989f]. As seen in this table the general aviation group in SIMMOD model was equivalent to a small aircraft in this project. SIMMOD maintains the separation between aircraft along airspace links and passing through airspace nodes based upon these four groups.

5.3.3 Diagonal Separation on Final Approach

As it was explained before the main difference between the first four scenarios modeled are the diagonal separation distances along their final approaches. Due to the final approach separation distances between runways all of the runways in this project are classified as dependant runways required throughout the simulation. As mentioned in the section describing the project goals the different runway capacity and delay results could be obtained by different
diagonal separation distances. The response of the delay curve to each different diagonal separation criterion represents the sensitivity of the system modeled to ATC procedural changes. This diagonal separation is of particular interest in future airfield operations as the FAA is trying to enhance the capacity of the existing airport infrastructure. SIMMOD does not have a function to calculate the diagonal separation between aircraft in the airspace during the simulation, thus some application of SIMMOD model's functions were used for all aircraft to maintain the given diagonal separation during final approach. During the development of application concepts for different diagonal separation distances many "equivalent" concepts were tried until a practical solution to the problem representation was found. For example, in case of a Fanway configuration a 2 NM diagonal separation distance between each approach route can be maintained by using the arrival strategy option flag "0" at common entering node in which every aircraft is being released with 2 NM separation [FAA, 1989d]. In the real world the common node is not required but in SIMMOD the common node technique is an alternative to provide the required separation distance for safe aircraft approaches. At least 6 NM of distance from runway threshold to airspace common node is required for 2 NM diagonal separation as shown in Fig. 5.7 (note that there are 3 intersecting approach paths). Also,
the capacity of each link between the threshold and the common node was considered a major control factor for maintaining diagonal separation minima. In the Fanway case only one aircraft was allowed in each link starting at the common node. In a similar fashion the 1.5 NM diagonal separation for Fanway can be obtained by just reducing the distance between the common node and runway threshold from 6 NM to 4.5 NM as shown in Fig. 5.7. Also the separation distance for releasing a departure from the common approach node is changed from 2.0 to 1.5.

A 2.0 NM diagonal separation for two parallel runway approaches can be maintained using the following scheme. Shown in Fig. 5.8 it is seen that at least 7 NM of the common approach route are required in order for every aircraft to use the existing Instrument Landing System. A common approach link with tight in-trail separation constraints is used to model a parallel runway system. A common node is located 7 NM outside the runway threshold in order to maintain the separation distance of 2 NM the final approach airspace is divided into two sectors denoted as inner and outer common approach sectors. In the outer sector with length of 4 NM from the common node to runway, only one aircraft is allowed per link. The common node as well as Fanway case is provided the separation value 2.0 NM to release every aircraft with 2.0
Fig. 5.7a 2.0 NM Diagonal Separation

Fig. 5.7b 1.5 NM Diagonal Separation

Legend:  

\[ \text{\small A, B, C, D Real World} \]

\[ \text{\small A', B', C', D' In SIMMOD Simulation} \]

Fig. 5.7 Diagonal Separation for Fanway
Fig. 5.8a 2.0 NM Diagonal Separation

Fig. 5.8b 1.5 NM Diagonal Separation

Legend:  
- A, B, C, D Real World
- A', B', C', D' In SIMMOD Simulation

Fig. 5.8 Diagonal Separation for Two Parallel Runway
NM separation. The links in the inner sector whose length is 3 NM allow one aircraft per link as shown in Fig. 5.8. The fourth configuration studied having 1.5 NM diagonal separation distance for two parallel runway could be maintained based on the same concepts as the previously explained method. As seen in Fig. 5.8b the length of the inner should be 3 NM with allowance one aircraft per link and the common node's value is 1.5 NM. In this particular case the capacity should be two per link in second sector whose length is 4 NM.

5.4 Aircraft Operations

5.4.1 Aircraft Speeds and Runway Rolling Times

The aircraft operational speeds and rolling times on the runway are among the major factors affecting the runway capacity and delay. In order to reduce the user input effort SIMMOD has baseline aircraft speeds rolling times. In this
### TABLE 5.4 Aircraft Speed and Roll Time

<table>
<thead>
<tr>
<th>Taxi Speed</th>
<th>Runway Speed</th>
<th>Taxiway Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35 mph (Average)</td>
<td>15 mph (Average)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Approach Speed (Large Aircraft)</th>
<th>From:</th>
<th>To:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold</td>
<td>10 NM</td>
<td>20 NM</td>
<td>150 - 180 mph</td>
</tr>
<tr>
<td>20 NM</td>
<td>30 NM</td>
<td>240 mph</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Runway Roll Time</th>
<th>Landing</th>
<th>50 seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Takeoff</td>
<td>45 seconds</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Runway Crossing Time</th>
<th>15 Seconds</th>
</tr>
</thead>
</table>

Table 5.4. All of these values are baseline parameters that
project the values used for all simulation runs are shown in Table 5.4. All of these values are baseline parameters that remained unmodified between runs in order to maintain consistency in the simulation results.

5.4.2 Arrival and Departure Procedures

The procedures are very sensible factors controlling the aircraft arrivals and departures on related runways. This is specially true in the case of dependent runways such as those comprising a Fanway configuration and two dependent parallel runways. Dependent procedure separation rules are well described in the FAA's handbook for air traffic controllers [FAA,1989f]. Departure time intervals of 60 seconds are used if a aircraft follows similar group aircraft. Assuming an average takeoff speed of 120 knots, the total flight distance would be 2 NM during the first 60 seconds after brake release. For the Fanway and two dependent case such as parallel runways 10 seconds of time interval or 0.7 NM distance separation were adopted as a safe limitation for departure procedures following an arrival on a different runway. This will model realistically the engine spool-up time and the motion to the takeoff position of the aircraft in question. For the
<table>
<thead>
<tr>
<th>Leading Procedure</th>
<th>Following Procedure</th>
<th>Limitation of following procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival or Landing at any runway</td>
<td>All arrivals</td>
<td>Controlled in air route</td>
</tr>
<tr>
<td>Arrival same runway</td>
<td>Departure same runway</td>
<td>60 sec and 1 NM</td>
</tr>
<tr>
<td>Departure same runway</td>
<td>Departure same runway</td>
<td>60 sec and 2 NM</td>
</tr>
<tr>
<td>Arrival leading runway</td>
<td>Departure related runway</td>
<td>10 sec &amp; 0.7 NM</td>
</tr>
<tr>
<td>Departure leading runway</td>
<td>Departure related runway</td>
<td>10 sec &amp; 0.7 NM</td>
</tr>
</tbody>
</table>
purpose of comparison, the same procedure rules are applied to
the three runway configurations as shown in Table 5.5.

5.4.3 Aircraft Mix

Real world scenarios usually involve several groups of
aircraft operating in an airport. At the start of this
project three different aircraft groups were applied to the
scenarios described in Section 5.3.2 of this report.

Initial simulation efforts used an aircraft mix equivalent to
that of Denver Stapleton international Airport consisting of
29% small, 61% large and 10% heavy aircraft. In order to
maintain a consistent aircraft mix for all scenarios using the
multi-arrival and multi-departure features of SIMMOD an all
large aircraft population was the best alternative. The
reader should be aware that multi-arrival/multi-departure
procedures generate random aircraft traffic simulating global
increases in demand. Unfortunately, the analyst does not have
full control of the aircraft population being artificially
generated. Due to this limitation it was decided to use a
single aircraft group in all simulations thus maintaining
consistent mixes in all the scenarios investigated in this project.
5.4.4 Aircraft Operation Methods

A small number of aircraft operations over a reduced length of simulation time was used in this project to reduce the computational time for every run. Twenty minutes of simulation time proved to be the basics of all scenarios investigated. Nominally, 20 aircraft (i.e., 10 arrivals and 10 departures) were used as baseline scenario. Increments of 12 aircraft per hour were then implemented to generate a standard delay curve. This is shown below:

<table>
<thead>
<tr>
<th>Case</th>
<th>Initial Aircraft</th>
<th>Time</th>
<th>Final Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48 Aircraft/ 1 Hour</td>
<td>--&gt; 16 Aircraft/ 20 Min.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>--&gt; 20</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>72</td>
<td>--&gt; 24</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>84</td>
<td>--&gt; 28</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>96</td>
<td>--&gt; 32</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>108</td>
<td>--&gt; 36</td>
<td></td>
</tr>
</tbody>
</table>

As mentioned previously, in SIMMOD all arrivals start at an airspace node and all departures begin at a gate, thus the operation time setting is very hard. In other words, there is no way to setup aircraft operation time on runway

87
during the given time directly in SIMMOD model. Therefore, in this project the aircraft starting time at the first airspace node was assigned to match that of the first departure entering the departure queue. This matching procedure was performed through several simulation trials using with SIMMOD animation capabilities.

5.5 Scenario Input Data

The planned runway configurations and airspace were digitized by format function in SIMMOD model on screen work with mouse (digitizer is better), and then other data for airspace files, airfield files and events files were inputted by using the menu driven screen. For convenience and time saving files corrections or modifications were done by using ASCII file editor. As shown in Appendix A the sample file data contained a total of 84 data input files produced for 28 cases of five scenarios investigated this project.
6.0 RESULTS AND DISCUSSION

6.1 Result Outputs

The simulation results of 5 configuration scenarios were obtained through 28 cases repeated five times to unbiased the results. These results are shown in Tables 6.1 through 6.3 and Appendix B. In SIMMOD the simulation results are presented through several methods. The output data values shown in Tables 6.1 through 6.3 are concentrate on values obtained from the "Standard Report" as attached in Appendix B which is considered the best reporting mechanisms of SIMMOD for the purpose of runway capacity and delay.
### TABLE 6.1 Fanway Average Aircraft Delay

<table>
<thead>
<tr>
<th>Diagonal separation</th>
<th>Aircraft operations</th>
<th>Ground delay</th>
<th>Airspace delay</th>
<th>Ground plus Airspace</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 NM</td>
<td>48</td>
<td>0.41</td>
<td>0.49</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.67</td>
<td>0.98</td>
<td>1.66</td>
</tr>
<tr>
<td></td>
<td>72</td>
<td>0.93</td>
<td>1.34</td>
<td>2.17</td>
</tr>
<tr>
<td></td>
<td>84</td>
<td>1.23</td>
<td>1.66</td>
<td>2.89</td>
</tr>
<tr>
<td></td>
<td>96</td>
<td>1.71</td>
<td>1.76</td>
<td>3.47</td>
</tr>
<tr>
<td></td>
<td>108</td>
<td>2.64</td>
<td>1.75</td>
<td>4.39</td>
</tr>
<tr>
<td>1.5 NM</td>
<td>48</td>
<td>0.41</td>
<td>0.19</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
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<td>Airspace delay</td>
<td>Ground plus Airspace</td>
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TABLE 6.3 Single Runway Average Aircraft Delay

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<th>Ground plus Airspace</th>
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<td>4.34</td>
<td>1.96</td>
<td>6.30</td>
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</table>
6.2 Capacity and Delay Comparison

In order to compare the capacity and delay of every runway, the data which had been obtained from Standard Report was extracted to make a graph representing the average delay time versus the number of aircraft operations as shown in Fig. 6.1. For the purpose of comparison the practical capacity of each scenario were obtained from the graph. Table 6.4 shows each the practical capacity of every calculated under the assumption that the acceptable average delay time is 3 minutes.

Fig. 6.1 and Table 6.4 indicate that the practical capacity of the Fanway configuration is 7.2% greater than that of the parallel runway configuration under 2.0 nautical mile diagonal separation distance. The same analysis shows that the Fanway practical capacity is 12.8% greater than the parallel runway configuration if 1.5 NM diagonal separation distance is used.
Fig 6.1 Aircraft Operations versus Average Delay Relationship
<table>
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<tr>
<th>Runway Configuration</th>
<th>Practical Capacity</th>
<th>Normalized Values</th>
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<tr>
<td></td>
<td></td>
<td>Fanway 2.0 NM</td>
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<tr>
<td>Fanway (2.0 NM)</td>
<td>89</td>
<td>1.000</td>
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<td>Fanway (1.5 NM)</td>
<td>97</td>
<td>1.090</td>
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<tr>
<td>Parallel (2.0 NM)</td>
<td>83</td>
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<td>Single</td>
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<td>0.607</td>
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# TABLE 6.5 Delay Time Analysis

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<th>Practical Capacity 80</th>
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<td>Delay Time (Min.)</td>
<td>Normalized Values</td>
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<td>Fanway (2.0 NM)</td>
<td>1.00</td>
<td>1.000</td>
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<td>Fanway (1.5 NM)</td>
<td>0.78</td>
<td>0.780</td>
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<td>Parallel (1.5 NM)</td>
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<tr>
<td>Single</td>
<td>2.61</td>
<td>2.610</td>
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</tbody>
</table>

96
Also, the Fanway practical capacity is 64.8% greater when compared to the single runway capacity and parallel runway practical capacity is 53.7% greater than that of the single runway. These analysis indicate that the Fanway configuration has strong merit in view of increasing the airport capacity when compared to a parallel runway configuration.

From a delay time point of view, the delay time analysis values in Table 6.5 were extracted from each runway configuration graph as seen in Fig. 6.1. For the purpose of delay time analysis, two aircraft operation cases 50 and 80, were considered in order to see the differences between the low and high density of aircraft operations. Table 6.5 shows that there is no delay time difference between the Fanway and the parallel runway under the low aircraft operation 50 when the diagonal separation is 2.0 NM but in case of high operation density the delay time of the Fanway configuration is 15.1% less than that of the parallel runway under 2.0 NM diagonal separation distance.
6.3 **Diagonal Separation Distance Sensitivity**

The sensitivity analysis performed for various diagonal separation distances was normalized to show capacity gains as depicted in Table 6.4. As expected the practical capacity of the Fanway configuration is increased as much as 9.0% if a reduction in the diagonal separation distance from 2.0 NM to 1.5 NM is implemented. A somewhat unexpected result was observed for the parallel runway configuration as distance changed. In case of the parallel runway an increase of only 3.6% was observed as the diagonal separation distance from 2.0 NM to 1.5 NM. A potential reason for this minor change might be found through detailed observation of the average aircraft delay results shown in Table 6.2. According to the simulation results the airspace delay times were reduced by about 22%, but the ground delay time was increased about 9% when the diagonal separation distance was changed from 2.0 NM to 1.5 NM. Even though the increased ground delay time 9% is less than reduced airspace delay time 22%, the ground delay contribution is much higher than airspace delay thus increasing the total capacity slightly. It can be expected that the aircraft fuel consumption should be reduced through
### TABLE 6.6 Aircraft Fuel Consumption Comparison

<table>
<thead>
<tr>
<th>Runway Configuration</th>
<th>Aircraft Operations</th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>48</td>
<td>60</td>
<td>72</td>
</tr>
<tr>
<td>Fanway (2.0 NM)</td>
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<td>1,800 (1.00)</td>
<td>2,057 (1.00)</td>
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<tr>
<td>Fanway (1.5 NM)</td>
<td>1,693 (0.98)</td>
<td>1,690 (0.94)</td>
<td>1,733 (0.84)</td>
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<tr>
<td>Parallel (2.0 NM)</td>
<td>1,938 (1.12)</td>
<td>2,083 (1.16)</td>
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</tr>
<tr>
<td>Parallel (1.5 NM)</td>
<td>1,925 (1.11)</td>
<td>2,006 (1.11)</td>
<td>2,080 (1.01)</td>
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</table>

Remark: ( ); Comparison base is Fanway (2.0 NM).
changing the diagonal separation from 2.0 NM to 1.5 NM.

The fuel consumption analysis results as shown in Table 6.6 were extracted from three different numbers of aircraft operation "Fuelburn" reports which were produced by post-processing of SIMMOD. According to the fuelburn analysis on the parallel runway, an 0.6% to 3.0% of fuel consumption reduction was observed as a result of a change in the diagonal separation from 2.0 NM to 1.5 NM even though there is no advantage in delay time reduction in the case of low density aircraft operation. The diagonal separation change caused the Fanway to reduce fuel consumption 2%, 6% and 16% depending on the number of aircraft operations.
6.4 SIMMOD vs. Mathematical Methods

In order to find out relationships existing between SIMMOD simulation result and mathematical hand calculation method, two parallel runway configurations were selected in this project. All assumptions and data were applied to mathematical methods detailed in Advisory Circular 150/5060-5 which were described in Chapter 3.2.2. First, the spacing category "3,000 ft to 4,299 ft" was selected because the all simulated parallel runway spacing in this project is 3,350 ft in this project. It is seen that the hourly capacity is 85 aircraft with average delay time 0.9 minute as shown in Table 6.5. But the SIMMOD simulation results shown in Fig.6.1 yield a practical capacity of 48 aircraft per hour under the same condition and an average delay time of 0.9 minutes. The mathematical calculation method shows approximately 77% more capacity than SIMMOD simulation result which means that there is a definite gap between these two methods. A second comparison was considered in order to find out the main reason that influence this gap between the two methods. For the second calculation the category of the two parallel runway
spacing is assumed "2,500 ft to 2,999 ft" because the actual spacing value 3,350 ft is closed to lower category. In this second case the capacity of parallel runway is 70 aircraft and the average delay time is 1.5 minutes as shown in Table 6.6. Meanwhile SIMMOD simulation results shows that the runway capacity is 59 aircraft and the delay time being 1.5 minutes. Even though the capacity result from mathematical method is still 17% higher than that of SIMMOD, this second assumption has reduced the gap between two methods to a manageable level. Actually it is not easy to judge which method is right or wrong because each method has its own assumptions and is based on different conditions. It is possible however to judge the merits of each one through the comparison of the output results. According to a current FAA publication [FAA, 1989f] which shows the potential IFR arrival capacity at the top 100 airport in U.S., the current best IFR arrival capacity is 36 aircraft when the runway configuration is a dependent parallel runway. Thus it can be seen that SIMMOD simulation results are more reasonable than the mathematical method as the Advisory Circular has a limitation in dividing the spacing category.

One of the main difference in delay time calculation between SIMMOD and the Advisory Circular method seems to be related to aircraft procedural concepts. In SIMMOD the total arrival delay time is less than departure delay time as shown in
Appendix C because the arriving aircraft are assumed to have priority, but the results in Tables 6.7 and 6.8 which followed the AC method show that the average time for arriving aircraft is much higher than that of departing aircraft.
TABLE 6.7 Delay Time Calculation for Category "3,000 ft-4,299 ft"

Delay Time Calculation for Parallel Runway

1. Hourly Capacity Calculation (use Fig. 3.2, 3.3)
   a. Select runway: Diagram No. 11
   b. Fig. Number: 3-50 for capacity under IFR
      3-95 for delay under IFR
   c. mix index: C + 3D = 100 + 0 = 100 (class C: 100%)
   d. Percent arrivals (PA): 50%
      Hourly capacity base (C'): 85
      Touch and Go factor (T): 1.00
      Taxiways exit factor (E): 1.00
   e. Hourly Capacity = C'*T*E = 85 aircraft per hour

2. Hourly Delay Time Calculation (use Fig. 3.5, 3.6)
   a. Calculate hourly capacity: 85
   b. Identify hourly demand (HD): 74 (assumed)
   c. Peak 15 min. demand (Q)= 74 * 0.25 = 19
   d. Hourly demand to capacity ratio (D/C)= 74/85= 0.87
   e. Arrival delay index (ADI): 1.0
      Departure delay index (DDI): 0.47
   f. Arrival delay factor (ADF)= ADI*(D/C)=1.0 * 0.87=0.87
      Departure delay factor (DDF)= DDI*(D/C)=0.47*0.87=0.41
   g. Demand profile factor (DFP)= (100 * Q)/ HD
      = (100 * 19)/ 74 = 25.7
   h. Average delay for arriving aircraft (HAHA): 1.7 minutes
      Average delay for departing aircraft (DAHD): 0.1 minutes
   i. Hourly delay (DTH)= HD { PA* DAHA+ (100-PA) * DAHD }/100
      = 74 {50* 1.7+ (100-50)*0.1}/100
      = 66.6
      Average delay = 66.6/74=0.9 min.
TABLE 6.8 Delay Time Calculation for Category "2,500 ft - 2,999 ft"

<table>
<thead>
<tr>
<th>Delay Time Calculation for Parallel Runway</th>
</tr>
</thead>
</table>

1. Hourly Capacity Calculation (use Fig. 3.2, 3.4)

a. Select runway: Diagram No. 10
b. Fig. Number: 3-49 for capacity under IFR
   3-95 for delay under IFR

c. mix index: $C + 3D = 100 + 0 = 100$ (class C: 100%)
d. Percent arrivals (PA): 50%  
   Hourly capacity base (C): 70  
   Touch and Go factor (T): 1.00  
   Taxiways exit factor (E): 1.00  
   Hourly Capacity = $C \times T \times E = 70$ aircraft per hour

2. Hourly Delay Time Calculation (use Fig. 3.5, 3.6)

a. Calculate hourly capacity: 70
b. Identify hourly demand (HD): 70 (assumed)
c. Peak 15 min. demand (Q) = 70 * 0.25 = 18
d. Hourly demand to capacity ratio (D/C) = 70/70 = 1.00
e. Arrival delay index (ADI): 1.0  
   Departure delay index (DDI): 0.5
f. Arrival delay factor (ADF) = ADI/(D/C) = 1.0 / 1.0 = 1.00  
   Departure delay factor (DDF) = DDI/(D/C) = 0.5 / 1.0 = 0.50
g. Demand profile factor (DPF) = (100 * Q) / HD  
   = (100 * 18) / 70 = 25.7
h. Average delay for arriving aircraft (HAHA): 2.9 minutes  
   Average delay for departing aircraft (DAHD): 0.1 minutes
i. Hourly delay (DTH) = HD * (PA * DAHA + (100-PD) * DAHD) / 100  
   = 70 * (50 * 2.9 + (100-50) * 0.1) / 100  
   = 105.0
   Average delay = 105.0 / 70 = 1.5 min.
7.0 Conclusions and Recommendations

7.1 Conclusions

The goal of this project was to compare the capacity and delay of three different type runway configurations by using the computer simulation model SIMMOD. The main effort in performing this project has been focused to find out the advantage of the Fanway concept. In addition, a comparison of two different types of aircraft approach diagonal separations
were examined. In order to compare the capacity and delay time and to find out diagonal separation sensitivity a total of 5 scenarios with 28 cases were simulated using the SIMMOD. Through this comparison and analysis the merits of SIMMOD were checked and the simulation results were compared against a mathematical method which followed the Advisory Circular in order to correlate results. mathematical methods.

Through this project performance the Fanway configuration has been evaluated positively as follows:

- The Fanaway could increase airport capacity or reduce delay time without large land extension.
- The practical capacity of Fanway is 7.2% greater than that of the parallel runway under current flight rule.
- In the delay time point of view the Fanway could reduce the delay time about 15.1%.
- As shown in Fig. 6.1 the practical capacity gap between Fanway and parallel runway is being widening with increasing aircraft operations. From this trend the Fanway can be expected to receive stronger support when it is applied to solve the more congested airport problem than any of the other runway configurations including the parallel runway.
- An evaluation of the Fanway indicated that it could not
only reduce the delay time but also the fuel consumption.

Through the diagonal separation sensitivity analysis the following conclusions can be made:

- The Fanway configuration has more advantage when it is applied to the future diagonal separation goal 1.5 NM than the current separation rule 2.0 NM as shown in Table 7.1 which presents a numerical benefit of Fanway compared to the parallel runway.

- The effectiveness of distance reductions in a parallel runway configuration is not as high as the Fanway case.

- In the case of parallel runway when the diagonal separation had been reduced from 2.0 NM to 1.5 NM the aircraft delay time in airspace was decreased about 22% but the ground delay time was increased by 9 % because of ground capacity limitation but the fuel consumption could be reduced by 18.6% when the aircraft operation is 60 in parallel runway.
### TABLE 7.1 Benefits of Fanway over Parallel Runway

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<th>Diagonal Separation</th>
<th>Practical Capacity (1)</th>
<th>Delay Time (2)</th>
<th>Fuel Consumption (3)</th>
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<tr>
<td>2.0 NM (Current)</td>
<td>+ 6.0%</td>
<td>- 15.1%</td>
<td>- 15.6%</td>
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<tr>
<td>1.5 NM (Future Goal)</td>
<td>+ 14.3%</td>
<td>- 32.1%</td>
<td>- 18.6%</td>
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Remark: (1) Assume the acceptable delay time is 3 minutes.
(2) When the aircraft operation number is 80.
(3) When the aircraft operation number is 60.
The conclusions which were obtained from the comparison between SIMMOD simulation and mathematical methods are as shown follows:

- A comparison of airport capacity and delay time calculation results based on the different method seemed very hard and dangerous.
- Generally speaking the runway capacity resulting from the mathematical method which followed the Advisory Circular was higher than that of SIMMOD.
- The runway capacity and delay time which were obtained from AC seem to have stepped sensitivity that could mislead airport planners and designers to select an unsuitable capacity which looks optimistic.
- The spacing category of the parallel runway in Advisory Circular is required to be more divided.
- The aircraft operation procedure in SIMMOD which assumed the arriving aircraft has priority is considered a more reasonable idea than the Advisory Circular method which showed that the delay time of the arriving aircraft were much higher than that of departing aircraft.

As seen in the previous discussion the SIMMOD was used as a tool in this project to compare the different runway configurations and to find out the sensitivity of the
variation in diagonal separation. Through applying the SIMMOD to this project some advantages and disadvantages were discovered. They are as follows:

- The SIMMOD simulation model could be applied to any type of airfield configuration, even to a new type like a Fanway which is not mentioned in the current Advisory Circular 150/5060-5.

- The SIMMOD program logic makes it possible to represent the real world in simulation.

- The digitizing functions make it easier for an user to create or to modify the real configuration through the monitor screen.

- The animation function in the SIMMOD post-processing part was used as a very convenient and important tool to see whether there is any error in simulation processing such as an aircraft operation procedure.

- The SIMMOD post-processing function could produce many useful varieties of data such as airspace and ground delay time and fuel consumption that could help airport planners or air space controllers without entering any additional data input.

- If once the SIMMOD simulation input data was confirmed to be correct and the animation showed that the simulation result is closed to that of a real world, it
make it possible to analyze airport and airspace problem quicker.

- It is not easy to learn and use SIMMOD and a misunderstanding of the SIMMOD logic can lead to erroneous results.

- A worse case scenario is expected when wrong concepts are applied to the SIMMOD if there is no error in the relationship between airspace and ground. SIMMOD could simulate the erroneous data and produce wrong results without checking the correctness of the data.

- Sometimes many debugs were necessary during a simulation run or the simulation processing was stopped without a clear explanation. Thus it is recommended to revise SIMMOD to overcome this deficiencies.

7.2 Recommendations

As mentioned in the conclusion the Fanway was evaluated as an useful configuration through using the SIMMOD simulation model. Some results seem different from previous research. For example, Lucas [Lucas, 1983] pointed out that the Fanway
can reduce an arrival airfield delay by 35% and a FAA publication [FAA, 1989f] mentioned that approximately 14 total additional arrivals per hour are possible if the diagonal separation are changed to 1.5 NM. In the course of this project the relationship of each result was not examined because it required an analysis of each background. Thus further comparison of each result is required with a knowledge of all the inter relationships and an understanding of the assumptions of each method.

In this project the small number of aircraft were simulated over a period of 20 minutes to save computational time because the SIMMOD simulation times are very long under the DOS operating system. Thus it is recommended that future studies consider considerably longer periods of time to simulate more appropriately several peak hour airport operations. For this an OS/2 or UNIX environment should be used.

In terms of aircraft distributions a more realistic aircraft distribution should be used.

A recent research work [Kim, 1990] pointed out that a high speed exit on the runway contributes to the reduction of runway occupancy time (ROT) and it provides enhancement in runway capacity. But in this project the use of high speed
exits due to the limited capabilities of the model in this area. Thus further research is recommended to define the application of optimum high speed exits to the Fanway configuration.

Even though SIMMOD simulation results showed that the Fanway could contribute to enhance the airport capacity, but more research is need to validate the operational safety of the concept. A actual aircraft operations are strongly recommended to establish safe final approach control procedures avoiding wake turbulence. Also the ergonomics of these operations should be further investigated.
Bibliography


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Appendix A. SIMMOD Input Data

Remark: Fanway 2.0 NM, 72 Aircraft Operations

Airspace

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118
LINKS Over = 0, Wake = 1, Cap = 10 ac, Del = 1 min, Mlinks = 19
0003 LINK_3 8 7 100 270 6 1 1 5 1 0 ;
0004 LINK_4 9 8 100 270 5 1 0 5 1 0 ;
0005 LINK_5 10 11 100 270 4 1 0 5 1 0 ;
0006 LINK_6 11 12 100 270 3 1 0 5 1 0 ;
0007 LINK_57 38 76 100 278 4 1 0 5 1 0 ;
0008 LINK_58 36 59 100 261 4 1 0 5 1 0 ;
0009 LINK_59 69 53 99 259 6 1 1 5 1 0 ;
0010 LINK_60 70 69 101 232 5 1 0 5 1 0 ;
0011 LINK_61 72 55 99 280 6 1 1 5 1 0 ;
0012 LINK_62 73 72 100 304 5 1 0 5 1 0 ;
0013 LINK_63 76 77 117 320 3 1 0 5 1 0 ;
0014 LINK_64 79 79 98 227 3 1 0 5 1 0 ;
0116 LINK_116 7 121 40 270 7 1 1 3 1 0 ;
0117 LINK_127 53 121 44 245 7 1 1 3 1 0 ;
0118 LINK_128 55 121 44 294 7 1 1 3 1 0 ;
0119 LINK_129 121 37 60 270 8 0 0 1 1 0 ;
0130 LINK_130 121 6 60 269 8 0 0 1 1 0 ;
0131 LINK_131 121 39 60 269 8 0 0 1 1 0 ;

ROUTES Def sep dist = 2.5 nm, Max route = 6, nodes/route = 5
1 ARR-1 ; 9 8 7 121 6 ;
2 DEP-1 ; 10 11 12 ;
3 ARR-2 ; 70 69 53 121 37 ;
4 DEP-2 ; 36 59 79 ;
5 ARR-3 ; 73 72 55 121 39 ;
6 DEP-3 ; 38 76 77 ;

PROCEDURES Def time sep = 50 sec, dist sep = 3 n miles
1 ARR FC2 27X 6 ;
2 DEP FC2 27X 6
3 ARR FC2 26X 37 ;
4 DEP FC2 26X 37
5 ARR FC2 28X 39 ;
6 DEP FC2 28X 39

119
AIRCRAFT There are 4 aircraft groups

1 GA Min ceiling = 1000 feet, min rwy vis = 2500
T 220.00 T 220.00 T 220.00 T 200.00 T 200.00 T 200.00 T 200.00 T 180.00 T 160.00 T 140.00
T 130.00 ;
T 200.00 T 200.00 T 200.00 T 180.00 T 180.00 T 160.00 T 140.00 T 120.00
T 110.00 ;
T 180.00 T 180.00 T 180.00 T 160.00 T 160.00 T 140.00 T 120.00 T 100.00
T 100.00 ;
2.0 ; 1.0 ; 110 ;
2.50 2.50 2.50 6.00 ;
0. 1.0 .2 1.0 1.0 1.0 ;
60 61 ;

2 SMW Min ceiling = 200 feet, min rwy vis = 1800
T 270.00 T 270.00 T 250.00 T 240.00 T 220.00 T 200.00 T 180.00 T 160.00
T 140.00 ;
T 250.00 T 250.00 T 230.00 T 220.00 T 200.00 T 180.00 T 160.00 T 140.00
T 120.00 ;
T 230.00 T 230.00 T 210.00 T 200.00 T 180.00 T 160.00 T 140.00 T 120.00
T 110.00 ;
2.0 ; 1.0 ; 180 ;
2.50 2.50 2.50 6.00 ;
0. 1.0 .2 1.0 1.0 1.0 ;
33 34 36 39 46 47 48 49 50 55 54 55 56 57 59 64 65 66 ;

3 LRG Min ceiling = 100 feet, min rwy vis = 1200
T 380.00 T 350.00 T 320.00 T 290.00 T 260.00 T 230.00 T 200.00 T 170.00
T 150.00 ;
T 360.00 T 330.00 T 300.00 T 270.00 T 240.00 T 210.00 T 180.00 T 150.00
T 130.00 ;
T 340.00 T 310.00 T 280.00 T 250.00 T 220.00 T 190.00 T 160.00 T 130.00
T 120.00 ;
2.0 ; 1.0 ; 210 ;
2.50 2.50 2.50 5.00 ;
0. 1.0 .2 1.0 1.0 1.0 ;
5 6 7 9 10 11 13 23 24 25 26 27 28 29 32 35 37 38 40 41 42 43 44 45 51 52 55 62 63 ;

4 HVY Min ceiling = 0 feet, min rwy vis = 700
T 380.00 T 350.00 T 320.00 T 290.00 T 260.00 T 230.00 T 200.00 T 170.00
T 150.00 ;
T 360.00 T 330.00 T 300.00 T 270.00 T 240.06 T 210.00 T 180.00 T 150.00
T 130.00 ;
T 340.00 T 310.00 T 280.00 T 250.00 T 220.00 T 190.00 T 160.00 T 130.00
T 120.00 ;
2.0 ; 1.0 ; 210 ;
2.50 2.50 2.50 4.00 ;
0. 1.0 .2 1.0 1.0 1.0 ;
1 2 3 4 8 12 13 15 14 16 17 18 19 20 21 22 30 31 ;
AIRPORTS Def ceiling = 1000 ft, def rwy vis range = 10000 ft
1 FC2 Elev = 0 6 10 37 36 39 38 ;

120
No description entered
11;
;
1; 2;
;
13;
;
1; 4;
;
15;
;
1; 6;
;
GO

Airfield (Ground)

PRINT 1
AFNODES In this run, 89 is the largest node number
FC2 6 10 13 14 15 16 17 18 21 24 26 36 37 38 39 41 42 47 48 81 82 83 84 85 86 87 89
COORDINATES In this run, there are 27 nodes having coordinates.

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122
RUNWAYS Taxi Speed = 35 mph. Crossing delay = 5
1  27X  09X  96  1500  0  15  97  21  20  FC2
2  25X  08X  80  1500  0  15  98  62  32  FC2
3  28X  10X  99  1500  0  15  96  54  53  FC2

DEPARTQ These are the airfield departure queues.
1  FC2 QUE-1  6
2 ;
2  FC2 QUE-2  37 1
4 ;
3  FC2 QUE-3  39 1
6 ;

GATES There are 1 boarding gates in this simulation
1  89  4  100 ONLY  FC2 YES ALL 92 ;
;

TAXIPATHS These are the user defined taxi paths.

TAMPS There are 4 ground data groups in this run
1  30  15
  0.  1200  1.00  1200 ;
  0.  2000  1.00  2000 ;
  0.  15  1.00  15 ;
  0.  10  1.00  10 ;
  60  61 ;
2  30  15
  0.  3500  1.00  3500 ;
  0.  4000  1.00  4000 ;
  0.  15  1.00  15 ;
  0.  10  1.00  10 ;
  33  34  36  39  46  47  48  49  50  53  54  55  56  57  59  64  65  66 ;
3  30  15
  0.  4000  1.00  4000 ;
  0.  5000  1.00  5000 ;
  0.  22  1.00  22 ;
  0.  22  1.00  22 ;
  5  6  7  9  10  11  23  24  25  26  27  28  29  32  35  37  38  40  41  42  43  44  45  51  52  58  62
  63 ;
4  30  15
  0.  4500  1.00  4500 ;
  0.  5500  1.00  5500 ;
  0.  35  1.00  35 ;
  0.  35  1.00  35 ;
  1  2  3  4  8  12  13  14  15  16  17  18  19  20  21  22  30  31 ;

AIRCRAFT These are the airlines serving the airports in this run.
1 G/A GNAB
2 SML AIRL
3 LAG AIRL

123
4 HVY AIRL

COST 35 50

GO

Events

SETPLAN 0. 1 0 3 FC2 27X FC2 26X FC2 28X *
TRACE 0. 0 ; 182 1 *
TRACE 0. 0 ; 183 1 *
TRACE 0. 0 ; 184 1 *
TRACE 0. 0 ; 185 1 *
TRACE 0. 0 ; 186 1 *
TRACE 0. 0 ; 1 1 *
TRACE 0. 0 ; 2 1 *
TRACE 0. 0 ; 3 1 *
TRACE 0. ; 181 1 *
MULTDEP 8.00000 LRG 4 5 FC2 2 ? ONLY 20 *
MULTDEP 8.00000 LRG 4 5 FC2 4 ? ONLY 20 *
MULTDEP 8.00000 LRG 4 5 FC2 6 ? ONLY 20 *
MULTARR 8.28183 LRG 4 5 FC2 1 ? ONLY 20 *
MULTARR 8.28183 LRG 4 5 FC2 3 ? ONLY 20 *
MULTARR 8.28183 LRG 4 5 FC2 5 ? ONLY 20 *
END.SIM 11.00000 *

124
Appendix B. SIMMOD Standard Report

GLOBAL REPORT AT 11:00:00 AFTER 1 ITERATION

OVERALL RECAP -- 07/31/1990 AT 15:17:39 (D) FARWAY 2.0 NM 72/HOUR

GROUND DELAY AND TRAVEL TIME STATISTICS (MINUTES)

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<th>TOTAL MEAN</th>
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AIR DELAY AND TRAVEL TIME STATISTICS (MINUTES)

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<th>S.D.</th>
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<tr>
<td>GLOBAL AIR TOTALS</td>
<td>24</td>
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<td>2</td>
<td>0</td>
<td>44</td>
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125
OVERALL DELAY AND TRAVEL TIME STATISTICS (MINUTES)

<table>
<thead>
<tr>
<th>ALL ROUTES</th>
<th>NUM</th>
<th>AVE TOTAL DELAY</th>
<th>AVE TOTAL TRAVEL</th>
<th>AVE TOTAL TIME</th>
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</thead>
<tbody>
<tr>
<td>GROUND PLUS AIR</td>
<td>A/C</td>
<td>MEAN</td>
<td>TOTAL</td>
<td>MEAN</td>
</tr>
<tr>
<td>ARRIVE SUBTOTALS</td>
<td>12</td>
<td>4</td>
<td>48</td>
<td>13</td>
</tr>
<tr>
<td>DEPART SUBTOTALS</td>
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<td>2</td>
<td>24</td>
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<td>TRANSIT SUBTOTALS</td>
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<tr>
<td>GLOBAL TOTALS</td>
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<td>3</td>
<td>72</td>
<td>11</td>
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SECTOR OCCUPANCY STATISTICS

<table>
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<tr>
<th>SECTOR</th>
<th>NUM</th>
<th>NAME</th>
<th>ITERATION VALUES</th>
<th>CUMULATIVE AVERAGES</th>
<th>NUMBER</th>
<th>MAX</th>
</tr>
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<td>1 DEFAULT</td>
<td>.31</td>
<td>11</td>
<td>.31</td>
<td>11</td>
<td>24.0</td>
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</tr>
</tbody>
</table>

AFTER 1 ITERATION OF RUN: 07/31/1990 AT 16:17:39 (O) FANWAY 2.0 NM 72/HOUR
THE OVERALL NUMBER OF FLIGHTS LATE (BY 5-MINUTE BUCKET) ARE:
21 FLIGHTS HAD A TOTAL AIR DELAY GREATER THAN OR EQUAL TO 0 AND LESS THAN 5 MINUTES.
3 FLIGHTS HAD A TOTAL AIR DELAY GREATER THAN OR EQUAL TO 5 AND LESS THAN 10 MINUTES.

AFTER 1 ITERATION OF RUN: 07/31/1990 AT 16:17:39 (O) FANWAY 2.0 NM 72/HOUR
FOR 5 SEC MINIMUM DELAY, THE OVERALL RUNWAY CROSSING DELAY STATISTICS (IN SECONDS) ARE:

<table>
<thead>
<tr>
<th>RUN#</th>
<th>APT</th>
<th>RUNWAY NAME</th>
<th>DELAYED XNGS</th>
<th>MEAN DELAY</th>
<th>MAX DELAY</th>
<th>TOTAL DELAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FC2</td>
<td>27X/09X</td>
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<td>0.</td>
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</tr>
<tr>
<td>2</td>
<td>FC2</td>
<td>26X/08X</td>
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<tr>
<td>3</td>
<td>FC2</td>
<td>28X/10X</td>
<td>4</td>
<td>44.6</td>
<td>48.4</td>
<td>178.5</td>
</tr>
<tr>
<td>ALL</td>
<td>FC2</td>
<td>TOTALS</td>
<td>4</td>
<td>44.6</td>
<td>48.4</td>
<td>178.5</td>
</tr>
</tbody>
</table>

AFTER 1 ITERATION, THE RANDOM SEED VALUES FOR EACH OF 10 STREAMS ARE:
1-728486615 2-1335884653 3-158967721 4-937458397 5-18533129840
6-1157260309 7-15726055 8-48108509 9-1797920909 10-477424540

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Appendix C. SIMMOD Delay Time Report

**FC2 Airport - All Runway Arrival Ground and Air Travel and Delay Times**

Based on 1 iteration included in the following禁毒版
01/01 07/31/1990 at 16:17:30 (G) Farway 2.0 mn 72/Hour
All Airlines, Airports, and Iterations are included in this report.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>FC2 Overall Arrival Times (min)</th>
<th>Average Arrival Times (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Travel</td>
<td>Delay</td>
</tr>
<tr>
<td></td>
<td>Flow</td>
<td>TOT SDV</td>
</tr>
<tr>
<td>06:00-07:00</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>07:00-08:00</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>08:00-09:00</td>
<td>12.00</td>
<td>150.2</td>
</tr>
<tr>
<td>09:00-10:00</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>10:00-11:00</td>
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<td>0.00</td>
</tr>
<tr>
<td>11:00-12:00</td>
<td>0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

FC2 Totals: 12.00 | 150.2 | 47.5 | 2.72 | 9.17 | 3.35 | 22.00 | 34.32 | 3.63 | 0.53 | 0.00

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>26x Overall Arrival Times (min)</th>
<th>Average Arrival Times (min)</th>
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</thead>
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<tr>
<td></td>
<td>Travel</td>
<td>Delay</td>
</tr>
<tr>
<td></td>
<td>Flow</td>
<td>TOT SDV</td>
</tr>
<tr>
<td>06:00-07:00</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>07:00-08:00</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>08:00-09:00</td>
<td>4.00</td>
<td>47.7</td>
</tr>
<tr>
<td>09:00-10:00</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>10:00-11:00</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>11:00-12:00</td>
<td>0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

26x Totals: 4.00 | 47.7 | 21.5 | 2.64 | 9.20 | 2.72 | 22.00 | 33.92 | 5.21 | 0.17 | 0.00

<table>
<thead>
<tr>
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<th>Average Arrival Times (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Travel</td>
<td>Delay</td>
</tr>
<tr>
<td></td>
<td>Flow</td>
<td>TOT SDV</td>
</tr>
<tr>
<td>06:00-07:00</td>
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<td>0.00</td>
</tr>
<tr>
<td>07:00-08:00</td>
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<td>0.00</td>
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<tr>
<td>08:00-09:00</td>
<td>4.00</td>
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<tr>
<td>10:00-11:00</td>
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<td>0.00</td>
</tr>
<tr>
<td>11:00-12:00</td>
<td>0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

27x Totals: 4.00 | 49.7 | 10.0 | 1.96 | 9.08 | 3.35 | 22.00 | 34.43 | 2.50 | 0.23 | 0.00

<table>
<thead>
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</thead>
<tbody>
<tr>
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<td>Travel</td>
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<td></td>
<td>Flow</td>
<td>TOT SDV</td>
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<td>06:00-07:00</td>
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<td>08:00-09:00</td>
<td>4.00</td>
<td>52.8</td>
</tr>
<tr>
<td>09:00-10:00</td>
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<td>0.00</td>
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<tr>
<td>10:00-11:00</td>
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<td>0.00</td>
</tr>
<tr>
<td>11:00-12:00</td>
<td>0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

26x Totals: 4.00 | 52.8 | 15.1 | 0.71 | 9.22 | 3.96 | 22.00 | 35.20 | 3.18 | 0.60 | 0.00

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FCZ AIRPORT -- ALL SUNDAY DEPARTURE GROUND AND AIR TRAVEL AND DELAY TIMES
BASED ON 1 ITERATION INCLUDED IN THE FOLLOWING LINKED RUN:
01:01 07/31/1990 AT 16:17:39 (C) SATURDAY 2.0 HR 72/HOUR
ALL AIRLINES, AIRPORTS, AND ITERATIONS ARE INCLUDED IN THIS REPORT.

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<thead>
<tr>
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<th>AVERAGE DEPARTURE TIMES (MIN)</th>
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<tbody>
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<td>DEPARTURE</td>
<td>TRAVEL</td>
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<tr>
<td></td>
<td>FLOW</td>
<td>TOT</td>
</tr>
<tr>
<td>06:00-07:00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>07:00-08:00</td>
<td>0</td>
<td>0</td>
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<tr>
<td>08:00-09:00</td>
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<td>119.6</td>
</tr>
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<td>09:00-10:00</td>
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</tr>
<tr>
<td>10:00-11:00</td>
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<td>PCZ TOTALS:</td>
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</tr>
<tr>
<td></td>
<td>FLOW</td>
<td>TOT</td>
</tr>
<tr>
<td>06:00-07:00</td>
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<th>AVERAGE DEPARTURE TIMES (MIN)</th>
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<tr>
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<td>FLOW</td>
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<td>27K TOTALS:</td>
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<td>FLOW</td>
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<td>10:00-11:00</td>
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<tr>
<td>11:00-12:00</td>
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<tr>
<td>28K TOTALS:</td>
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</tbody>
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