Empirical Analysis of Runway Occupancy with Applications to Exit Taxiway Location and Automated Exit Guidance

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Airfield delay has a substantial economic impact on the users and suppliers of air transportation in the United States. A possible cost-effective measure to enhance runway capacity is to reduce the headway between aircraft arrivals and departures. Previous studies indicate that this alteration in operational procedure may increase runway capacity between 15 and 40 percent. Such a reduction in aircraft headway, however, implies that runway occupancy may become a constraint. Existing jet aircraft runway occupancy is addressed. Using data obtained from videotaped aircraft arrivals at four major airports in the western United States, factors that contribute most to arrival runway occupancy are analyzed. In particular, observed differences caused by airport-, aircraft-, and airline-related factors are identified. A model based on typical time-velocity relationships is developed, and the applications of such a model are presented. Using the model, two feasible alternatives are identified for a potential decrease in runway occupancy, which could then provide a possible increase in airfield capacity. Those alternatives are the development of exit taxiway automation, and the introduction of Integrated Landing Management systems to match aircraft headways with existing runway occupancy times. Such a motivational system would be provided by the use of a real-time automated exit guidance system. The most serious impacts of such a system are those that deal with safety, which are beyond the scope of this paper. The ability to expand capacity at U.S. airports is of primary concern to the aviation industry. In particular, the potential for more efficient utilization of existing airport facilities is the most cost-effective procedure of upgrading airfield capacity. Airport capacity are not all caused by runway occupancy and its related impacts. Nevertheless, Gosling et al. (1) estimate that approximately $75 million per year (1981 dollars) can be saved in aircraft operating costs by reducing runway occupancy, with even larger savings possible in the future. Although runway occupancy is not a constraint, further increases in runway capacity implied by changes in operational procedures require reducing the headway between aircraft. Therefore, runway occupancy may become a critical factor. To better understand the potential for reducing runway occupancy time, a field study was performed by videotaping aircraft operations at four major airports in the western United States. The components of the landing sequence were analyzed on the basis of aircraft type (which is significant, especially because of the recent introductions of various Stage III aircraft) to statistically determine differences between airport-, aircraft-, and airline-related factors and to determine the parameter distributions.

The scope of this paper is to provide some insight into the possibilities of studying changes within the arrival process by developing a landing process model, sampling the various parameter distributions within the model, and illustrating how such a model can be applied toward improved exit taxiway location and innovations such as real-time deceleration guidance. With an improved knowledge of the aircraft arrival process, the potential exists for more effective airfield designs, thereby making capacity enhancement alternatives possible for the future.

BACKGROUND

Various studies concerning runway occupancy have produced similar results. In 1978, Koenig (2) analyzed observations collected in 1972 and 1973 and concluded that the dominant factor influencing a carrier's exit selection was its terminal gate location. Other controlling factors identified were incoming traffic density, flight crew performance, airline procedure, and passenger comfort. Significant differences were found between carriers motivated and not motivated by operational factors to exit early. It was estimated that feasible exits currently exist, although they are highly underutilized because of the availability of more favorable exits in terms of gate location. Also, it was estimated that further reductions in runway occupancy of between 2 and 16 sec could be anticipated if motivational factors were better incorporated.

In a study conducted in 1979, Jackson and Moy (3) verified Koenig's findings. They found that airline gate location had the most influence on runway occupancy. Thus it appeared, given certain conditions, that measures did exist to enhance runway capacity by employing motivational factors to decrease runway occupancy time. In addition, Jackson and Moy concluded that Instrument Flight Rule conditions actually led to a decrease in runway occupancy time because of an increase in operational awareness. This finding, however, was contrary to the conclusions reached in a later study by Steuart and Gray (4), which showed that runway occupancy times actually increase during poor weather conditions because of lower exit acceptance speeds and less braking adjustment to meet a particular exit.
One of the key variables involved in reducing runway occupancy time is the placement of exit taxiways. Methods for determining the location of exit taxiways (particularly high-speed taxiways) during saturation conditions were first developed around 1959. Two early studies by Horonjeff et al. (5, 6) employed analytical models whereby optimal runway exit locations were determined from the standpoint of minimizing runway occupancy and wave-off probabilities. Later, in 1974, Daellenbach and Joline used dynamic programming concepts to optimize the placement of exit taxiways. Daellenbach’s solution (7) determined exit locations using any joint probability distribution function of deceleration distances and times and any number of exits, which minimized the expected probability of a wave-off. Joline (8), using empirical exit distributions measured for the aircraft mix at O’Hare International Airport, developed an objective function to locate exit taxiways by minimizing runway occupancy time given capital investment constraints.

With the various methods of determining exit taxiway locations, empirical observations suggest that many aircraft use high-speed exits at approximately 20 to 40 mph below their design speeds (9, 10). In separate studies, completed at different airport locations, Akinneya and Braaksma (9), FAA (10), and Hosang (11) concluded that, among other reasons, high-speed exits were underutilized because of the desire to avoid unnecessary risk or passenger discomfort, the location of other exits in better proximity to the terminal building, and the incompatibility between aircraft performance with exit locations and geometric designs. FAA (10) analyzed existing runway occupancy statistics and concurrently developed design criteria and requirements for the redesign of high-speed exits. The results led FAA (12) to publish suggested exit taxiway locations for an “average” aircraft mix. Similar design specifications are provided by the International Civil Aviation Organization (ICAO) Aerodrome Design Manual (13).

Even today, there still appears to be a disparity in runway occupancy times among the various aircraft types. Of the methods used to determine exit taxiway locations, none rely on the individual parameters of the various aircraft types, nor are they based on any criterion for passenger comfort. The previous models are formulated on generalized relationships between landing distances and occupancy times and, in certain instances, the probability of a wave-off. If operational procedures are altered to increase capacity such that the landing sequence becomes critical, more detailed information will be necessary to assimilate the possibilities of obtaining such increases in capacity.

**MODEL OF THE LANDING SEQUENCE**

The runway occupancy model is based on the ability to use Monte Carlo simulation to generate aircraft arrivals that would reflect the input parameter distributions of the design aircraft, or those in use at the airport in question. The model is employed to analyze any changes in the parameter distributions or, in the case of exit taxiway locations, to determine the probability that an aircraft is able to accept an exit at any given location along the runway. Such cumulative acceptance curves may be estimated by trial runs of a given number of simulated aircraft arrivals. The percentage of aircraft accepting those exits can then be determined for any number of different exit taxiway locations by repeating the simulation for each exit location.

Input variables may be represented by random numbers with known means and variances that reflect the influences of environmental and airport conditions, as well as pilot technique. The general outline of the model is founded on basic kinematic equations that are developed in several discrete components, similar to those presented by Coggins (14). In order to distinguish between phases, time-velocity diagrams and a simplified profile view of typical aircraft arrivals are shown in Figure 1.

Initially, the aircraft passes the runway threshold at a height \( H_T = 0 \) and travels approximately at a constant velocity \( V_T \) until the flare maneuver, at which time the aircraft begins an in-air deceleration. This deceleration may take place at the runway threshold as well. Given the height at which the in-air deceleration is initiated, \( H_T \), the approximate glide slope of the aircraft, \( S \) (feet/foot), and the wind speed component parallel to the moving aircraft, \( V_w \) (ft/sec) \( [(+] = \text{headwind}, (-) = \text{tailwind}] \), the time and distance to flare may be estimated by

\[
T_f = \frac{S(H_T - H_f)}{(V_T - V_w)}
\]

\[
D_f = S(H_T - H_f) = 19(H_T - H_f)
\]

for a 3-degree glide slope

After initiating the flare maneuver, the aircraft begins its in-air deceleration, \( a_{\text{air}} \), until the point of main gear touchdown. The touchdown airspeed of the aircraft, \( V_{TD} \), is not an independent variable. It is dependent on the airspeed at threshold. Thus, by describing the relationship between the touchdown speed and the speed at the runway threshold \( [V_{TD} = f(V_T)] \) the time and distance to main gear touchdown may be estimated by

\[
T_{TD} = \frac{(V_{TD} - V_T)}{a_{\text{air}}} + T_F \quad (V_T = V_T)
\]

\[
D_{TD} = V_T(T_{TD} - T_F) + \frac{1}{2} a_{\text{air}}(T_{TD} - T_F)^2 + D_F
\]

The sequence continues as the aircraft rotates to nose gear touchdown where it experiences a slight roll deceleration \( a_{\text{roll}} \) due to the resistance gained by the surface friction between the pavement and the aircraft’s main landing gear. The roll deceleration appears to be slightly larger than the in-air deceleration as the resistance gained by surface friction overcomes the resistance lost by the aerodynamic drag of the flare maneuver. Given this deceleration and the difference in time for the aircraft to rotate from main gear down until nose gear down \( (T_{NG} - T_{TD}) \) the airspeed \( V_{NG} \) and distance \( D_{NG} \) at nose gear touchdown may be found from

\[
V_{NG} = (T_{NG} - T_{TD}) a_{\text{roll}} + V_{TD}
\]

\[
D_{NG} = V_{TD}(T_{NG} - T_{TD}) + \frac{1}{2} a_{\text{roll}}(T_{NG} - T_{TD})^2 + D_{TD}
\]

Immediately after touchdown, the deceleration rate reaches a maximum with the occurrence of reverse thrust and braking.
Depending on the exit location, aircraft speed is then adjusted to a safe handling speed for that exit. This can occur in two ways. First, the pilot may adjust deceleration to a lower rate so that the aircraft is at a safe acceptance speed by the time the exit is reached (Figure 1a). Second, the pilot may coast on the runway and engage in several distinct deceleration patterns (Figure 1b). An average braking deceleration rate will be used in this paper (Figure 1c). If this average deceleration rate allows the simulated aircraft to accept the exit or to stop before reaching the exit, it will be assumed that the pilot adjusted (decreased) the deceleration rate to meet the exit acceptance speed. This would be reflected in an average deceleration rate lower than the initial rate generated in the Monte Carlo simulation.

Once the aircraft begins braking deceleration, it traverses the runway until it comes to a point where a decision is made whether to accept a given exit and to turn off the runway. This decision point is assumed to be at the intersection of the exit taxiway centerline and the runway centerline. Therefore, knowing the average braking deceleration rate \(a_{\text{brake}}\), the velocity \(V'\) at any point \(x\), measured in feet from the runway threshold, can be determined from

\[
V' = \left[ V'_{\text{GC}} + 2a_{\text{brake}} (x - D_{\text{NG}}) \right]^{1/2}
\]  

(7)

for which the prime denotes groundspeed. Comparing \(V'\) with the exit acceptance velocity \(V'_{\text{E}}\), the velocity at which a safe exit maneuver may be initiated, it can be determined whether an aircraft will accept a given exit placed at a distance \(x\) from the runway threshold. The time and distance to the exit are calculated by

\[
T_E = \frac{(V'_{\text{E}} - V'_{\text{NG}})}{a_{\text{brake}}} + T_{\text{NG}}
\]  

(8)

\[
D_E = \frac{V'^2_{\text{E}} - V'^2_{\text{NG}}}{2a_{\text{brake}}} + D_{\text{NG}}
\]  

(9)

If no information is known concerning runway friction factors and gradients, which are effective when estimating stopping distances under inclement weather conditions and for abnormal runway grades, Equation 9 may be rewritten as

\[
D_E = \frac{(V'_{\text{E}} - V'_{\text{NG}})^2}{2g} (f + G) + D_{\text{NG}}
\]  

(10)

where

\[
g = \text{acceleration of gravity (32.2 ft/sec}^2),
\]

\[
f = \text{coefficient of friction between the tires and the runway surface, and}
\]

\[
G = \text{grade of the runway over which the aircraft is traveling [(+) = upgrade, (-) = downgrade].}
\]

The final segment of the landing process involves the time an aircraft takes to clear the runway from the time it initiates its turn off the runway. This increment is a function of the exit type. Using the exit acceptance speed, the time to clear the runway can be found by dividing the arc length traversed by the exit acceptance speed. This value is only an approximation because a slight deceleration will still be taking place.
PARAMETER DISTRIBUTIONS

Field Study

In order to determine the input parameter distributions as well as the influence of various airport-, aircraft-, and airline-related factors, including environmental conditions and pilot technique, a field study was performed. It involved simultaneously videotaping arriving aircraft, recording approach speeds from the ARTS III BRITE radar display, and recording tower-to-aircraft communication at the following four airports: Metropolitan Oakland International Airport (OAK), Phoenix Sky Harbor International Airport (PHX), San Francisco International Airport (SFO), and San Jose International Airport (SJC).

At each airport, standard videotaping equipment was used to film as many air carrier jet aircraft as possible during a 2-hr time frame that was prearranged with the FAA. Aircraft were filmed from the control tower and were followed throughout the landing sequence as they appeared approximately 1 mi out from the runway threshold. The aircraft were then followed through touchdown, braking, and exiting until at least the tail of the aircraft had crossed the runway edge striping as it proceeded onto the exit taxiway. While the aircraft was being videotaped, its approach speed at each mile from the runway threshold, beginning at the outer marker (5 nautical mi out), was recorded from the BRITE radar display. Concurrently, tower-to-aircraft communication was recorded to obtain existing wind information and any special instructions given to and among the pilots. In addition, weather information was obtained from the Automated Terminal Information System.

A complete analysis of the landing sequence was conducted for 180 aircraft. This included the aircraft type (B727, MD80, etc.), airline, flight number, runway, airport, date, approximate time, weather conditions, groundspeed at 5 mi out (outer marker), distances and times to touchdown, height at threshold, runway occupancy time, and any special instructions given to a pilot. In addition, the velocity at touchdown was estimated by fitting a smooth curve to a plot of velocity versus position from the runway threshold, using the information obtained from the BRITE radar screen. In all, 20 hr of videotaping was produced, with the traffic density during the 2 hr of filming varying considerably between airports. An additional 100 arrivals were analyzed by recording aircraft type, airline, exit location, runway occupancy time, and the radio transmission between the pilots and the control tower. These observations were incomplete because of the inability to reference positions in the video image for certain situations (crossing threshold, touchdown, etc.).

Once the aircraft was viewed over the runway, time and distance information was recorded with the aid of a stopwatch contained within the video image and an aerial photograph of the airfield surface. The height of the aircraft at threshold (referenced from the bottom of the nose gear) could be estimated to the nearest 5 ft by using video-enhancing computer software and proportioning known heights of the aircraft from the bottom of its nose gear to the top of the cabin with the respective heights in the video image.

Distance references were made from touchdown markings as well as centerline striping and any other distinct objects that could be witnessed in the image. Times to touchdown (both main gear and nose gear) were recorded to the nearest second and referenced from the time the aircraft crossed the runway threshold. Distances (to both main gear and nose gear touchdown) were also referenced from the runway threshold using the aircraft's nose gear position and recorded to the nearest 100 ft. In an attempt to verify position and threshold velocity estimations, the average speed from threshold to main gear touchdown and from threshold to nose gear touchdown was recorded for each arrival. (All recorded speeds were estimated to the nearest 5 knots.)

For most observations, speed estimations, such as those at touchdown and at other points along the runway, could not be obtained until the aircraft was close enough to the camera location because of the inability to distinguish known lengths and corresponding times at locations further away. However, using an average of the speeds from threshold to main gear touchdown and threshold to nose gear touchdown along with their corresponding positions, an average braking deceleration rate was estimated from touchdown to exit. It is emphasized that this is only an approximation because of the inability during the initiation of reverse thrust and braking, actual deceleration rates may be higher. A summary of the previously described information, segregated by aircraft type, is presented in Table 1.

Once the aircraft began to turn off the runway, its velocity at the decision point was determined by measuring the time that the aircraft nose gear traversed the final runway centerline hash mark of known length. Information by aircraft type for each exit is presented in Table 2. On the average, for both high-speed and right-angle exits, the average exit speed for heavy aircraft is approximately 7 knots less than that for large aircraft. Standard deviations of the various exit speeds are approximately 5 knots. Table 2 also indicates that the high-speed exits at Oakland appear to be entered at velocities closer to their design speed, because of their location and spiral (or transitional) design. In addition, the right-angle taxiways at Phoenix show relatively high speeds. For the most part, aircraft at Phoenix were able to “cut the corner” and not make as sharp a right turn as necessary at San Francisco because of the airfield pavement layout. Also, note that San Francisco exit taxiway J has the same average exit speed as exit taxiway T because of the difference in the aircraft mix using the exits. Both taxiways are high-speed designs, but taxiway T has a more gradual radius change and thus a higher design speed. In fact, the design speed of 60 knots is nearly
TABLE 1 EMPIRICALLY MEASURED PARAMETER DISTRIBUTIONS BY AIRCRAFT TYPE

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>Airspeed @ Threshold (knots)</th>
<th>Height @ Threshold (feet)</th>
<th>Distance to MG Down (feet)</th>
<th>Time to MG Down (seconds)</th>
<th>Distance to NG Down (feet)</th>
<th>Rotation (seconds)</th>
<th>Deceleration (ft/sec/sec)</th>
<th>Avg. Brake</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAe146</td>
<td>117</td>
<td>52</td>
<td>1980</td>
<td>11.3</td>
<td>2660</td>
<td>4.4</td>
<td>3.91</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>10.66</td>
<td>12.49</td>
<td>600</td>
<td>3.17</td>
<td>652</td>
<td>1.84</td>
<td>1.14</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>105-140</td>
<td>30-70</td>
<td>800-3200</td>
<td>5-17</td>
<td>1700-3900</td>
<td>2-8</td>
<td>1.7-3.9</td>
<td></td>
</tr>
<tr>
<td>Num. of Observations</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>B727</td>
<td>130</td>
<td>49</td>
<td>1870</td>
<td>8.5</td>
<td>2490</td>
<td>3.4</td>
<td>5.71</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>11</td>
<td>7.36</td>
<td>534</td>
<td>2.30</td>
<td>731</td>
<td>2.90</td>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>135-165</td>
<td>25-65</td>
<td>1100-2800</td>
<td>5-13</td>
<td>1500-3600</td>
<td>1-7</td>
<td>3.3-9.9</td>
<td></td>
</tr>
<tr>
<td>B737</td>
<td>129</td>
<td>54</td>
<td>2260</td>
<td>11.1</td>
<td>3000</td>
<td>3.9</td>
<td>5.76</td>
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</tr>
<tr>
<td>Standard Deviation</td>
<td>10.51</td>
<td>6.07</td>
<td>436</td>
<td>2.12</td>
<td>455</td>
<td>1.95</td>
<td>0.52</td>
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</tr>
<tr>
<td>Range</td>
<td>115-145</td>
<td>45-60</td>
<td>1400-2600</td>
<td>7-13</td>
<td>2300-3700</td>
<td>1-7</td>
<td>5.0-6.4</td>
<td></td>
</tr>
<tr>
<td>Num. of Observations</td>
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<td>68</td>
<td>68</td>
<td>68</td>
<td>68</td>
<td>68</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>B777</td>
<td>128</td>
<td>56</td>
<td>2360</td>
<td>11.6</td>
<td>3290</td>
<td>4.9</td>
<td>5.34</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>7.20</td>
<td>10.11</td>
<td>652</td>
<td>3.26</td>
<td>991</td>
<td>2.02</td>
<td>1.28</td>
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</tr>
<tr>
<td>Range</td>
<td>115-140</td>
<td>45-70</td>
<td>1500-3400</td>
<td>7-16</td>
<td>2200-5500</td>
<td>3-10</td>
<td>2.5-7.4</td>
<td></td>
</tr>
<tr>
<td>Num. of Observations</td>
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<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>MD80</td>
<td>134</td>
<td>54</td>
<td>1950</td>
<td>9.3</td>
<td>2650</td>
<td>3.5</td>
<td>5.49</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>12.75</td>
<td>9.90</td>
<td>457</td>
<td>2.11</td>
<td>505</td>
<td>1.48</td>
<td>1.31</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>105-160</td>
<td>35-70</td>
<td>1300-3100</td>
<td>6-14</td>
<td>1800-4000</td>
<td>1-8</td>
<td>1.7-8.7</td>
<td></td>
</tr>
<tr>
<td>Num. of Observations</td>
<td>28</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>All Heavies (B747, L1011, DC8, DC10)</td>
<td>141</td>
<td>64</td>
<td>2530</td>
<td>11.2</td>
<td>3970</td>
<td>5.9</td>
<td>5.91</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>7.19</td>
<td>10.46</td>
<td>828</td>
<td>3.53</td>
<td>1161</td>
<td>3.04</td>
<td>1.34</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>130-155</td>
<td>45-80</td>
<td>1300-4400</td>
<td>5-19</td>
<td>2300-6000</td>
<td>1-11</td>
<td>3.9-7.7</td>
<td></td>
</tr>
<tr>
<td>Num. of Observations</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

20 knots greater than the speed at which pilots are willing to begin to negotiate a turn onto the exit taxiway. Air traffic controller guidance was recorded and the runway occupancy time was determined as the time during which the aircraft began to cross the runway threshold until the tail of the aircraft had cleared the runway. Those runway occupancy times measured at the various airports for aircraft that were motivated to exit, either by terminal gate location or by air traffic controller guidance, as well as those that were not motivated are presented in Table 3. Comparison with other published studies indicates relative similarity in runway occupancy times even though some of the earlier studies are analyses of aircraft landings conducted 10 to 20 years ago. Thus, major changes in runway occupancy times have not occurred with the introduction of various Stage III aircraft. More important, note the wide range of runway occupancy times for motivated carriers.

Review of Other Data Sources

In order to provide a realistic and accurate model of the landing process, it is necessary to know the distributions of the various parameters involved, and as previously noted, it was not possible to obtain all the necessary information from the videotaped arrivals. Therefore, various other sources were consulted.

First, the height at flare, which could not be distinctly observed in the video image, was presented in a study by Schoen et al. (17) based on observations of various turbojet aircraft in a study by Geoffrian and Kibardin (18) published much earlier, in 1962. The average height at which the flare maneuver took place was estimated to be 32 ft with a standard deviation of 15 ft above the runway surface. From the flare maneuver to touchdown, it is also necessary to project the in-air deceleration rate, which could vary quite significantly
TABLE 2 EXIT SPEED ANALYSIS FOR ALL AIRCRAFT TYPES

<table>
<thead>
<tr>
<th>Airport - Runway</th>
<th>Exit</th>
<th>Avg. Exit Speed (kn)</th>
<th>% Large</th>
<th>% Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>OAK - 29</td>
<td>6 (H)</td>
<td>50</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>7 (H)</td>
<td>45</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>PHX - 8R</td>
<td>C5 (R)</td>
<td>29</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>C6 (R)</td>
<td>35</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>C7 (R)</td>
<td>29</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>C8 (R)</td>
<td>28</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>SFO - 28L</td>
<td>D (R)</td>
<td>28</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>E (H)</td>
<td>35</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>J (H)</td>
<td>43</td>
<td>86</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>K (R)</td>
<td>29</td>
<td>43</td>
<td>57</td>
</tr>
<tr>
<td>SFO - 28R</td>
<td>D (R)</td>
<td>22</td>
<td>0</td>
<td>100</td>
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<tr>
<td></td>
<td>E (H)</td>
<td>33</td>
<td>87</td>
<td>13</td>
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<tr>
<td></td>
<td>K (R)</td>
<td>28</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>T (H)</td>
<td>43</td>
<td>21</td>
<td>79</td>
</tr>
</tbody>
</table>

* - Letters in parentheses denote High-speed (H), or Right-angle (R) exits.

Average Exit Speeds (knots)

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>Right Angle</th>
<th>High Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>32</td>
<td>46</td>
</tr>
<tr>
<td>Heavy</td>
<td>25</td>
<td>39</td>
</tr>
</tbody>
</table>

TABLE 3 RUNWAY OCCUPANCY TIME SUMMARY

<table>
<thead>
<tr>
<th>Airport - Runway</th>
<th>Aircraft</th>
<th>Num. of Observations</th>
<th>Range</th>
<th>Average ROT (seconds)</th>
<th>Previous Studies: Avg. ROT (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motivated Carriers:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHX - 8R</td>
<td>Large</td>
<td>54</td>
<td>41-62</td>
<td>49.7</td>
<td>---</td>
</tr>
<tr>
<td>OAK - 29</td>
<td>Large</td>
<td>20</td>
<td>32-57</td>
<td>44.5</td>
<td>---</td>
</tr>
<tr>
<td>SJC - 30L</td>
<td>Large</td>
<td>10</td>
<td>36-56</td>
<td>45.3</td>
<td>51.3 (16)</td>
</tr>
<tr>
<td>SFO - 28L</td>
<td>Large</td>
<td>37</td>
<td>37-68</td>
<td>47.3</td>
<td>49.1 (2)</td>
</tr>
<tr>
<td>SFO - 28R</td>
<td>Large</td>
<td>52</td>
<td>42-68</td>
<td>52.0</td>
<td>46.3 (2)</td>
</tr>
<tr>
<td>SFO - 28R</td>
<td>Heavy</td>
<td>13</td>
<td>47-77</td>
<td>54.6</td>
<td>56.0 (2)</td>
</tr>
<tr>
<td>All Observations:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SFO - 28L</td>
<td>Large</td>
<td>53</td>
<td>37-83</td>
<td>54.3</td>
<td></td>
</tr>
<tr>
<td>SFO - 28L</td>
<td>Heavy</td>
<td>12</td>
<td>35-82</td>
<td>64.0</td>
<td></td>
</tr>
<tr>
<td>SFO - 28R</td>
<td>Large</td>
<td>82</td>
<td>42-77</td>
<td>54.3</td>
<td></td>
</tr>
<tr>
<td>SFO - 28R</td>
<td>Heavy</td>
<td>27</td>
<td>47-92</td>
<td>63.1</td>
<td></td>
</tr>
</tbody>
</table>

Dashes indicate that previous runway occupancy studies were not available.

Across aircraft types because of the disparity among the existing aerodynamic designs. Not much data is currently available concerning aircraft in-air deceleration rates, yet Horonjeff and McKelvey (15) project an aggregate average in-air deceleration of 2.5 ft/sec², and from a recent draft report on runway friction tests by Yager et al. (19), deceleration rates of 2.2 ft/sec² and 1.7 ft/sec² were observed for the B737-100 and B727-100 aircraft, respectively. Unfortunately, no information concerning the actual distributions of these deceleration rates is readily available.

Various sources were also consulted for information concerning the relationship between the speed at threshold and the corresponding speed at touchdown. Horonjeff and McKelvey (15) provide information that speeds at touchdown are on the order of 5 to 8 knots less than the speed across threshold. In addition, Yager et al (19) displayed time-velocity relationships in which the groundspeed difference between threshold and touchdown for the B737-100 was 8.5 knots \( (V_{TD} = 0.93V_T) \) and 5 knots \( (V_{TD} = 0.97V_T) \) for the B727-100. Similarly, B727-200 simulator data, obtained from the National Aeronautics and Space Administration Ames Research Center, showed that the airspeed at touchdown was approximately 97 percent of the airspeed at threshold. Finally, Schoen et al. (17) presented results as given in the earlier study (18) that, on the average, touchdown speeds were approximately 8.63 knots less than the corresponding speed at threshold \( (V_{TD} = 0.935V_T) \) with a standard deviation of 5.07 knots \( (0.038V_T) \).

As mentioned earlier, once the aircraft touches down, it begins to exhibit a slightly greater deceleration rate. From a study by Yager et al. (19), the average roll deceleration for
the B727-100 was calculated to be about 2.4 ft/sec², which is approximately 40 percent higher than the in-air deceleration rate. Also, it is believed that differences in roll deceleration rates vary depending more on the weight of the aircraft than on the individual aerodynamic design. No other published values for roll deceleration rates have been found. However, because the in-air and roll deceleration rates account for only a small portion of the overall deceleration rate, their estimates are not as important as the average braking deceleration rates.

Braking rates are obviously dependent on the relationship between the aircraft touchdown point and the available locations of exit taxiways in relation to the terminal building. Maximum braking rates can approach between 10 and 16 ft/sec² (19) depending on surface friction and the braking maneuver (automatic or manual) performed. More important, it is necessary to determine the comfort threshold for aircraft passengers because such a value is necessary when determining realistic exit taxiway locations. Whereas few studies have investigated comfortable rates for aircraft occupants, automobile occupants appear to have a comfort threshold of 8 ft/sec² (20). Although conditions could not be controlled in the field study so as to determine an exact value, Figure 2 indicates that 8 ft/sec² appears to be the maximum rate at which aircraft deceleration takes place. In some instances, for those touchdown points that are less than 2,000 ft from the exit accepted, pilots were willing to reach a maximum of 10 ft/sec². In addition, of the three aircraft witnessed to have deceleration rates over 9 ft/sec² two of them were cargo carriers. This seems to imply that the human comfort threshold for aircraft deceleration rates is near 8 ft/sec² as well, but as mentioned earlier, these average values somewhat underestimate the instantaneous decelerations taking place.

Besides the criterion for comfort, surface conditions play an important role in the ability of an aircraft to decelerate to a safe exit speed. Approximate values for the coefficient of friction (f) between the tires and the runway surface have been noted in previous research. Specifically, Schoen et al. (17) estimated the following available ground coefficients of friction: dry pavement, 0.8; wet pavement, 0.4; packed snow, 0.2; and ice, 0.1. These values suggest that considerably longer runway occupancy times can be expected in inclement weather.

STATISTICAL ANALYSIS

To determine the parameter distributions and to distinguish possible differences between certain external factors, various statistical analyses were performed on the data obtained from the field study. Statistics for those parameters measured in the field study are given in Tables 1 through 3. In addition, using a one-way analysis of variance (ANOVA), parameters were tested to differ among airports, aircraft types, and airlines at a 0.05 level of significance. Higher-level ANOVA tests were not used because it was observed that all airlines did not use all airports nor did airlines always use the same aircraft type at each airport.

Investigation of the data by aircraft type indicated that environmental conditions seemed to have little impact on the individual parameters. Because all the operations were witnessed under Visual Flight Rules (VFR) conditions, this is not surprising, yet even the Phoenix observations, which include somewhat different environmental conditions, were not statistically significantly different from the Bay Area observations. The temperatures ranged from 60°F at Oakland to 82°F at Phoenix (95°F temperatures occurred at San Jose, but only during 10 observations). Pressures ranged from 29.81 in. of mercury at Phoenix, to 30.34 in. at San Francisco. These variations are within 2 percent of standard pressure and 4.5 percent of standard temperature conditions.

![Figure 2](https://via.placeholder.com/150)

**FIGURE 2** Relationship between average braking rate and touchdown location.
Interairport Differences

Intuitively, the configuration of the runway and taxiway system as well as the placement of exit taxiways has a large impact on runway occupancy. This analysis, however, investigated specific aspects within the landing sequence, as well as the overall result that makes one airport significantly different from another.

For all the types of air carrier aircraft flying into San Jose International, significant differences in the height at threshold, distance and time to main gear touchdown, and thus distance and time to nose gear touchdown resulted. This is due to the displaced threshold design used by arriving aircraft at San Jose. For example, the aggregate average height at threshold at the three remaining airports was nearly 50 ft, whereas for those aircraft sampled at San Jose the average height was 24 ft, with a range of 10 to 35 ft. Furthermore, lower height-at-threshold values propagated to lower touchdown distances and times. (For this reason, data obtained from San Jose were removed from the aggregated aircraft type parameter distributions given in Table 1.)

It should be evident from Table 2 that the high-speed exit taxiways in place at Metropolitan Oakland International Airport are utilized closest to their potential. This observation, matched with the fact that all airlines are motivated to exit early because of their terminal location, yields the lowest runway occupancy minimum and average time values. With only two exits in place, this seems to be an economical optimum in terms of construction cost as well as the availability to increase capacity. However, it should be noted that exit taxiway placement and its relationship to the terminal location significantly affect the taxiing times for aircraft. Thus, depending on the incoming traffic density, the ultimate solution to the placement of exit taxiways may not be found using a simulation concerned with the arrival sequence alone, but incorporated within network optimizations that are found in other simulation and optimization programs. Programs that deal with optimizations during saturation conditions are described in a recent article in Airport Forum (21) and in existing FAA simulations (22). In addition, Tosic et al. (23) present an optimization to locate exit taxiways such that the cost of taxiing to the terminal building is minimized. Such an optimization is relevant during periods of low incoming traffic density.

Interaircraft Differences

Several ANOVA tests were performed on heavy aircraft to determine whether the parameters of individual aircraft types were sufficiently similar to group them under one classification. Results indicated that heavy aircraft were statistically similar, with the exception of the B767. More specifically, the airspeeds at threshold values expected for the B767 were significantly lower than those for other heavy aircraft (F-ratio = 13.89, Probe > F = 0.00). Lower values for this parameter propagated into lower comparable values for some of the other parameters. Table 1, however, indicates that not all of the parameters show significant differences. For example, the times to touchdown among all heavy aircraft are quite similar.

Similarities were also noted in the parameter values given in Table 1 between the B757 and the B767. This is expected, because the design and operating characteristics of the two aircraft are very similar. Even though they may be classified differently (the weight of the B757 is just under the minimum for classification as a heavy aircraft, and the B767 is just over the weight separation), they operate in a very similar manner. In many respects, including airspeed at threshold, the two aircraft operate more like large aircraft, yet their exiting and turning capabilities are similar to those of heavy aircraft.

Analyses of runway occupancy times for large aircraft across all exits illustrated a significant difference between individual aircraft types (F = 2.95, Prob > F = 0.01). However, when B757 aircraft were omitted from this classification, the differences in runway occupancy times became insignificant (F = 1.35, Prob > F = 0.25). This indicates the similarity between runway occupancy times among large aircraft, with the exception of the B757. Moreover, after the BAe146 is omitted, the F-ratio drops even further to 0.80 with a probability of 0.49. However, when differences in exit distances, aggregated among all airports are analyzed, there is relatively little difference between large aircraft types (F = 0.77, Prob > F = 0.58). Without the B757, the F-ratio and corresponding probability remain fairly constant (F = 0.79, Prob > F = 0.53). Furthermore, without the BAe146, the F-ratio change is again insignificant (F = 0.73, Prob > F = 0.54). Therefore, the exit distances for large aircraft are relatively similar, but the runway occupancy times vary, chiefly because of the BAe146 and the B757.

It is postulated that even though the BAe146 is able to make the same exits as its larger counterparts, the aircraft is typically slower across threshold, and even slower in comparison with other large aircraft immediately after touchdown. In addition, even though there is no significant difference in average braking deceleration between large and heavy aircraft, there is a significant difference among individual aircraft types (F = 2.64, Prob > F = 0.01). When the BAe146 are removed from this aggregation, the F-ratio drops to 0.73 with a probability of 0.67. Most likely this is not because of the braking characteristics of the aircraft itself, but because the lower arrival speed of the BAe146 forces it to taxi for some time on the runway before reaching a suitable exit.

The B757 differences are believed to be the result of other factors. The B757 exhibits deceleration and speed characteristics similar to those of other large aircraft. However, it is believed that because of the large amount of torque built up at the nose gear during exiting maneuvers, the aircraft has a slower exit acceptance velocity than other large aircraft and, in turn, takes longer to exit the runway after reaching the exit decision point.

Interairline Differences

Strong differences in parameter means between airlines and airports resulted within the B737 aircraft classification. Analyses of distances and times to touchdown indicated significant differences between airports; however, this difference was isolated to the differences in only one airline at one airport. Also, significant differences in the height at threshold resulted between airlines. Again, this was attributed to one airline.
Similar differences occurred for other aircraft types as well. For instance, the height at threshold for the MD80s showed a significant difference among airlines ($F = 3.07$, Prob $> F = 0.04$). Omitting the data for one airline (for which there were only two observations) and rerunning the ANOVA test, it was determined that no significant difference resulted between airlines ($F = 1.64$, Prob $> F = 0.20$). Also, because the distance to touchdown was significantly higher because of one airline, the same procedure was repeated with the BAc146 observations, and no significant difference resulted.

Thus in all of the witnessed deviations, one airline could be singled out for the observed differences. In some instances this is probably due to the relatively few observations made of that airline. In other cases, many observations were made and so company procedure may play some part in the observed differences. In consideration of the observations made and the large number of airlines witnessed, differences attributed to one airline do not suggest a strong influence in airline operational procedure, at least up to the point of touchdown. However, it has been well documented in past studies (2, 3) that overall runway occupancy is very much dependent on airline operational procedure.

The data analyzed in this study support the same conclusion. Results of the ANOVA test for differences among airline landing distances for all large aircraft are as follows:

<table>
<thead>
<tr>
<th>Airport</th>
<th>$F$ Ratio</th>
<th>Prob $&gt; F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFO</td>
<td>9.66</td>
<td>0.00</td>
</tr>
<tr>
<td>PHX</td>
<td>1.46</td>
<td>0.21</td>
</tr>
<tr>
<td>OAK</td>
<td>1.69</td>
<td>0.20</td>
</tr>
<tr>
<td>SJC</td>
<td>0.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

San Francisco is the only airport that shows a significant difference among the airlines. This is because at the other airports, pilots are motivated to exit by the proximity of the terminal. By observing the relationship between the airline gate locations and the position of the exit taxeways, it can be seen that the results are consistent with the hypothesis that gate location is a primary motivational factor. The overwhelming majority of airlines is motivated to exit early at the other airports because gate location is displaced further the longer the aircraft is on the runway. San Francisco provides the only opportunity for certain carriers to taxi longer on the runway in order to be closer to the airline's gate location.

Because the landing sequence, for the most part, is independent of airline operating procedure up to the point of touchdown, differences in landing distance should be a result of differences among deceleration rates. In fact, average braking deceleration rates were found to differ significantly among airlines for certain aircraft types.

Distribution Modeling

Data obtained from the field study were also investigated to determine the type of distribution shown by the given parameters. Because of the limited number of observations, however, it was difficult to determine the exact distribution by aircraft type. When the various aggregated parameter histograms are observed, the distributions in Table 1 appear to be normal. After data obtained from the earlier study of turbojet aircraft were analyzed (18), it was discovered by Schoen et al. (17) that many of the parameters in the landing sequence followed a Pearson Type III distribution. The lack of available data segregated by aircraft type and obtained from field studies, especially recent studies, has prevented definite descriptions of the input parameter distributions themselves.

Parameter Interrelationships

Because of the independent nature of random number generation, it is necessary to determine possible correlations between the generated parameters. Some relationships are obvious and are accounted for in the mathematics of the model. For example, there is an obvious correlation between the time to touchdown and the height and speed at threshold. Such relationships are explicitly developed in the mathematical algorithm presented earlier.

As showed in Figure 2, a significant relationship did exist between the average braking deceleration and the remaining distance between nose gear touchdown and the exit chosen. This relationship arises from adjustment of aircraft speeds by air traffic controllers to maintain proper separations on final approach. Although other dependencies, such as the aircraft approach speed and the existing traffic density, are known to occur, they are difficult to measure.

For two reasons, another correlation was expected to exist between the height and airspeed at threshold. First, as witnessed in Table 1, heavy aircraft tend to have higher speeds and higher heights at threshold, whereas large aircraft have lower speeds and lower heights. Second, because an aircraft on final approach has a high speed, the pilot's instinct would be to decelerate by decreasing the aircraft's rate of descent, providing for a higher height at threshold. However, after a linear regression analysis was performed, no definite relationship could be explained. The first hypothesis was tested by analyzing all observations, and a correlation coefficient of +0.09 was determined. Even though some positive correlation was found, it was not enough to explicitly explain the relationship. Testing of the second hypothesis was performed by analyzing one given aircraft type (B737 aircraft at Phoenix), and a correlation coefficient of +0.17 was found. Again, no definite relationship could be determined. In both instances, however, the differences could be explained by the individual aircraft weights. Although this parameter has a definite impact on both the height and airspeed at threshold, it was not measured or accounted for in the field study.

RUNWAY OCCUPANCY AND AIRFIELD CAPACITY

To measure the potential increases in airport capacity, Lebron (24), using the FAA Airfield Capacity Model (with defined airfield configurations and aircraft mixes), evaluated various capacity enhancement schemes to determine their effect. The study concluded that capacity could be increased between 33 and 100 percent by the addition of new runways or multiple approach paths. Also, it was found that reductions in separation criteria could provide an increase in capacity between 15 and 25 percent, and reduced variability in interarrival times and reduced runway occupancy time could produce an increase in capacity between 16 and 18 percent.
Because there may be many constraints on physical expansion, that is, additional runways, of existing airport facilities, alterations in current operational procedures may be a beneficial means for increasing runway capacity. Although the subject of multiple approach path concepts is beyond the scope of this paper, the reduction in separation standards is directly related to runway occupancy.

The capacity $C$ of a runway can be defined as the inverse reciprocal of the weighted headway ($h$) between aircraft operations, or

$$C = \frac{1}{h}$$

(11)

Simply stated, if separation standards are reduced, the corresponding headway between aircraft is reduced and capacity is increased. If a runway consisting of 100 percent arrivals is analyzed, the capacity can be rewritten as

$$C = \frac{1}{h} = \frac{v}{s}$$

(12)

where $v$ is the aircraft approach speed and $s$ is the distance separation between aircraft arrivals. This equation indicates that other alternatives are available to increase capacity by changing operational procedures. In a paper fully devoted to those procedures, Kanafani (25) proposes that aircraft may increase their approach speeds to increase runway capacity. However, as approach speeds increase, so will the corresponding runway occupancy times, and increases in capacity will eventually be limited. A more promising innovation to increase capacity would be to relax existing fixed-distance separations and base aircraft separations on headways by adjusting approach speeds, distance separations, or both (25). In addition, to obtain the maximum capacity potential available under the current criterion of restricting the runway surface to one aircraft at a time, these headways may be matched with existing runway occupancy times and any necessary safety buffers. This principle extends to mixed operations as well.

Because time is the key element in the response to unforeseen circumstances, it would be possible, theoretically, to negotiate safety issues with headway control rather than distance control. Of course, such a procedure must be researched from a safety standpoint. Moreover, safety concerns should extend beyond collision risk analysis; the impact on air traffic controllers and pilots must be rigorously analyzed as well. In addition, other problems may exist with a reduction in arrival spacing and must be addressed in a comprehensive research effort. These problems include Instrument Landing System signal interference, beacon system garbling, and potential conflict caused by missed approaches (26).

**APPLICATIONS**

In order to achieve any of the potential capacity previously identified, measures should be deployed to decrease the runway occupancy time mean and variance. By applying the runway occupancy model, exit taxiway locations could be analyzed in terms of minimizing runway occupancy time for a given mix of aircraft. Also, the model could be applied within an automated environment by providing real-time deceleration guidance or within a larger Integrated Landing Management (ILM) system to sequence aircraft operations with existing runway occupancy times. As stated earlier, this provides the maximum potential capacity gain from any change in operational procedure.

**Exit Taxiway Location**

A practical application of the runway occupancy model would be to estimate, for a given exit taxiway located any distance from the runway threshold, the probability that a given aircraft type (B727, MD80, and so forth) is able to accept that exit. By repeating the process at various locations from the runway threshold and for each aircraft type, the exit acceptance cumulative distribution function could be determined. The results are then weighted by the aircraft mix, and final design recommendations can be made after factors such as benefits and costs have been included.

As a test, the statistical parameters of the B737 aircraft typically in operation at Phoenix Sky Harbor were used as inputs to the model: an average braking deceleration rate of 6.5 ft/sec$^2$ (standard deviation of 1 ft/sec$^2$) and an average exit acceptance velocity of 30 knots (standard deviation of 5 knots). A comparison of the actual exit selection distribution and runway occupancy time (ROT) distribution with those predicted by the model is shown in Figure 3. The actual distribution was based on approximately 50 arrivals, whereas the model is based on a significantly higher number of arrivals (values were averaged on the basis of separate runs of 100 aircraft per run). The two graphs are very similar, with greater deviations occurring at the extremes. These deviations in the exit acceptance distribution could be attributed to the lack of knowledge of the exact parameter distributions, possible undiscovered interrelationships between the generated parameters, or braking adjustments made by the pilot to meet an exit in better proximity to the aircraft's terminal gate location. The differences between the actual and modeled runway occupancy times at locations further from the runway threshold are because of the omission of exit taxiways other than the one being analyzed. If the model simulated multiple exits, certain aircraft would have been able to exit earlier, reducing taxi time and thereby lowering the average runway occupancy time. Because space restrictions limit further discussion of the exit taxiway location analysis, including the adaptations to multiple exit locations, the reader should consult a paper by Gosling and Ruhl (27), which is fully devoted to the subject.

In addition, Phoenix Sky Harbor's Runway 8R is unique because all exit taxiways are right-angle exits, and high-speed exits are prevented because of the taxiway system design. However, by using the model, the impact of an added high-speed exit can illustrate the runway occupancy time savings possible. If a 60-knot high-speed exit taxiway were added, preliminary results suggest that the 50 percent acceptance distance would be reduced to 5,000 ft with an average runway occupancy time of 41 sec, a 20 percent time savings. Even though the above situation shows a possible improvement at Phoenix Sky Harbor, the same adjustments may not have similar impacts elsewhere.
Automated Exit Guidance

Further capacity enhancements, in terms of the aircraft arrival sequence, have been proposed by Gosling et al. (1). In this respect, automating the landing process would give the pilot a visual target, with the use of new or existing centerline lighting systems and sophisticated on-line analyses, to select an exit as well as to determine the optimum profile guidance for an arriving aircraft depending on existing environmental conditions and traffic density. Once data on current airport conditions and individual aircraft characteristics are obtained, the model could estimate the optimum exit taxiway location. With the use of existing radar and additional sensors located within the runway pavement, real-time updates could be used to reaffirm predicted variables, thus providing more accurate information to the pilot in communicating the optimum exit as well as to determine the optimum profile guidance and traffic density.

With the use of existing radar and additional sensors located within the runway pavement, real-time updates could be used to reaffirm predicted variables, thus providing more accurate information to the pilot in communicating the optimum exit taxiway location. The aircraft's stall speed is based on its landing weight. Such a variable is difficult to estimate, but by using simplifying assumptions concerning average load factors or by representing the landing weight as 85 percent of the maximum landing weight for the individual aircraft type (13), reasonable estimates for the airspeed at threshold may be calculated. The same logic may also be applied to predict the average threshold speeds for the various aircraft types in the exit taxiway location analysis.

Another procedure to predict the speed at threshold is an estimation based on the aircraft's approach speed at the outer marker. This procedure requires additional information concerning the air deceleration from the outer marker to threshold, which should be distinguished from the in-air deceleration initiated during the flare maneuver. Average air deceleration rates from the outer marker (5 nautical mi from the runway threshold) to the threshold have been calculated for each observation made during the field study. From such information, it appears that the BAE146 yields higher average deceleration rates compared with all the other observations. The BAE146 observations have been removed from the data file in order to obtain a general regression model, which appears in Figure 5, for all aircraft. Note that the model has very significant t-statistics and F-ratios along with a correlation coefficient of +0.93.

Thus, if a given radar source (possibly the same system that produces the BRITE radar display) can read the airspeed at 5 mi out, and given information concerning existing enron-
mental conditions, the velocity at threshold can be predicted. Again, this value could be confirmed at a later time using sensors and detectors within the runway surface. Additional information concerning the airline gate location and traffic density (motivation versus nonmotivation) can further adjust the model to all the aircraft to exit at the optimum location.

Such a system would benefit air traffic controllers by relieving them of the duty to provide certain ground control tasks that can be performed by automation. Also, by incorporating real-time deceleration guidance within the larger ILM framework of controlling separations by headways and sequencing arrivals and departures according to their runway occupancy times, significant increases in capacity may be achieved.

CONCLUSIONS AND RECOMMENDATIONS

The potential to increase existing airfield capacity does exist, with substantial gains largely developed by the addition of new runways and multiple approach path concepts. Capacity increases from 15 to 40 percent may be expected with more efficient use of existing high-speed exit taxiways, a reduction in runway occupancy time mean and variance, and a change in operational procedure from rather arbitrarily defined distance separation standards to aircraft separations based on headways. However, a substantial research effort is necessary before deploying any system based on headways, particularly an ILM system, in order to address various safety implications.

The model developed in this paper may prove to be beneficial to future airfield analyses because changes due to differences in the operational parameters among individual aircraft types may be taken into account. More important, the model applies to all types of aircraft (including those not accounted for in this study) given that the necessary operational parameters are available. These parameters may be found in aircraft informational manuals, aircraft simulator data, or data contained in this paper and in the literature cited. Statistical analyses produced in this paper show that if data are not readily available for individual aircraft types, the categories of large and heavy aircraft may be used to simplify the analysis, except in the case of B757 and B767 aircraft. Because the operational similarities of these aircraft combine the traits of both large and heavy aircraft, they should be provided their own classification. More data (most efficiently determined from aircraft simulator runs) are necessary to analyze the operational performance of the various aircraft types (specifically the BAe146) with regard to their in-air deceleration and roll deceleration rates. Moreover, further research is necessary to fully understand the parameter differences that occur during poor weather conditions because this is a time during which capacity is most strained.
Exit taxiways may be located such that runway occupancy or operational cost is minimized, depending on the airfield in question. However, even if exit taxiways are placed to minimize runway occupancy, overall system capacity may be limited because of conflicts among the runway, taxiway, and terminal location network. The mathematical model presented in this paper may be used independently, or it may be used in conjunction with any of the previously described models to optimize exit taxiway placement because those models require aircraft exit selection distributions as input (with or without considering runway occupancy time). This applies to those models that are concerned with demand rates above, or below, saturation conditions.

Finally, the introduction of an automated exit guidance system may have a substantial impact on creating more unused capacity by motivating carriers to use exit taxiways that may be bypassed for reasons others than safety. Moreover, such a system may be used for interarrival separation based on aircraft headways to achieve even larger capacity gains. The automated exit guidance system may benefit controllers by relieving them of certain ground control responsibilities, and it will assist pilots by offering landside guidance that could be extended beyond the exit taxiway to provide a networkwide, system-optimal positioning system.

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