Time-Space Analysis
Airport Runway Capacity

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CEE 3604
Introduction to Transportation Engineering

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Why Time Space Diagrams?

To estimate the following:

- Headway between operations at various transportation facilities
- Spacing between operations
- Capacity of transportation systems
- Determine basic level of service
Sample Time Space Diagrams

We examine time space diagram applications for the following systems:

a) Rail (done in class)

b) Automobile (done in class)

c) Airport (air transportation)

The rest of the handout applies time-space diagram principles to estimate the capacity of a single runway at an airport.
Factors Affecting Runway Capacity

There are numerous factors that affect runway capacity. Here are some of the most relevant:

- Runway configuration (number of runways in use, location of runway exits, etc.)
- Aircraft mix (percent of aircraft in various wake vortex categories)
- Weather conditions (visibility, ceiling, wind direction and speed)
- Airport equipage (type of navaids, ATC equipment)
- Operating procedures (noise considerations, special approach and departure procedures)
Sample Use of Technology to Use Multiple Runways

- Radar surveillance is required at large airports to allow simultaneous use of parallel runways (shown in the Figure)

Runway 1

Airport Terminal

Runway 2

Independent arrival streams

4,300 ft. or more
Independent Triple and Quadruple Approaches To Parallel Runways (IFR)

• The idea behind this concept is to allow triple and quadruple parallel approaches to runways separated by 5,000 feet using standard radar systems (scan update rate of 4.8 seconds) at airports having field elevations of less than 1,000 feet.

• Increase to 5,300 ft. spacing between runways for elevations above 5,000 ft.

[Diagram showing Runway 1, 2, and 3 with 5,000 ft. or more spacing]
Independent Departures and Standard Radar

- Simultaneous departures can be conducted if two parallel runways are located 2,500 ft.
Independent Departures and Arrivals with Standard Airport Radar

- Simultaneous departures and arrivals can be conducted if two parallel runways are located 2,500 ft.

**Departure Stream**

Runway 1

2,500 ft.

Runway 2

**Arrival Stream**
Time-Space Analysis

• A simple technique to assess runway and airspace capacity if the headway between aircraft is known.

• The basic idea is to estimate an expected headway, $E(h)$, and then estimate capacity as the inverse of the expected headway.

$$\text{Capacity} = \frac{1}{E(h)}$$

$E(h)$ is expressed in time units (e.g., seconds)
**Time-Space Analysis Nomenclature**

\( \delta_{ij} \) is the minimum separation matrix (miles). For this class we assume includes air traffic control buffers times.

\( T_i \) is the arrival time (to the runway) of the lead aircraft

\( T_j \) is the arrival time (to the runway) of the following aircraft

\( T_{ij} \) is the headway between two successive aircraft (s)

\( \delta \) is the minimum arrival-departure separation (miles)
\( ROT_i \) is the runway occupancy time for aircraft \( i \) (s)

\( V_i \) is the speed of aircraft \( i \) (lead aircraft) in miles per hour
Time-Space Analysis Nomenclature

$V_j$ is the trailing aircraft speed (miles per hour)

$\gamma$ is the common approach length (miles). This is the distance outside the runway where aircraft fly a common path aligned with the runway.
Possible Outcomes of a Single Runway Time-Space Diagram

Since aircraft approaching a runway arrive in a random pattern we distinguish between two possible scenarios:

- **Closing case** - Instance when the approach of the lead aircraft is less than that of the trailing aircraft ($V_i \leq V_j$)

- **Opening Case** - Instance when the approach speed of lead aircraft is higher than trailing aircraft ($V_i > V_j$)
Closing Case (Equations)

*Headway* \((T_{ij} = T_j - T_i)\) assuming control is exercised as the lead aircraft passes the entry gate (at a distance \(\gamma\)) from the runway is,

\[
T_{ij} = \frac{\delta_{ij}}{V_j}
\]

NOTE: the distance \(\gamma\) does not influence the outcome of this analysis because the following aircraft (fast) is “closing on” the lead vehicle (slow).
Closing Case Diagram (Arrivals Only)

Space

Runway

ROT<sub>i</sub>  ROT<sub>j</sub>

γ

V<sub>i</sub>  1  V<sub>j</sub>

1

T<sub>i</sub>  T<sub>j</sub>

δ<sub>ij</sub>

Entry Gate

Time

V<sub>i</sub> < V<sub>j</sub>
Opening Case (Equations)

Headway \( (T_{ij} = T_j - T_i) \) is,

\[
T_{ij} = \frac{\delta_{ij}}{V_j} + \gamma \left( \frac{1}{V_j} - \frac{1}{V_i} \right)
\]

assuming control is exercised as the lead aircraft passes the entry gate.

NOTE: The second term in the previous equation measures the time aircraft (i) and (j) space themselves further over a distance \( \gamma \). This term is important because
Opening Case Diagram (Arrivals Only)

Space

Runway

ROT$_i$

ROT$_j$

Time

Entry Gate

$\delta_{ij}$

$\gamma$

$V_i > V_j$

$T_i$

$T_j$

$V_i$

$V_j$

$1$

$1$
Mixed Operations (Arrivals/Departures)

\[ T_1 = T_i + \text{ROT}_i \]

\[ T_2 = T_j - \delta / V_j \]

Gap (G) exist if \( T_2 - T_1 > 0 \)

TD\(_i\) is the departure runway occupancy time
Atlanta Hartsfield-Jackson Airport

- 5 Runways
- 3 Arrival Runways
- 2 departure Runways

Departures
Termsinals
Arrivals
Arrivals (peak hour)
Runway Operations at Atlanta Airport

source of data: Federal Aviation Administration
## Air Traffic Control (ATC) Arrival-Arrival In-Trail Separations

Typical In-trail Separations (in **nautical miles**) near Airport Runways at Large-hub Commercial Airports. Includes Buffers Applied by ATC.

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
<th>Heavy</th>
<th>Large</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td></td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Large</td>
<td></td>
<td>3</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Small</td>
<td></td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Separations are in nautical miles
Air Traffic Control (ATC) Departure-Departure In-Trail Separations

Typical In-trail Separations (in seconds) for Departing Aircraft on the same Runway. Includes Buffers Applied by ATC.

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
</tr>
<tr>
<td>Heavy</td>
<td>120</td>
</tr>
<tr>
<td>Large</td>
<td>60</td>
</tr>
<tr>
<td>Small</td>
<td>60</td>
</tr>
</tbody>
</table>

Separations are in seconds
## Aircraft Groups: Who Is Who?

<table>
<thead>
<tr>
<th>Group</th>
<th>Takeoff Gross Weight (lb)</th>
<th>Example Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>&lt; 41,000</td>
<td>All single engine aircraft, light twins, most business jets and commuter aircraft</td>
</tr>
<tr>
<td>Large</td>
<td>41,000-255,000</td>
<td>Large turboprop commuters, short and medium range transport aircraft (MD-80, B737, B727, A320, F100, etc.)</td>
</tr>
<tr>
<td>Heavy</td>
<td>&gt; 255,000</td>
<td>Boeing 757&lt;sup&gt;a&lt;/sup&gt;, Boeing 747, Douglas DC-10, MD-11, Airbus A-300, A-340,</td>
</tr>
<tr>
<td>A380</td>
<td>1,234,000</td>
<td>Airbus A380 (pending reductions)</td>
</tr>
</tbody>
</table>

---

Wake Vortex Groups

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<sup>a</sup> For purposes of terminal airspace separation procedures, the Boeing 757 is classified by FAA in a category by itself. However, when considering the Boeing 757 separation criteria (close to the Heavy category) and considering the percent of Boeing 757 in the U.S. feet, the four categories does provide very similar results for most airport capacity analyses.
Small Aircraft

Typically these aircraft can have one (single engine) or two engines (twin engine). Their maximum gross weight usually is always below 14,000 lb.

Single-Engine GA

Cessna 172 (Skyhawk)

Twin-Engine GA

Beechcraft 58TC (Baron)

Beechcraft A36 (Bonanza)

Cessna 421C (Golden Eagle)
Corporate Aircraft

Typically these aircraft can have one or two turboprop driven or jet engines (sometimes three). Maximum gross mass is up to 40,910 kg (90,000 lb)

Small
- Raytheon-Beechcraft King Air B300
- Cessna Citation II

Large (> 41,000 lb)
- Gulfstream G-V
Commuter Passenger Aircraft

Usually twin engine aircraft with a few exceptions such as the DeHavilland DHC-7 which has four engines. Their maximum gross mass is below 31,818 kg (70,000 lb)

- **Small**
  - Fairchild Swearingen Metro 23
  - Bombardier DHC-8
  - Saab 340B

- **Large (> 41,000 lb)**
  - Embraer 145
Commercial Aircraft (Single-Aisle)

Certified under FAR/JAR 25. Their maximum gross mass usually is below 68,182 kg (150,000 lb).

- Fokker F100
- Airbus A-320
- Boeing 737-300
- McDonnell-Douglas MD 82

All Large (> 41,000 lb)
Commercial Transport Aircraft (Wide-Body)

These are transport aircraft employed to fly routes of less than 3,000 nm (typical). Their maximum gross mass usually is above 159,090 kg (350,000 lb)

- Airbus A340-200
- Boeing 777-200
- Boeing 747-400
Super-heavy Aircraft

- Airbus A380 was introduced into service in 2008

A380-800 at LAX Airport (A. Trani)
Example Problem # 1

Determine the saturation capacity of an airport serving two groups of aircraft: a) heavy (70% of the population) and b) small (30% of the population). Assume the common approach length to be 7 miles.

<table>
<thead>
<tr>
<th>Aircraft Group</th>
<th>Runway Occupancy (s)</th>
<th>Approach Speed (nautical miles per hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td>Small</td>
<td>40</td>
<td>70</td>
</tr>
</tbody>
</table>
Determine Aircraft Mix and Probabilities

The following is a probability matrix establishing the chance that an aircraft of type (i) follows aircraft of type (j). We assume random arrivals.

Table 4. Probability Matrix ($P_{ij}$). Aircraft (i) follows aircraft (j).

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
<th>Heavy</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td></td>
<td>$(0.7) \times (0.7) = 0.49$</td>
<td>$(0.7) \times (0.3) = 0.21$</td>
</tr>
<tr>
<td>Small</td>
<td></td>
<td>$(0.3) \times (0.7) = 0.21$</td>
<td>$(0.3) \times (0.3) = 0.09$</td>
</tr>
</tbody>
</table>

NOTE: verify that $\sum_{i,j} P_{ij} = 1.0$
Compute Headways Between Successive Arrivals

Closing case:
Lead = small, Following = heavy aircraft

\[ T_{S-H} = \frac{\delta_{S-H}}{V_H} = \frac{3}{150} = 0.02 \text{ hours} \]

Usually is convenient to express headway in seconds.

\[ T_{S-H} = \frac{\delta_{S-H}}{V_H} = \left( \frac{3}{150} \right) 3600 = 72 \text{ seconds} \]
Compute Headways Between Successive Arrivals

Closing case (apply this case when speeds are equal):

Lead = small, Following = small aircraft

\[ T_{s-s} = \frac{\delta_{s-s}}{V_s} = \left( \frac{3}{70} \right) 3600 = 154 \text{ seconds} \]

Lead = heavy, Following = heavy aircraft

\[ T_{h-h} = \frac{\delta_{h-h}}{V_h} = \left( \frac{5}{150} \right) 3600 = 120 \text{ seconds} \]
Compute Headways Between Successive Arrivals

Opening case:

Lead = heavy, Following = small aircraft

\[ T_{H-S} = \frac{\delta_{H-S}}{V_S} + \gamma \left( \frac{1}{V_S} - \frac{1}{V_H} \right) \text{ seconds} \]

\[ T_{H-S} = \left( \frac{7}{70} \right) 3600 + 7 \left( \frac{1}{70} - \frac{1}{150} \right) 3600 = 552 \text{ seconds} \]
Arrival Aircraft Headway Table

The following table summarizes the computed headways for all cases when an aircraft of type (i) follows aircraft of type (j). We assume random arrivals.

Table 5. Headways (seconds) when aircraft (i) follows aircraft (j).

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
<th>Heavy</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>120</td>
<td>552</td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td>72</td>
<td>154</td>
<td></td>
</tr>
</tbody>
</table>
Compute Expected Value of Headway

The expected value of the headway is:

\[ E(T_{ij}) = \sum_{i,j} P_{ij} T_{ij} \text{ for all } i,j \text{ pairs} \]

\[ E(T_{ij}) = P_{H-H} \times T_{H-H} + P_{S-H} \times T_{S-H} + P_{H-S} \times T_{H-S} + P_{S-S} \times T_{S-S} \]

\[ E(T_{ij}) = 0.49(120) + 0.21(72) + 0.21(552) + 0.09(154) \]

\[ E(T_{ij}) = 203.7 \text{ seconds} \]
Compute Arrivals-Only Capacity

- The capacity as the inverse of the expected headway

\[ \text{Capacity} = \frac{1}{E(T_{ij})} \text{ vehicles per second} \]

\( E(T_{ij}) \) is expressed in time units (e.g., seconds)

Using more standard units of capacity (aircraft per hour),

\[ \text{Capacity} = \frac{3600}{E(T_{ij})} \text{ vehicles per hour} \]
Arrivals-Only Capacity

For the single runway example the arrivals-only capacity is,

\[ C_{\text{arrivals}} = \frac{3600}{203.7} = 17.7 \text{ aircraft arrivals per hour} \]

NOTE: this value is low for a busy airport. At busy airports small aircraft are generally handled at a different runway if possible to improve the capacity of a runway operated by heavy aircraft.
Example of Departure-Departure Separation

Airbus A320 starts takeoff roll at time = 0

Embraer 145 (a regional jet) starts the takeoff roll ~50 seconds after Airbus A320 started its takeoff roll

Normally Air Traffic allows departures every 60 seconds when aircraft weigh less than 255,000 lb and the aircraft belong to the same group

source: A.A. Trani
Departure Capacity Only (Single Runway)

Space or Distance Traveled (meters)

Runway

Ti-d  Tj-d  Tk-d

Headway between successive departures  Headway between successive departures

Tij-d = time between successive departures (same concept used for arrivals)

Note: Not all aircraft belong to the same group.

Headways or time between departures are different.
Departure Only Capacity (Single Runway)

### Departure-Departure Separation Matrix

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
</tr>
<tr>
<td>Heavy</td>
<td>120</td>
</tr>
<tr>
<td>Large</td>
<td>60</td>
</tr>
<tr>
<td>Small</td>
<td>60</td>
</tr>
</tbody>
</table>

Separations are in seconds

### Probability Matrix (Pij)

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
</tr>
<tr>
<td>Heavy</td>
<td>(0.7) x (0.7) = 0.49</td>
</tr>
<tr>
<td>Small</td>
<td>(0.3) x (0.7) = 0.21</td>
</tr>
</tbody>
</table>

### Departure Departure Separation Matrix

\[
E(h_{\text{departures}}) = \sum_{ij} P_{ij} \left(T_{ij-d}\right)
\]

\[
E(h_{\text{departures}}) = P_{S-S} \left(T_{S-S-d}\right) + P_{S-H} \left(T_{S-H-d}\right) + P_{H-H} \left(T_{H-H-d}\right) + P_{H-S} \left(T_{H-S-d}\right)
\]

\[
E(h_{\text{departures}}) = 0.09(60) + 0.21(60) + 0.49(120) + 0.21(120) = 83 \text{ s}
\]

\[
C_{\text{departures}} = 3600 / 83 = 43.3 \text{ departures/hr}
\]
Analysis of Runway Gaps

Gaps can be studied for all four possible instances studied so far. For example, if a heavy aircraft is followed by a small one, there is a headway of 552 seconds between two successive arrivals. This leaves a large gap that can be exploited by air traffic controllers to handle a few departures on the same runway.

The gap for a heavy-small case is,

\[ G_{H-S} = T_2 - T_1 = \left( T_s - \frac{\delta}{V_s} \right) - (T_H + ROT_H) \]
Example of Departure-Arrival Separation (δ)

- Boeing 737-300 starts takeoff roll at time = 0
- Embraer 175 crosses the runway threshold ~40 seconds after Boeing 737-300 started its takeoff roll
- Embraer 175 typical approach speed is 125 knots (see Appendix 1 of FAA AC 150/5300-13a)
- Distance to threshold in 40 seconds is: 1.4 nautical miles!

Typical departure-arrival separation is 2 nm at most US airports

Source: A.A. Trani
Gap Analysis

Assume the arrival of the heavy aircraft occurs at time $t=0$ seconds.

$$G_{H-S} = \left( 552 - \frac{2}{70} \times 3600 \right) - (0 + 60)$$

$G_{H-S} = 389$ seconds

The expected time between successive departures at this airport is 83 seconds (see Table 2 adjusted by the probability values computed). A gap of 389 seconds is sufficient to “launch” four departures. You can do the
same analysis for all other instances and estimate the departure capacity of the runway per hour.

Gap: Lead aircraft = small, following aircraft = small

\[ G_{s-s} = \left( 154 - \frac{2}{70} \right) 3600 - (0 + 40) \]

\[ G_{s-s} = 11 \text{ seconds} \]

One departure can be injected when a small aircraft follows another small aircraft. While 11.1 seconds is small gap, the fact is any gap > 0 will in theory result in one departure as long as the pilot responds quickly to ATC commands.
Gap: Lead aircraft = small, following aircraft = heavy

\[ G_{S-H} = \left( 72 - \frac{2}{150} \times 3600 \right) - (0 + 40) \]

\[ G_{S-H} = -16 \text{ seconds} \]

No departures can be scheduled when a small aircraft follows a heavy aircraft.
Gap: Lead aircraft = heavy, following aircraft = heavy

\[ G_{H-H} = \left(120 - \frac{2}{150} \times 3600\right) - (0 + 60) \]

\[ G_{H-H} = 12 \text{ seconds} \]

One departure (on the average) can be scheduled between a heavy aircraft followed by another heavy aircraft.
The analysis of gaps for four arrival instances is presented in Table 6. The number of departures per gap is also presented in Table 6.

Table 6. Gaps (seconds) when aircraft (i) follows aircraft (j). Successive departures per gap are shown in parenthesis. Expected value of departure occupancy time is $E(TD_i) = 83$ seconds.

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
<td>Small</td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td>12 (1)</td>
<td>389 (4)</td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td>-16 (0)</td>
<td>11 (1)</td>
<td></td>
</tr>
</tbody>
</table>
Analysis of Arrival Gaps

The final question that needs to be answered is: how many times each gap happens during the period of interest?

From our analysis of arrivals only, we determined that on the average hour 17.7 arrivals could be processed at the runway. Since two successive arrivals are needed to form a gap, we can infer that around 16.7 gaps are present in one hour.

The probabilty of each one of the four arrival instances is known and has been calculated in Table 4. Thus using these two pieces of information we estimate the number
of times gaps will occur during one hour. Consider a heavy aircraft leading another heavy aircraft. Forty nine percent of the time this instance occurs at the airport. Thus for 16.7 gaps per hour this represents an equivalent number of hourly departures per arrival instance $(ED_{H-H})$, 

$$ED_{H-H} = TG(P_{H-H})(DG_{H-H})$$

where: $TG$ is the total number of gaps per hour, $P_{H-H}$ is the probability that a heavy aircraft follows another heavy, and $DG_{H-H}$ is the number of departures per gap for each instance (numbers in parentheses in Table 6).
\[ ED_{H-H} = 16.7(0.49)(1) = 8.18 \]
equivalent departures per hour

Similarly,

\[ ED_{H-S} = 16.7(0.21)(4) = 14.03 \]
\[ ED_{S-H} = 16.7(0.21)(0) = 0 \]
\[ ED_{S-S} = 16.7(0.09)(1) = 1.50 \]
equivalent departures per hour
Departures with Arrival Priority

Table 7 summarizes the number of departures per hour per instance.

Table 7. Equivalent departures per hour per arrival instance when aircraft (i) follows aircraft (j).

<table>
<thead>
<tr>
<th>Trailing Aircraft</th>
<th>Heavy</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Aircraft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td>8.18</td>
<td>14.03</td>
</tr>
<tr>
<td>Small</td>
<td>0.00</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Total departures per hour = **23.7 departures per hour**
Recapitulation of Results so Far

\[ C_{\text{arrivals}} = \frac{3600}{203.7} = 17.7 \text{ arrivals per hour} \]

\[ C_{\text{departures}} = 23.7 \text{ departures per hour} \]

These results indicate that a single runway can process 17.7 arrivals per hour and during the same period process 23.7 departures per hour using the gaps formed by the arrivals.

Total operations = 41.4 aircraft per hour
Final Note

If only departures are processed at this runway (no arrivals), the departures only capacity is the reciprocal of the departure headway (83 seconds),

\[ C_{dep-NA} = \frac{3600}{83} = 43.3 \text{ departures per hour} \]

Airport engineers use a capacity diagram illustrated in the figure to display all three hourly capacity results in a single diagram. These diagrams represent a Pareto frontier of arrivals and departures. The airport can be operated inside the Pareto boundary.
Interpretation of Arrival-Departure Diagram

- Line segment A-B represents a region where arrivals are given priority over departures. 17.7 arrivals per hour are processed and up to 23.7 departures per hour.

- Line segment B-C represents a tradeoff region. Here we increase the separation between successive arrivals to allow more departures. In the limiting case (no arrivals), only departures and processed at a rate of 43.3 per hour.

- Any operating point inside the Pareto frontier is feasible. Points outside the boundary encompassed by line segments A-B and B-C cannot be sustained for long periods of time.
Example # 2

- Charlotte Douglas International airport (CLT) in North Carolina.

- The airport has a total of 4 runways. Three of them are parallel runways oriented North-South and spaced more than 5,000 feet (see a diagram below).

- The preferential operational scheme is to use both North-South runways in mixed operations (i.e., arrivals and departures on the same runway) on runways 36R and 36C. Runway 36L is used mainly for arrivals because its location is far away from the terminal buildings.

- For this analysis assume the crossing runway (labeled 05-23) is not used due to pavement repairs.
CLT Airport Configuration

source: Google Earth
# CLT Airport Data

**Table 1. Operational Data for CLT Airport.**

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Percent Mix (%)</th>
<th>Runway Occupancy Time (s)</th>
<th>Approach Speed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>10</td>
<td>48</td>
<td>120</td>
</tr>
<tr>
<td>Large</td>
<td>80</td>
<td>54</td>
<td>135</td>
</tr>
<tr>
<td>Heavy</td>
<td>10</td>
<td>62</td>
<td>145</td>
</tr>
</tbody>
</table>

**Table 2. Arrival-Arrival Separation Matrix (values in cells are nautical miles).**

<table>
<thead>
<tr>
<th>Following Aircraft</th>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Large</td>
<td>3</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Heavy</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

**Table 3. Departure-Departure Separation Matrix (values in cells are seconds).**

<table>
<thead>
<tr>
<th>Following Aircraft</th>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>60</td>
<td>90</td>
<td>120</td>
</tr>
<tr>
<td>Large</td>
<td>60</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>Heavy</td>
<td>60</td>
<td>60</td>
<td>90</td>
</tr>
</tbody>
</table>
Arrivals Only Capacity

- First do the analysis for one runway
- Then extend to multiple runways
Arrivals Only Capacity

- For a single runway,

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
</tr>
<tr>
<td>Small</td>
<td>90</td>
</tr>
<tr>
<td>Large</td>
<td>147</td>
</tr>
<tr>
<td>Heavy</td>
<td>221</td>
</tr>
</tbody>
</table>

Table 4. Headways Between Successive Arrivals. Headways are in seconds.

The expected value of $T_{ij}$ is 91.74 seconds. The arrivals-only capacity is calculated to be:

$$C_{\text{arrivals}} = \frac{3600}{91.74} = 39.2 \text{ aircraft/hr}$$
Departure Capacity - Single Runway

• Calculate the expected headway between successive departures

• Use the minimum departure-departure matrix (shown on page 47) and the probability matrix (P<sub>ij</sub>) calculated from Table 1 on page 47
Departure Capacity - Single Runway

\[ E(h_{\text{departures}}) = \sum_{ij} P_{ij} T_{ij}^{\text{Departures}} \]

\[ E(h_{\text{departures}}) \] is the expected headway between departures in seconds

\[ P_{ij} = \text{probability that aircraft of class i follows aircraft of class j} \]

\[ T_{ij}^{\text{Departures}} = \text{is the minimum time between} \]

departures on the same runway when aircraft of class i follows aircraft of class j

For the problem:

\[ E(h_{\text{departures}}) = 0.01 \times 60 + 0.08 \times 90 + 0.01 \times 120 + 0.08 \times 60 \]

\[ + 0.64 \times 60 + 0.08 \times 120 + 0.01 \times 60 + 0.08 \times 60 + 0.01 \times 90 \]

\[ E(h_{\text{departures}}) = 68.1 \text{ seconds} \]

\[ C_{\text{departures}} = \frac{1}{E(h_{\text{departures}})} \text{ departures/second} \]

\[ C_{\text{departures}} = \frac{3600}{E(h_{\text{departures}})} \text{ departures/hr} \]

\[ C_{\text{departures}} = \frac{3600}{68.1} = 52.9 \text{ departures/hr} \]
Airport Capacity (3 Runways)

Departures on 36C

Arrivals on 36L

Arrivals on 36R
## Airport Capacity (3 Runways Used Simultaneously)

<table>
<thead>
<tr>
<th>Runway</th>
<th>Type of Operation</th>
<th>Operations per hour</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>36L</td>
<td>Arrivals</td>
<td>39.2</td>
<td>Arrivals only</td>
</tr>
<tr>
<td>36C</td>
<td>Departures</td>
<td>52.9</td>
<td>Departures only</td>
</tr>
<tr>
<td>36R</td>
<td>Arrivals</td>
<td>39.2</td>
<td>Arrivals only</td>
</tr>
<tr>
<td>All runways</td>
<td></td>
<td>131.3</td>
<td>Maximum saturation capacity of the runway system at CLT airport</td>
</tr>
</tbody>
</table>
Observations

• The departure capacity of a typical runway is greater than the arrival capacity for the same runway

• Mixed operations (i.e., arrivals and departures) on a single runway require a tradeoff between arrivals and departures

• Some US airports conduct mixed runway operations due to their runway configuration:
  • San Diego - a single runway
  • LaGuardia - intersecting runways
Mixed Operations
Arrivals and departure on the Same Runway

Mixed Operations Analysis
Find the values of the gaps needed to allow one, two and three departures for each arrival gap. Using the gaps analysis explained in the course notes we find the following number of departures between successive arrivals.

Table 6. Number of Departures per Gap Between Successive Arrivals.

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
</tr>
<tr>
<td>Small</td>
<td>0</td>
</tr>
<tr>
<td>Large</td>
<td>1</td>
</tr>
<tr>
<td>Heavy</td>
<td>2</td>
</tr>
</tbody>
</table>

For a total of 38 gaps per hour this yields approximately 7 departures per hour with 100% arrival priority (i.e., leaving the arrivals at the saturation point). The following arrival-departure Pareto Diagram is generated for runways 36C and 36R.
Single Runway Pareto Diagram

Figure 2. Arrivals-Departure Diagram for Runway 36C or Runway 36R.
Multiple Runway Pareto Diagram

Arrivals/hr

Departures/hr

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(14, 117)

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Virginia Tech (A.A. Trani)