Runway Capacity Example

CEE 5614
Analysis of Air Transportation Systems

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Professor
Problem Description

- The airport to be studied in this problem is shown in Figure 1.
- The airport has two 9,000 foot runways with a configuration shown in the Figure 1.
- The airport has an airport surveillance radar (ASR) which tracks aircraft up to 60 miles from the airport site.
- Tables 1 and 2 show the typical ATC separations at the airport under IMC conditions.
- Tables 3 and 4 show the separations under VMC conditions.
- The airport has the following technical parameters: a) in-trail delivery error of 16 seconds, b) departure-arrival separation for both VMC and IMC conditions is 2 nautical miles, c) probability of violation is 5%.
- Arriving aircraft are “vectored” by ATC to the final approach fix (see Figure) located 7 miles from the runway threshold.
Problem Description

- The airport has an aircraft fleet mix made up of 10% small, 65% large and 25% heavy wake class aircraft.
- The characteristics of the aircraft are given in Table 5.
- Observed runway occupancy times in the field are: 48, 55, and 62 seconds for small, large and heavy aircraft, respectively.
- Assume the 3-point runway deceleration calculation method applies to this problem to estimate the time to cross the intersection.
Problem Description

- In your analysis assume departing aircraft accelerate on the runway at a constant rate of 2.2 m/s²
- Assume that ATC controllers release departures on runway 18-36, around 10 seconds after an arriving aircraft crosses the intersection between runways 09L-27R and 18-36
- Arrivals and departures are not airborne at the intersection
- For departures on runway 18-36 to occur, it is desired that when the departing aircraft is released from the takeoff position, the next arrival to runway 09L be no less than 2.0 nm from the arrival threshold
- This rule is used by ATC controllers to schedule departures on runway 36
Problem Description

- Departures 3
- Airport Surveillance Radar (ASR-8)
- Departures 1
- Departures 2
- Arrivals 09L
- Arrivals 09R
- 7 nautical miles
- 0.2 nm
- 0.3 nm
- 0.9 nautical miles
Problem Description
(IFR Separations)

Table 1. Minimum arrival-arrival separations under IMC conditions. Values in are nautical miles.

<table>
<thead>
<tr>
<th>Minimum Separation Matrix (nm)</th>
<th>Arrivals-Arrivals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>Trailing</td>
</tr>
<tr>
<td></td>
<td>Small</td>
</tr>
<tr>
<td>Small</td>
<td>3</td>
</tr>
<tr>
<td>Large</td>
<td>5</td>
</tr>
<tr>
<td>Heavy</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 2. Minimum departure-departure separations under IMC conditions. Values in are in seconds.

<table>
<thead>
<tr>
<th>Departure-Departure Separation Matrix (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
</tr>
<tr>
<td>Small</td>
</tr>
<tr>
<td>Small</td>
</tr>
<tr>
<td>Large</td>
</tr>
<tr>
<td>Heavy</td>
</tr>
</tbody>
</table>
Problem Description
(VFR Separations)

Table 3. Minimum arrival-arrival separations under VMC conditions. Values in are nautical miles.

<table>
<thead>
<tr>
<th>Minimum Separation Matrix (nm)</th>
<th>Arrivals-Arrivals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>Trailing</td>
</tr>
<tr>
<td></td>
<td>Small</td>
</tr>
<tr>
<td>Small</td>
<td>2.4</td>
</tr>
<tr>
<td>Large</td>
<td>5</td>
</tr>
<tr>
<td>Heavy</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 4. Minimum departure-departure separations under IMC conditions. Values in are in seconds.

<table>
<thead>
<tr>
<th>Departure-Departure Separation Matrix (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Small</td>
</tr>
<tr>
<td>Large</td>
</tr>
<tr>
<td>Heavy</td>
</tr>
</tbody>
</table>
## Problem Description
(Runway Performance)

Table 5. Runway Performance Data.

<table>
<thead>
<tr>
<th>Aircraft Group</th>
<th>Parameters</th>
<th>Representative Aircraft</th>
</tr>
</thead>
</table>
| Small aircraft | Approach speed = 125 knots  
                  Touchdown location = 1,200 feet  
                  Average deceleration = -4.2 ft/s²  
                  Free roll time = 2.0 seconds  
                  (after touchdown and before braking) | Cessna Citation 560, Citation 500, Beechcraft Jet 400 |
| Large aircraft | Approach speed = 145 knots  
                  Touchdown location = 1,300 feet  
                  Average deceleration = -4.2 ft/s²  
                  Free roll time = 2.0 seconds | Boeing 737-400 (B-737-400), Airbus A320 (A-320-200) |
| Heavy aircraft | Approach speed = 155 knots  
                  Touchdown location = 1,400 feet  
                  Average deceleration = -4.2 ft/s²  
                  Free roll time = 2.0 seconds | Boeing 747-400, Airbus A340-600 |
Questions

1. Calculate the arrival-departure saturation capacity diagram (Pareto diagram) under IMC conditions for this airport.
2. Calculate the arrival-departure saturation capacity diagram (Pareto diagram) under VMC conditions for this airport.

• State all your assumptions in your calculation.
Solution to the Problem

• Steps in the solution
• Start with a single runway analysis for IMC conditions
• Identify interactions between runways
• Use the principle of superposition whenever possible (i.e., study independent runways and then add their capacity)
• Set-up a manual simulation scheme to look at various operational strategies for the airport
Single Runway Analysis (Arrival Operations)

- Use the spreadsheet program provided in class or your own manual calculations

### Pij Matrix

<table>
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<tr>
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<th>Heavy</th>
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</thead>
<tbody>
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<td>0.065</td>
<td>0.025</td>
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<tr>
<td>Large</td>
<td>0.065</td>
<td>0.423</td>
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<tr>
<td>Heavy</td>
<td>0.025</td>
<td>0.163</td>
<td>0.063</td>
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</tbody>
</table>

### Augmented Matrix (Tij + Bij)

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<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
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<td>100.88</td>
<td>96.08</td>
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<tr>
<td>Large</td>
<td>178.34</td>
<td>100.88</td>
<td>96.08</td>
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<tr>
<td>Heavy</td>
<td>211.82</td>
<td>153.74</td>
<td>96.08</td>
</tr>
</tbody>
</table>

**IFR Conditions**

**Arrivals-Only Capacity**

30.98 per hour
Single Runway Analysis (departure operations)

<table>
<thead>
<tr>
<th>Pij Matrix</th>
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<tr>
<td></td>
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<tr>
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<td>Large</td>
<td>0.065</td>
</tr>
<tr>
<td>Heavy</td>
<td>0.025</td>
</tr>
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Departure-Departure Separation Matrix (seconds)

<table>
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<tr>
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<tr>
<td></td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Heavy</td>
</tr>
</tbody>
</table>

IFR Conditions
Departures- Only Capacity 45.07 per hour
IFR Capacity Pareto Diagram (Single Runway Analysis)

Saturation Capacity for a Single Runway at the Airport under Various Operational Conditions. The diagram applies to one runway (either 09L-27R or 09R-27L)

![IFR Capacity Pareto Diagram](image-url)
IFR Capacity Pareto Diagram (Two Parallel and Independent Runways)

Saturation Capacity for two runways at the Airport under Various Operational Conditions. The diagram applies to one runway (either 09L-27R or 09R-27L)

- (0, 62)
- (16, 62)
- (48, 51)
- (90, 0)
VFR Capacity Pareto Diagram
(Single Runway Analysis)

Saturation Capacity for a Single Runway at the Airport under Various Operational Conditions. The diagram applies to one runway (either 09L-27R or 09R-27L)

Arrivals (per hour)

Departures (per hour)

(0,35) (10,35) (25,26) (56,0)

VFR Conditions
VFR Capacity Pareto Diagram
(Two Parallel and Independent Runways)

Saturation Capacity for a Single Runway at the Airport under Various Operational Conditions. The diagram applies to one runway (either 09L-27R or 09R-27L)
Observations

- Arrivals on runways 09L and 09R are independent (> 4300 ft separation) (radar available)

- The Pareto diagram found for one runway replicates for the second parallel runway (also used in mixed operations mode)

- The arrivals-only saturation capacity of the two-runway system is 62 per hour

- The departures-only saturation capacity for two parallel runways is 90 per hour
Detailed Analysis for Intersecting Runways

• The intersecting runway is treated as another asset at the airport

• Need to answer the fundamental questions:

• Are there any gaps left by successive arrivals (do nothing) allowing departures from runway 36?

• Quantify the capacity benefit for IFR conditions
Approach

• Visualize the situation by drawing various operations

• Determine the added number of departures on runway 36 allowed with the “natural” arrival gaps on runway 09L

• Assume that departures on runway 09L are not processed since runway 36 offers clear advantages

• The diagrams that follow illustrate various steps in the sequence of events likely to happen at the airport as “closing” case, pairwise arrival sequences
Aircraft Positions at Time $t = 0$ s

minimum separation + buffer

$\delta_{ij} + \frac{B_{ij}}{3600} V_j$

$V_j$ in knots

$B_{ij}$ in seconds

Aircraft 1 crosses runway 09L threshold. Aircraft 3 follows in-trail at the required separation behind aircraft 1
Calculations of Travel Time for Landing Aircraft to Cross Runway Intersection

• Calculation of the travel times from threshold crossing point to runway intersection point

• The travel times to cross the intersection of runway 18-36 (as the aircraft lands on runway 09L) are: 5.8, 5.0 and 4.6 seconds for small, large and heavy aircraft, respectively

• These travel times influence the ATC tower controller (i.e. local controller) decision on when to clear a departure on the crossing runway
Calculations of Travel Time to Cross Runway Intersection for Departing Aircraft on Runway 36

\[ S = V_i t + \frac{1}{2} a t^2 \]

\[ t^2 = \frac{2S}{a} \]

\[ t = \sqrt{\frac{2S}{a}} \]

\[ t = \sqrt{\frac{2(555.6 \text{ m})}{2.2 \text{ m/s}^2}} = 22.5 \text{ seconds} \]

Aircraft departing runway 36 take \( \sim 23 \) seconds to cross the runway intersection.
Aircraft Positions at Time \( t=6 \) s

\[
\delta_{ij} + \frac{B_{ij}}{3600} V_j - \frac{6}{3600} (V_j)
\]

where:

- \( B_{ij} \) is the buffer time in seconds
- \( V_j \) is the following aircraft speed in knots
Aircraft Positions at Time t=16 s

Aircraft 2 starts its takeoff roll 10 seconds after aircraft 1 clears the intersection (this accounts for ATC situational awareness)

\[ \delta_{ij} + \frac{B_{ij}}{3600} V_j - \frac{16}{3600} (V_j) \]

where:
- \( B_{ij} \) in seconds
- \( V_j \) in knots
Aircraft Positions at Time $t = 39 \text{ s}$

Aircraft 2 just crossed the runway intersection after a takeoff roll of 23 seconds to reach the intersection point.

\[ \delta_{ij} + \frac{B_{ij}}{3600} V_j - \frac{39}{3600} (V_j) \]

where:

- $B_{ij}$ in seconds
- $V_j$ in knots

Runway 36
Runway 09L
Runway 27R
Critical Distance at \( t = 39 \) s

At \( t=39 \) seconds, the distance from runway threshold 09L to aircraft 3 has to be equal or greater than 2.0 nm.

\[
\delta = 2.5 \text{ nm} = \delta_{ij} + \frac{B_{ij}}{3600} V_j - \frac{39}{3600} V_j
\]

\[
\delta_{ij} + \frac{B_{ij}}{3600} V_j - \frac{39}{3600} V_j \geq 2.0 \text{ nm}
\]

Condition to release a departure between arrival gaps.
General Observations

• The time period between the leading aircraft arrival (i) on runway 09L and a single departure on runway 36 is around 39 seconds. Define,

\[ t_{n-36} = \text{time for } n \text{ departures on runway 36} \]

\[ t_{1-36} = 39 \text{ seconds} \]
\[ t_{2-36} = (39 + 80) = 119 \text{ seconds} \]
\[ t_{3-36} = (39 + 80 + 80) = 199 \text{ seconds} \]
\[ t_{n-36} = 39 + E(t_d)(n - 1) \text{ seconds} \]

where:
\[ n = \text{number of departures on runway 36} \]
\[ \text{per arrival gap on runway 09L} \]
\[ E(t_d) = \text{expected value of time between} \]
\[ \text{successive departures on runway 36} \]
General Observations

\[ t_{n-36} = \text{time for } n \text{ departures on runway 36} \]

- For each successive pair of arrivals on the primary runway (runway 09L-27R), we would have to subtract (\( t_{n-36} \)) seconds and check the suitability of each natural gap to release \( n \) departures on runway 36

- The procedure is analogous to a single runway with mixed operations
Analysis of Crossing Runway Operations (IFR Case)

**Augmented Matrix (Tij + Bij)**

<table>
<thead>
<tr>
<th></th>
<th>Trailing</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
</tr>
<tr>
<td>Small</td>
<td>112.80</td>
</tr>
<tr>
<td>Large</td>
<td>178.34</td>
</tr>
<tr>
<td>Heavy</td>
<td>211.82</td>
</tr>
</tbody>
</table>

**Time remaining on following aircraft approach segment (seconds)**

<table>
<thead>
<tr>
<th></th>
<th>Trailing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
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<tr>
<td>Small</td>
<td>73.80</td>
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<tr>
<td>Large</td>
<td>139.34</td>
</tr>
<tr>
<td>Heavy</td>
<td>172.82</td>
</tr>
</tbody>
</table>

- 39 seconds

**Time left for following aircraft to reach runway 09L threshold**
Analysis of Crossing Runway Operations (IFR Case)

Distance left between following aircraft and runway threshold (nm)

<table>
<thead>
<tr>
<th>n=1</th>
<th>Trailing</th>
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</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td>Small</td>
<td>2.56</td>
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<tr>
<td>Large</td>
<td>4.84</td>
</tr>
<tr>
<td>Heavy</td>
<td>6.00</td>
</tr>
</tbody>
</table>

Distance between following aircraft on runway 09L to runway threshold

\[ \delta_{ij} + \frac{B_{ij}}{3600} V_j - \frac{39}{3600} V_j \geq 2.0 \text{ nm} \]

Potential departures on runway 36 per arrival gap on 09L

<table>
<thead>
<tr>
<th>n</th>
<th>Trailing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>Small</td>
<td>1.00</td>
</tr>
<tr>
<td>Large</td>
<td>2.00</td>
</tr>
<tr>
<td>Heavy</td>
<td>2.00</td>
</tr>
</tbody>
</table>
Analysis of Crossing Runway Operations (IFR Case)

\[ ED_{g-ij} = P_{ij}DG_{ij}TG \]

- \( ED_{g-ij} \) = equivalent departures per gap between aircraft i and j
- \( P_{ij} \) = probability of i following j
- \( DG_{ij} \) = Departures per gap between i and j
- \( TG \) = total gaps per hour

Sample calculation

\[ ED_{s-s} = 0.010 \times 1.0 \times (30.97 - 1) = 0.3 \]

Total departures on runway 36 considering all arrival gaps on runway 09L
Preliminary Conclusions

- The total number of departures on runway 36 is estimated to be **33 per hour**
- This is slightly more than the number of arrivals on the primary runway (09L)
- Processing departures on runway 36 is advantageous:
  - 8 departures on runway 09L-27R per hour
  - 33 departures on runway 36-18 per hour
- Both results assume arrival priority on runway 09L-27R
Extending the Analysis for Runway 09L and 36 as Dependent Pair

- It is clear that departures operations on runway 36 are clearly coupled to arrivals to runway 09L.
- Now we study the situation where arrival gaps on runway 09L are increased allowing more departures on runway 36.
- As arrival gaps grow to infinity, the number of departures on runway 36 increase to 45 per hour.
- The advantages in the Pareto diagram are shown in the next page.
IFR Capacity Pareto Diagram
(Runways 09L and 36 as Coupled Pair)

Saturation capacity for two runways operated with dependent operations. Arrivals on runway 09L, departures on runway 36.
Capacity Benefits

- It is clear that an expansion of the Pareto diagram is a benefit to the capacity of the airport.

- Consider an operating point where the coupled runway pair handles 33 departures and 31 arrivals, the single runway 09L in mixed operations can only process 33 departures and 15 arrivals.
IFR Capacity Pareto Diagram
(Coupled Runway Pair 09L / 36 + Runway 09R)

Saturation capacity for three runways (coupled pair + single runway). Arrivals on runway 09L and 09R, departures on runway 36 and 09R.

Mixed operations on runways 09L and 09R (no operations on runway 36)

Arrivals on runway 09L, departures on runway 36 and mixed operations on 09R

IFR Conditions
Final Twist on Departure Capacity

- As the arrivals on runway 09L are reduced to zero (allowing more departures on runway 36 during departure rush periods) it is clear that substantial departure capacity gains are possible operating the coupled pair with sequenced departures (as shown).

- You can show that the departure saturation capacity of the coupled pair is ~80 per hour.

- This in the end increases the departure capacity of the airfield to 125 per hour.
Capacity Diagrams for Various Airports

CEE 5614
Analysis of Air Transportation Systems

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Professor
FAA Airport Capacity Benchmarks

- The FAA has conducted detailed capacity studies for the 31 most important airports to determine their VFR and IFR hour capacities.

- The details are included in the FAA Airport Capacity benchmark document.

Summary of Top 31 Airports

Runway Hourly Capacity

Airport 3 Letter Code

Virginia Tech - Air Transportation Systems Laboratory
Observations

- Airports with largest margins between VFR (Optimal) and IFR capacities are DFW (Dallas Forth Worth), DEN (Denver) and ORD (Chicago)

- These airports have multiple parallel runways that benefit from VFR rules

- Few airports such as San Diego (SAN), La Guardia (LGA), Chicago Midway (MDW) and Fort Lauderdale (FLL) have IFR capacities close to those for VFR

- Capacity is affected by:
  - Runway configuration
  - Weather
  - Aircraft fleet mix
Planned Improvements (VFR Weather)

- Airport authorities and the FAA have planned some improvements to the top 31 airports

ATL added a new runway in 2006
Airport # 1: Atlanta Hartsfield

- The busiest airport in the World

<table>
<thead>
<tr>
<th>Aircraft Class</th>
<th>% Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>2.3</td>
</tr>
<tr>
<td>Large</td>
<td>78.5</td>
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<tr>
<td>B757</td>
<td>12.0</td>
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<tr>
<td>Heavy</td>
<td>7.4</td>
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</table>

<table>
<thead>
<tr>
<th>Condition</th>
<th>Hourly Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>VFR</td>
<td>180-188</td>
</tr>
<tr>
<td>Marginal VFR</td>
<td>172-174</td>
</tr>
<tr>
<td>IFR</td>
<td>158-162</td>
</tr>
</tbody>
</table>

Capacity of 4 Runways

6,400 feet
Airport #1: Atlanta Hartsfield

- With 4 runways the hourly capacities of the airport are:
  VFR=180, MVFR =172 and IFR=158 per hour

source: FAA Airport Capacity Benchmarks
Airport # 1: Atlanta Hartsfield

- With 5 runways the hourly capacities of the airport are: VFR=237, MVFR =229 and IFR=202 per hour

source: FAA Airport Capacity Benchmarks
Airport # 1: Atlanta Hartsfield

- 4-runway Pareto diagram

IFR Conditions

- Note a small reduction in the number of departures under IFR conditions
- Departures wait for arrivals to cross threshold

source: FAA Airport Capacity Benchmarks
Airport # 1: Atlanta Hartsfield

- Departures are issued clearance once the arriving aircraft crosses the threshold
- For every arrival typically there is one departure on the close parallel runway

1000 feet

Runway 26R

Runway 26L

Arrival

Line up and wait

IFR Conditions
Airport # 2: Boston Logan

Aircraft Class | % Mix
---|---
Small | 15.2
Large | 70.0
B757 | 10.3
Heavy | 4.5

Condition | Hourly Capacity
---|---
VFR | 123-131
Marginal VFR | 112-117
IFR | 90-93

Runways 32 and 33L have 10 degree offset headings
Runway 32 is a visual runway

4,800 feet
Airport #2: Boston Logan

- With 4 runways the hourly capacities of the airport are: VFR=123, MVFR=112 and IFR=90 per hour

source: FAA Airport Capacity Benchmarks
Airport # 2: Boston Logan

- Pareto diagram (Arrivals on Runway 4R, Departures on runways 4R, 4L and 9)

IFR Conditions

- Note airport has an equivalent of one arrival runway in IFR conditions
- Good departure rate

source: FAA Airport Capacity Benchmarks
Airport #3: Reagan National Airport

Primary runway is 19
Runway 15 is limited to regional jets and turboprops

<table>
<thead>
<tr>
<th>Aircraft Class</th>
<th>% Mix</th>
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<tbody>
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</tr>
<tr>
<td>Large</td>
<td>96.3</td>
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<tr>
<td>B757</td>
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</table>

<table>
<thead>
<tr>
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<th>Hourly Capacity</th>
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<tbody>
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<tr>
<td>Marginal VFR</td>
<td>60-84</td>
</tr>
<tr>
<td>IFR</td>
<td>48-70</td>
</tr>
</tbody>
</table>

VFR Conditions
Airport #3: Reagan National Airport

source: FAA Airport Capacity Benchmarks
## Airport #3: Reagan National Airport

### Aircraft Class % Mix

<table>
<thead>
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### Condition Hourly Capacity

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<td>60-84</td>
</tr>
<tr>
<td>IFR</td>
<td>48-70</td>
</tr>
</tbody>
</table>

- Primary runway is 01 Runway 33 is limited to regional jets and turboprops Runway 04 for GA aircraft
Airport #3: Reagan National Airport

**IFR Conditions**

- Note airport has an equivalent of one arrival runway in IFR conditions
- Modest departure rate

Source: FAA Airport Capacity Benchmarks