1.231J/16.781J/ESD.224J Airport Systems – Fall 2007

# Geometric Specifications of Airfields

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## Airport Design Specifications

- The two most-commonly used sources of geometric specifications for airfield design are:
  1. ICAO Annex 14 (“Aerodromes”) and associated supplements and manuals
  2. FAA Advisory Circular 150/5300-13 (“Airport Design”)

  http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgAdvisoryCircular.nsf/MainFrame?OpenFrameSet
- FAA updates of specifications are usually developed earlier than updates to ICAO Annex 14 (e.g., Group VI standards)

*Reference: de Neufville and Odoni, Ch. 9, Secs. 2-3, 5-9*

# Classification (FAA)

**Aircraft Approach Category**

- A: Speed < 91 knots
- B: [ 91 - 121) knots
- C: [ 121 - 141) knots
- D: [ 141 - 166) knots
- E: Speed 166+ knots

**Airplane Design Group**

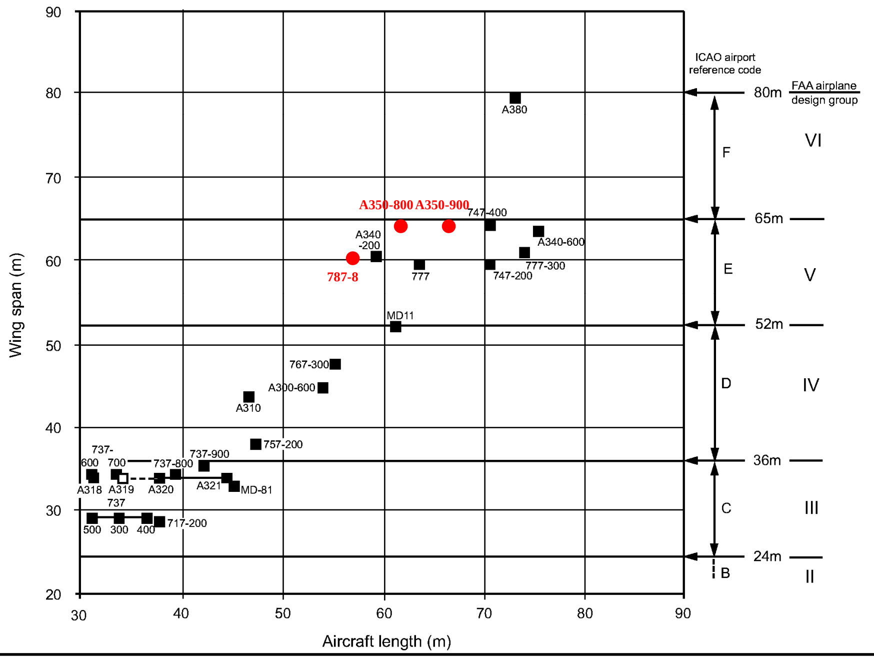
- I: Wing < 49 ft (15 m)
- II: [ 49 - 79) ft (15-24 m)
- III: [ 79 - 118) ft (24-36 m)
- IV: [ 118 - 171) ft (36-52 m)
- V: [ 171 - 214) ft (52-65 m)
- VI: [ 214 - 262) ft (65-80 m)

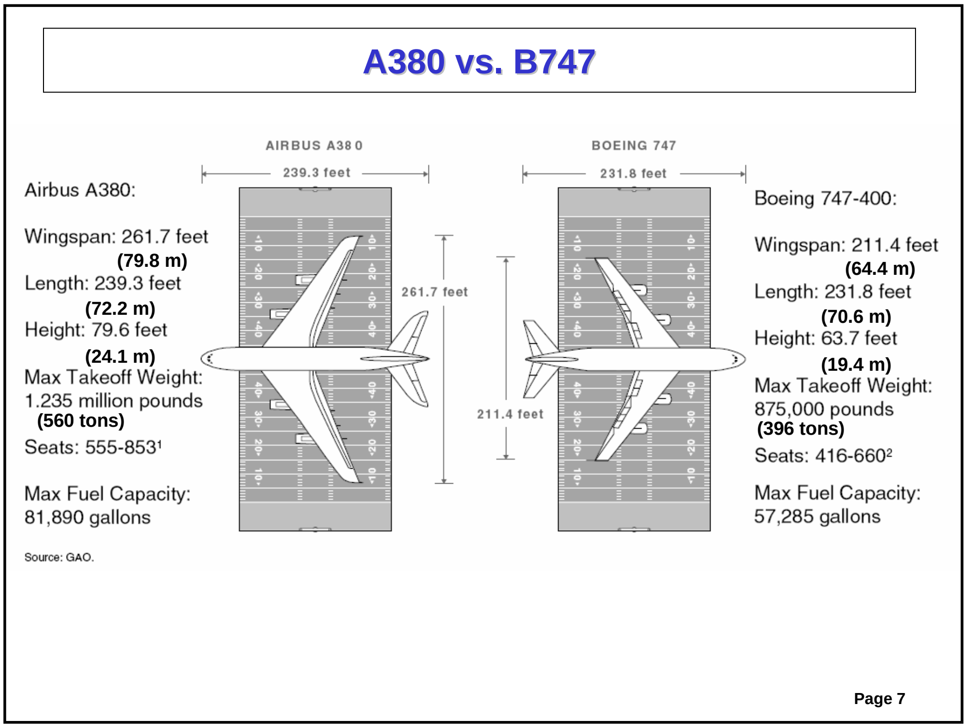
# Airport Reference Codes (ICAO)

| Code # | Reference field length | Code letter | Wing span | Main gear wheel span |
|---|---|---|---|---|
| 1 | Up to 800 m | A | Up to 15 m | Up to 4.5 m |
| 2 | 800-1200 m | B | 15 – 24 m | 4.5 – 6 m |
| 3 | 1200-1800 m | C | 24 – 36 m | 6 – 9 m |
| 4 | 1800 m + | D | 36 – 52 m | 9 – 14 m |
|  |  | E | 52 – 65 m | 9 –14 m |
|  |  | F | 65 – 80 m | 14 –16 m |

## Remarks re ICAO and FAA Airport Reference Codes

- **Practically all major commercial airports belong to the ICAO Code #4 class**
- **Main gear wheel span (ICAO) is “dominated” by wing span**
- **ICAO Code Letters A-F wing spans correspond *exactly* to FAA Airplane Design Groups I-VI wing spans**
- **Most geometric specifications for airports are determined by the wing span of the most demanding aircraft**





## A380 vs. B747

Airbus A380:

Wingspan: 261.7 feet
**(79.8 m)**
Length: 239.3 feet
**(72.2 m)**
Height: 79.6 feet
**(24.1 m)**
Max Takeoff Weight:
1.235 million pounds
**(560 tons)**
Seats: 555-853[1]

Max Fuel Capacity:
81,890 gallons

Boeing 747-400:

Wingspan: 211.4 feet
**(64.4 m)**
Length: 231.8 feet
**(70.6 m)**
Height: 63.7 feet
**(19.4 m)**
Max Takeoff Weight:
875,000 pounds
**(396 tons)**
Seats: 416-660[2]

Max Fuel Capacity:
57,285 gallons

Source: GAO.

## Runway Separations (FAA)*

| Runway Centerline To… | AIRPLANE DESIGN GROUP | | | | | |
|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI |
| | NON-PRECISION INSTRUMENT AND VISUAL | | | | | |
| Hold Line | 250 ft<br>75 m | 250 ft<br>75 m | 250 ft<br>75 m | 250 ft<br>75 m | 250 ft<br>75 m | 250 ft<br>75 m |
| Taxiway Centerline | 300 ft<br>90 m | 300 ft<br>90 m | 400 ft<br>120 m | 400 ft<br>120 m | 400/450/500<br>120/135/150 | 600 ft<br>180 m |
| Parking Area | 400 ft<br>120 m | 400 ft<br>120 m | 500 ft<br>150 m | 500 ft<br>150 m | 500 ft<br>150 m | 500 ft<br>150 m |
| | PRECISION INSTRUMENT | | | | | |
| Hold Line | 250 ft<br>75 m | 250 ft<br>75 m | 250 ft<br>75 m | 250 ft<br>75 m | 280 ft<br>85 m | 325 ft<br>98 m |
| Taxiway Centerline | 400 ft<br>120 m | 400 ft<br>120 m | 400 ft<br>120 m | 400 ft<br>120 m | 400/450/500<br>120/135/150 | 600 ft<br>180 m |
| Parking Area | 500 ft<br>150 m | 500 ft<br>150 m | 500 ft<br>150 m | 500 ft<br>150 m | 500 ft<br>150 m | 500 ft<br>150 m |

***For aircraft approach Cat. C and D**

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# Airfield Capacity

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## Airfield Capacity: I

- ☐ Objective
  - – To summarize fundamental concepts re. airfield capacity
- ☐ Topics
  - – Definitions of capacity
  - – Factors affecting capacity
  - – Separation requirements
  - – A simple model for a single runway
  - – Capacity envelopes and capacity coverage chart

*Reference: Chapter 10*

## Capacity Measures

- Maximum-Throughput Rate
  - Average number of demands a server can process per unit of time when always busy
    - $\mu$ = maximum throughput rate
    - *E(t)* = expected service time

$$\mu = \frac{1}{E(t)}$$

- Level of Service (LOS) related capacity
  - Number of demands processed per unit of time while meeting some pre-specified LOS standards (must know $\mu$ to compute)

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## Definitions: Runway Capacity*

- *Maximum Throughput (or Saturation) Capacity*

The expected ("average") number of runway operations (takeoffs and landings) that can be performed in one hour without violating ATC rules, assuming continuous aircraft demand.

- *Declared Capacity*

The capacity per hour used in specifying the number of slots available for schedule coordination purposes; used extensively outside US; no standard method for its determination; no generally accepted LOS; typically set to about 85-90% of saturation capacity; may be affected by apron capacity and terminal capacity

* *These definitions can be applied to a single runway or to the entire complex of runways at an airport.*

## LOS-Related Capacity Definitions (Less Common)

- Practical Hourly Capacity

  The average number of operations that can be performed in one hour on a runway (or, more generally, a system of active runways) with an average delay per operation of 4 minutes**.**

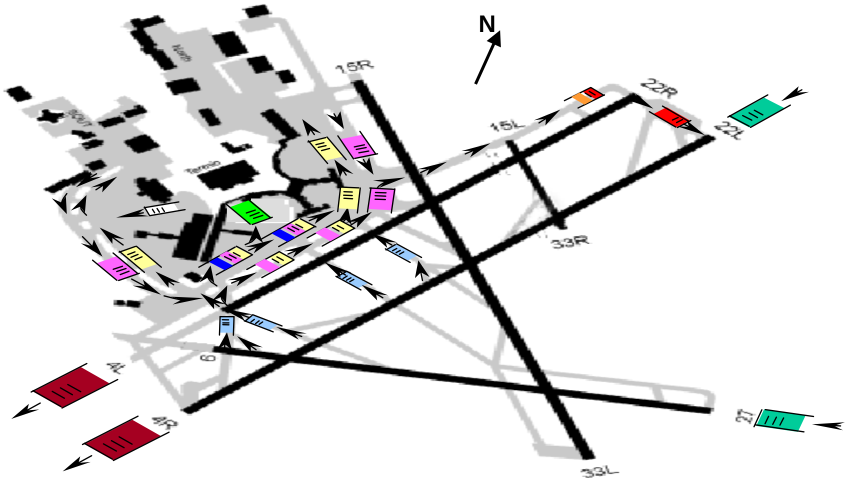
- Sustained Capacity

  The average number of operations per hour that can be "sustained" for periods of several hours; vaguely-defined, typically workload-related.

## Factors Affecting Capacity

- Number and layout of active runways
- Separation requirements (longitudinal, lateral)
- Weather (ceiling, visibility)
- Wind (direction, strength)
- Mix of aircraft
- Mix and sequencing of operations (landings, takeoffs, mixed)
- Quality and performance of ATM system (including human factor -- pilots and controllers)
- Runway exit locations
- Noise considerations

## Configuration 22L/27 - 22R/22L



Source: Idris (2000)

## Role of ATC Separation Requirements

- Runway (and airfield) capacities are constrained by ATC separation requirements
- Typically aircraft are separated into a small number (3 or 4) of classes
- Example: FAA classification
  - Heavy (H): 255000 lbs < MTOW
  - Large (L): 41000 lbs < MTOW < 255000 lbs
  - Small (S): MTOW < 41000 lbs
- Required separations (in time or in distance) are then specified for every possible pair of aircraft classes and operation types (landing or takeoff)
- Example: “arrival of H followed by arrival of S”

## IFR Separation Requirements: Single Runway (USA)

***Arrival-Arrival:***

**(1) Airborne separations on final approach (nmi):**

| | | Trailing aircraft | | |
|---|---|---|---|---|
| | | **H** | **L or B757** | **S** |
| **Leading aircraft** | **H** | **4** | **5** | **5/6*** |
| | **B757** | **4** | **4** | **5** |
| | **L** | **2.5 (or 3)** | **2.5 (or 3)** | **3/4*** |
| | **S** | **2.5 (or 3)** | **2.5 (or 3)** | **2.5 (or 3)** |

** Applies when leading aircraft is at threshold of runway*

**(2) Leading aircraft must be clear of the runway before trailing aircraft touches down**

## IFR Separation Requirements: Single Runway (USA) [2]

Departure-Departure **(approximate, in seconds)**

| | | Trailing aircraft | | |
|---|---|---|---|---|
| | | H | L + B757 | S |
| Leading aircraft | H | 90 | 120 | 120 |
| | B757 | 90 | 90 | 120 |
| | L | 60 | 60 | 60 |
| | S | 45 | 45 | 45 |

Arrival-Departure and Departure-Arrival

- ❑ Leading aircraft must be clear of runway at the instant when trailing aircraft starts takeoff roll or touches down on the runway, respectively. In D-A case, trailing arrival must also be at least 2 nmi from runway when takeoff run begins

## Separation Requirements (Italy; except Rome, Milan)

**Arrival/Arrival**
(in nautical miles)

$$\begin{array}{c|ccc} & H & M/L & S \\ \hline H & 5 & 5 & 7 \\ M/L & 5 & 5 & 5 \\ S & 5 & 5 & 5 \end{array}$$

**Departure/Departure**

120 seconds between successive departures

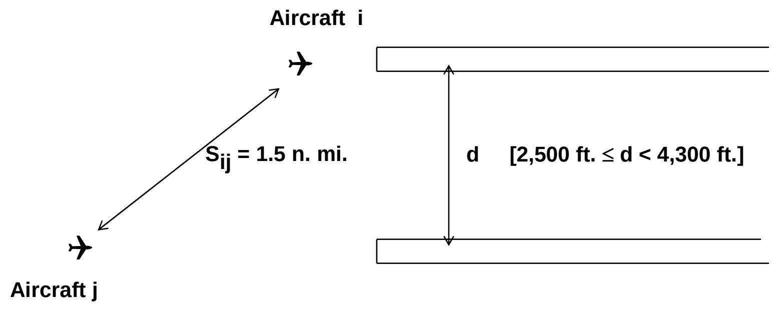
**Departure/Arrival**

Arrival must be at least 5 n.mi. away from runway threshold

## Parallel Runways (IFR): USA

| Separation between runway centerlines | Arrival/ arrival | Departure/ departure | Arrival/ departure | Departure/ arrival |
|---|---|---|---|---|
| 700-2499 ft | As in single runway | As in single runway | Arrival touches down | Departure is clear of runway |
| 2500- 4300 ft | 1.5 nmi (diagonal) | Indep’nt | Indep’nt | Indep’nt |
| 4,300 ft or more | Indep’nt | Indep’nt | Indep’nt | Indep’nt |

# Diagonal separation: medium-spaced parallel runways



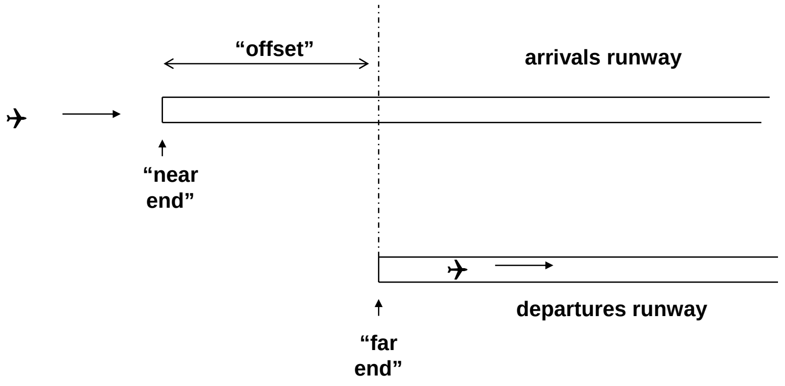
Aircraft i

$S_{ij}$ = 1.5 n. mi.

d [2,500 ft. ≤ d < 4,300 ft.]

Aircraft j

# Staggered parallels: arrivals on “near” runway



“offset”

arrivals runway

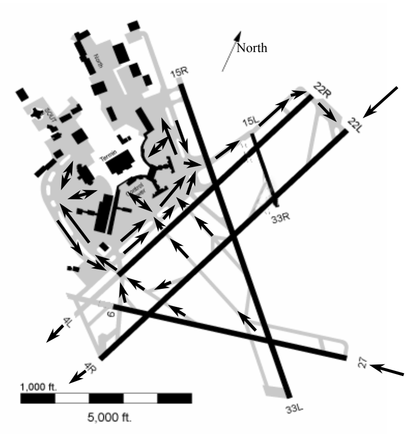
“near end”

departures runway

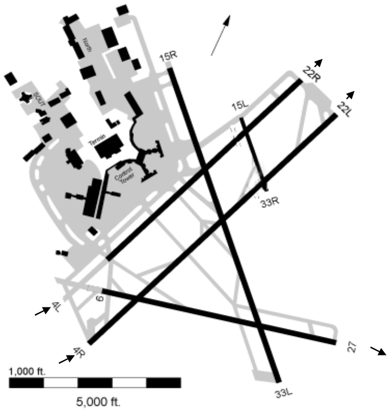
“far end”

## High-capacity configurations in opposite directions, Boston/Logan (VMC)

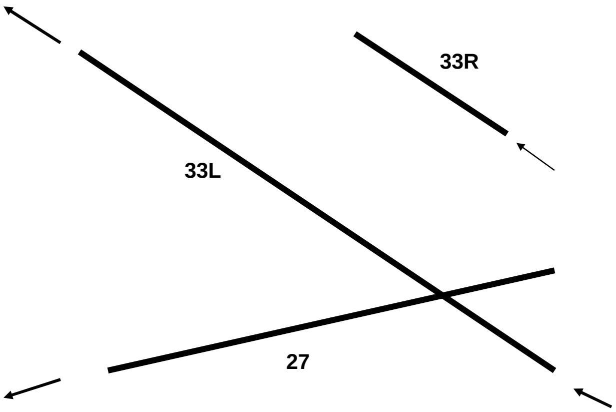
27/22L-22R/22L



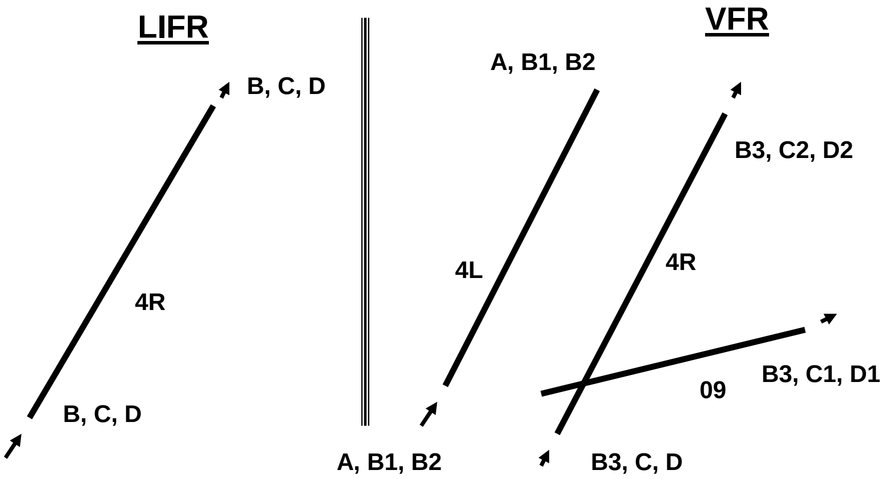
4R/4L-4L/4R/9



## Old low- capacity configuration in VMC, Boston Logan



## Configurations: Same Direction, Different Weather Conditions



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## Typical Approach for Estimating Runway Capacity

1. Compute average time interval for all possible aircraft class pairs i, j

   $t_{ij}$ = average time interval between successive movements of a pair of aircraft of types i and j (i followed by j) such that no ATC separation requirements are violated

2. Compute probability for all i, j

   $p_{ij}$ = probability of occurrence of the pair of aircraft types i and j (i followed by j)

3. Compute overall average service time and then capacity

$$E(t) = \sum_i \sum_j p_{ij} \cdot t_{ij} \qquad \mu = \frac{1}{E(t)}$$

# Numerical Example

Given: Single Runway
(Arrivals Only: IFR)
n = 5 N. Miles

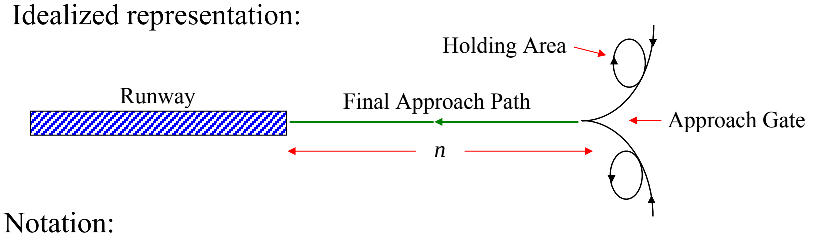
| Aircraft Types | | | |
|---|---|---|---|
| Type | Mix (%) | Approach Speed (kts) | Runway Occupancy Time (secs) |
| Heavy (1) | 20 | 140 | 60 |
| Large (2) | 50 | 120 | 55 |
| Small (3) | 30 | 100 | 50 |

$$\left[s_{ij}\right] = \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array} \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{bmatrix} 4 & 5 & 6^{*} \\ 3 & 3 & 4^{*} \\ 3 & 3 & 3 \end{bmatrix} \end{array}$$

*** Applies only with lead aircraft at threshold (all other separations apply throughout final approach).**

# Arrival Capacity Model of a Single Runway

- ❑ Idealized representation:



- ❑ Notation:
  - $n$: length of final approach path
  - $i$ ($j$): type [heavy/large/medium/small] of leading (trailing) aircraft
  - $v_i$: ground speed of type $i$ aircraft
  - $o_i$: runway occupancy time of type $i$ aircraft
  - $s_{ij}$: minimum longitudinal separation between two airborne aircraft
  - $T_{ij}$: minimum acceptable time interval between successive arrivals at the runway of type $i$ and type $j$ aircraft (**unknown**)

## Effect of Airborne Separation Requirement

- Closing Case
  - Second aircraft is faster, and must have required separation distance from first aircraft at runway threshold; separation at merge area (beginning of final approach) is greater than minimum
- Opening Case
  - Second aircraft is slower, and must meet separation requirement from first aircraft in merge area where approach is initiated; separation at runway threshold is greater than minimum

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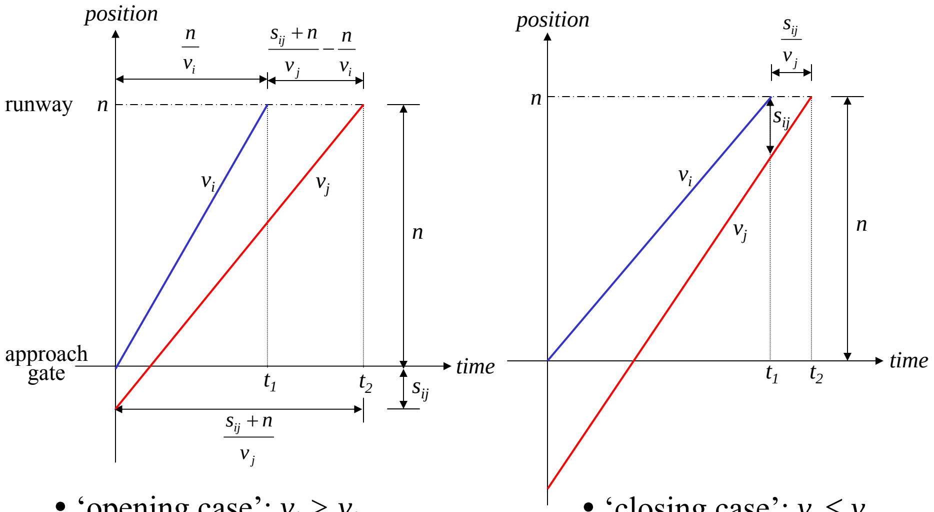
## Minimum Time Separation of Two Aircraft

- Minimum time separation is a consequence of:
  - Only a single aircraft can be on the runway at a given time instant
  - Minimum longitudinal separation must not be violated
- Question: What is the expression for the minimum time separation $T_{ij}$?
- $T_{ij} \geq o_i$
- Answer:

$$T_{ij} = \begin{cases} \max\left[\dfrac{n+s_{ij}}{v_j} - \dfrac{n}{v_i}, o_i\right] & \mathit{for}\ v_i > v_j \quad (\text{‘opening case’}) \\ \max\left[\dfrac{s_{ij}}{v_j}, o_i\right] & \mathit{for}\ v_i \leq v_j \quad (\text{‘closing case’}) \end{cases}$$

# Graphical Description of the Model



- ‘opening case’: $v_i > v_j$
- ‘closing case’: $v_i \leq v_j$

# Minimum Acceptable Average Inter-arrival Time

$$T_{ij} = \begin{cases} \max\left[\frac{n+s_{ij}}{v_j}-\frac{n}{v_i}, o_i\right] & \text{for } v_i > v_j \quad \text{(‘opening case’)} \\ \max\left[\frac{s_{ij}}{v_j}, o_i\right] & \text{for } v_i \leq v_j \quad \text{(‘closing case’)} \end{cases}$$

- ☐ $K$: number of aircraft types
- ☐ Number of ‘type *i* aircraft followed by type *j* aircraft’ pairs : $K^2$
- ☐ $p_{ij}$: probability of ‘type *i* aircraft followed by type *j* aircraft’ pair
- ☐ Minimum acceptable inter-arrival time: $E[T_{ij}] = \sum_{i}^{K}\sum_{j}^{K} p_{ij} \times T_{ij}$

# Matrix of Minimum Separations

- The number $T_{ij}$ in row i and column j is the minimum separation(sec) for the case of aircraft type i followed by type j

$$T_{ij} = \begin{bmatrix} 103 & 171 & 216 \\ 77 & 90 & 144 \\ 77 & 90 & 108 \end{bmatrix}$$

- Opening Case

$$T_{12} = \max\left( \frac{10\,\text{n.mi.}}{120\,\text{knots}} - \frac{5\,\text{n.mi.}}{140\,\text{knots}},\ 60\,\text{sec} \right)$$

$$= \max(171\,\text{sec}, 60\,\text{sec}) = 171\,\text{sec}$$

# Matrix of Minimum Separations [2]

- Closing Case

$$T_{31} = \max\left( \frac{3\,\text{n.mi.}}{140\,\text{knots}},\ 50\,\text{sec} \right)$$

$$= \max(77\,\text{sec},\ 50\,\text{sec}) = 77\,\text{sec}$$

- Stable Case

$$T_{22} = \max\left( \frac{3\,\text{n.mi.}}{120\,\text{knots}},\ 55\,\text{sec} \right)$$

$$= \max(80\,\text{sec},\ 55\,\text{sec}) = 80\,\text{sec}$$

- “Special” Case (also $T_{23}$)

$$T_{13} = \max\left( \frac{6\,\text{n.mi.}}{100\,\text{knots}},\ 60\,\text{sec} \right)$$

$$= \max(216\,\text{sec},\ 60\,\text{sec}) = 216\,\text{sec}$$

## Safety Buffer

- ☐ In practice, a safety buffer is added to the minimum separations between aircraft, to make up for imperfections in the ATC system
- ☐ Allow a buffer of an additional *b* = 10 seconds between each aircraft for safety (10 seconds implies about 1/3 n. mi. longitudinal separation)

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## Matrix of Average Time Separations

The $t_{ij}$ indicate the average separation (sec) between an aircraft of type i and a following aircraft of type j.

$$t_{ij} = T_{ij} + b$$

$$t_{ij} = \begin{bmatrix} 113 & 181 & 226 \\ 87 & 100 & 154 \\ 87 & 100 & 118 \end{bmatrix}$$

# Matrix of Pair Probabilities

- ✈Let $p_{ij}$ = probability that an aircraft of type i will be followed by one of type j
- ✈Assume first-come, first-served (FCFS) runway service

$$p_{ij} = \begin{bmatrix} 0.04 & 0.1 & 0.06 \\ 0.1 & 0.25 & 0.15 \\ 0.06 & 0.15 & 0.09 \end{bmatrix}$$

Example:

- 20% of aircraft are Type 1, 50% are Type 2
- Therefore, the probability of a Type 1 followed by a Type 2 is: $p_{12} = (0.2)*(0.5) = 0.1$

❑ *<u>Note</u>: This is valid only for a FCFS system; no sequencing.*

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# Numerical Example [2]

**Matrix of average time intervals, $t_{ij}$ (in seconds), for all possible pairs of aircraft types:**

$$[t_{ij}] = \begin{array}{c|ccc|} & 1 & 2 & 3 \\ 1 & 113 & 181 & 226 \\ 2 & 87 & 100 & 154 \\ 3 & 87 & 100 & 118 \end{array}$$

**Matrix of probabilities, $p_{ij}$, that a particular aircraft pair will occur:**

$$[\,p_{ij}] = \begin{array}{c|ccc|} & 1 & 2 & 3 \\ 1 & 0.04 & 0.1 & 0.06 \\ 2 & 0.1 & 0.25 & 0.15 \\ 3 & 0.06 & 0.15 & 0.09 \end{array}$$

## Numerical Example [3]

- By multiplying the corresponding elements of the matrices $[p_{ij}]$ and $[t_{ij}]$ we can compute the average separation (in seconds) between a pair of aircraft at the runway in question.

**That is:**

$$E(t) = \sum_i \sum_j p_{ij} \cdot t_{ij}$$

↑ **E(t) = 124 seconds**

**Numerically:**

$$E(t) = (0.04)(113) + (0.1)(181) + (0.06)(226) + (0.1)(87) + (0.25)(100) + (0.15)(154) + (0.06)(87) + (0.15)(100) + (0.09)(118)$$

**Saturation Capacity** $= \dfrac{3600\text{seconds}}{124\text{seconds}} =$ **29 aircraft**

## Numerical Example [4]

- The variance (a measure of variability) of the service times (intervals between successive landings in this case) can also be computed from:

$$\sigma_t^2 = \sum_i \sum_j p_{ij} \cdot [t_{ij} - E(t)]^2$$

- Or,

$(0.04)(113\text{-}124)^2 + (0.1)(181\text{-}124)^2 + \ldots. + (0.09)((118\text{-}124)^2$

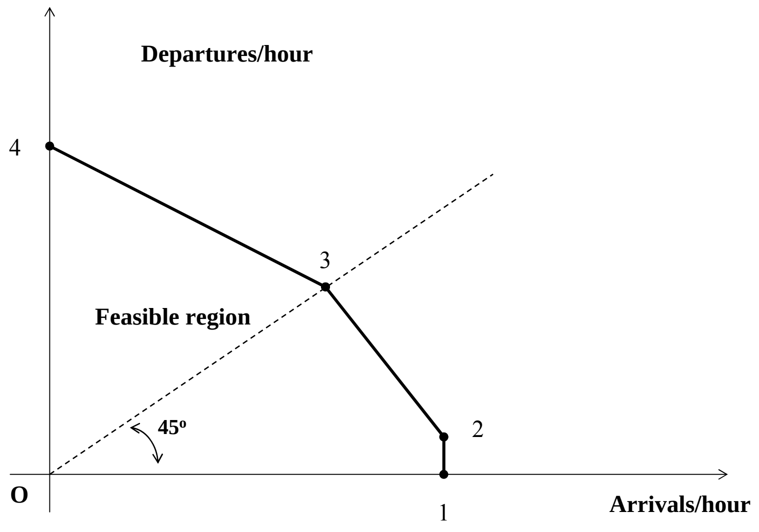
$= 1542 \text{ sec}^2$

- The standard deviation, $\sigma_\tau = \sqrt{1542} = 39$ seconds

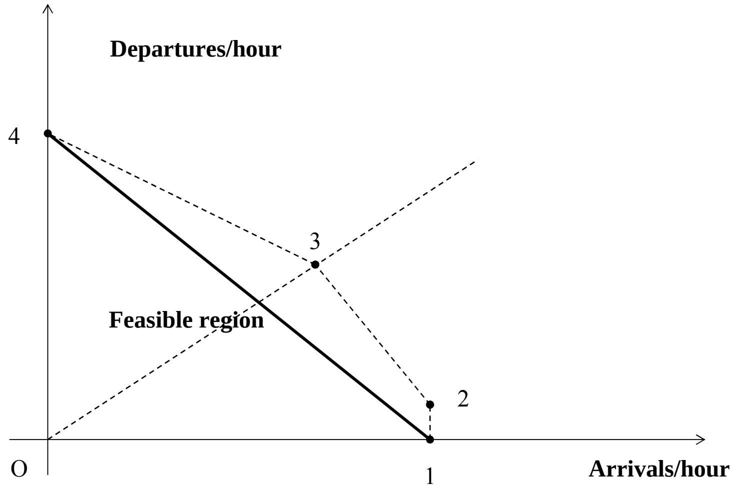
## Sensitivity of the model

- The model (and the runway's arrival capacity) is sensitive to
  - Airborne separation requirements (regular and wake-turbulence related)
  - Runway occupancy times
  - Final approach speeds of aircraft
  - Length of final approach
  - Safety-related margins (buffers) allowed by air traffic controllers
  - Mix of traffic (homogeneity)
  - Sequencing of aircraft

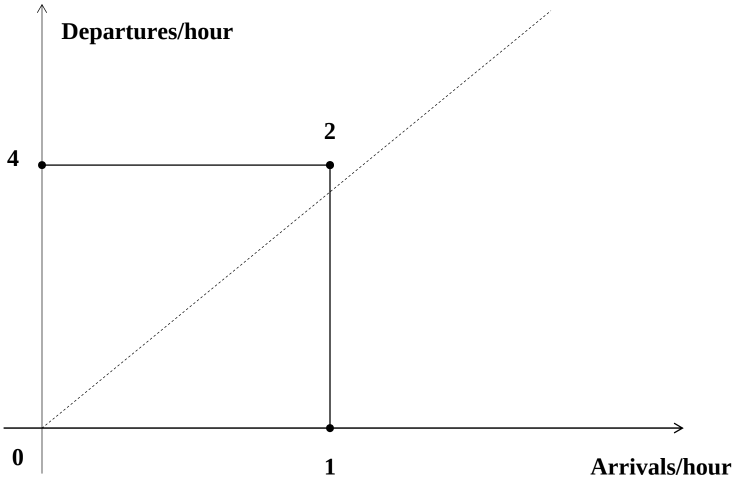
## Typical capacity envelope for a single runway

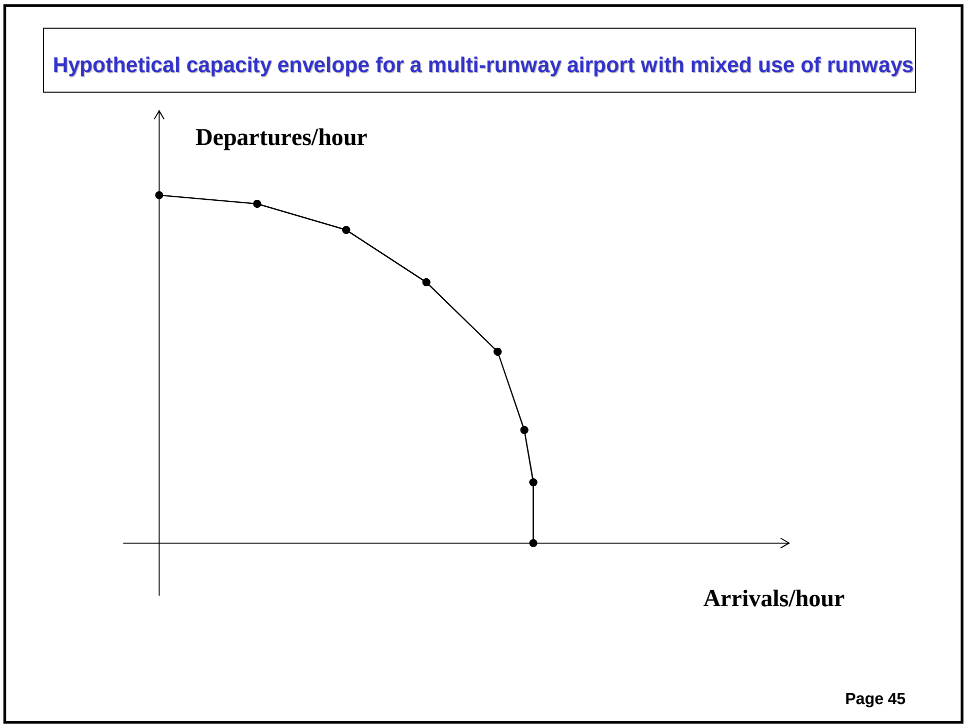


## Capacity envelope: strings of arrivals and departures

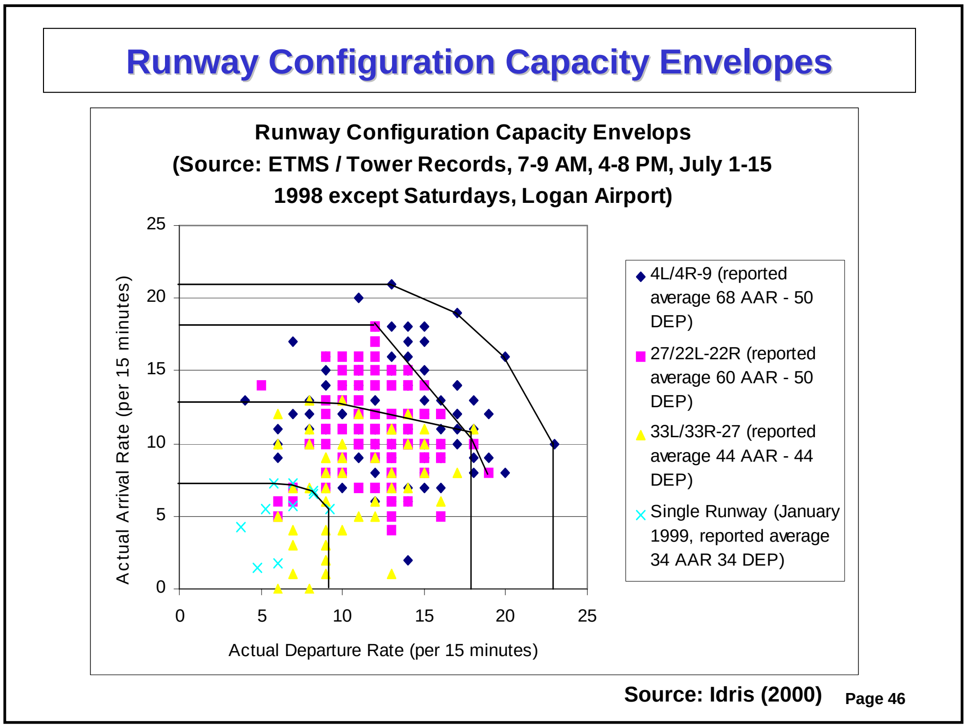


## Capacity envelope: two parallel runways, one for arrivals, the other for departures





## Hypothetical capacity envelope for a multi-runway airport with mixed use of runways



## Runway Configuration Capacity Envelopes

Runway Configuration Capacity Envelops
(Source: ETMS / Tower Records, 7-9 AM, 4-8 PM, July 1-15
1998 except Saturdays, Logan Airport)

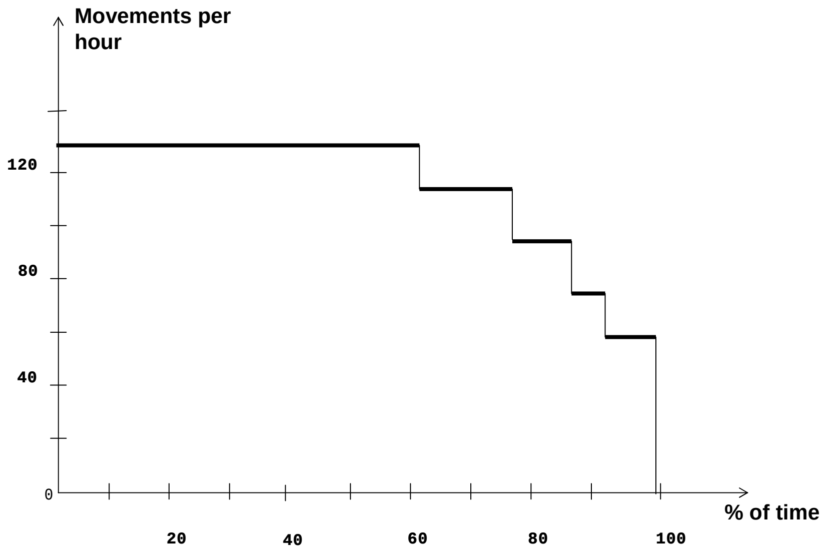
Source: Idris (2000)

# Capacity Coverage Chart

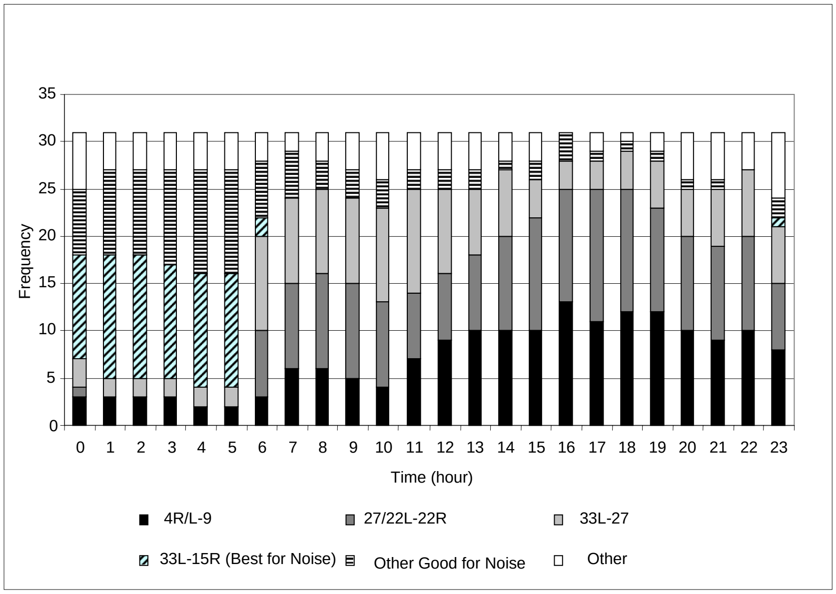
- CCC shows how much capacity is available for what percentage of time
- Assumptions:
  - airport will operate at all times with the highest capacity configuration available for prevailing weather/wind conditions
  - the capacity shown is for a 50%-50% mix of arrivals and departures

  *Note: Neither of these assumptions is necessarily true in practice (e.g., noise may be the principal consideration in selecting configuration during periods of low demand)*

# Annual Capacity Coverage Chart: Boston/Logan



## Configurations usage: Boston/Logan, Jan. 1999 (Logan FAA tower logs)



## Capacity Coverage Chart [2]

- The CCC summarizes statistically the supply of airside capacity
- CCC requires a capacity analysis for all weather/wind conditions and runway configurations
- “Flat” CCC implies predictability and more effective utilization of airside facilities
  - Operations (takeoffs and landings) can be scheduled with reference to a stable capacity level
  - Fewer instances of under-utilization and over-utilization of facilities

# Airfield Capacity: II

- ❑ Objective
  - – To summarize fundamental concepts re. airfield capacity
- ❑ Topics
  - – Capacities of other elements of the airfield
  - – Overall observations about capacities of airports

*Reference: Chapter 10*

# Range of Airfield Capacities

- ❑ The capacity of a single runway varies greatly among airports, depending on local ATC rules, traffic mix, operations mix, local conditions and the other factors identified earlier (12 – 60+ movements per hour is possible)
- ❑ At major commercial airports, in developed countries, the range is 25 – 60 movements per hour for each runway
- ❑ Depending on the number of runways and the airport's geometric configuration, total airfield capacity of major commercial airports ranges from 25 per hour to 200+ per hour

## Runway Capacity: US and Elsewhere

- US FAA capacity benchmarks (2004): 35 busiest airports
  - 26 of 35: VMC capacity > 100/hour; range: 56 – 279
  - 16 of 35: IMC capacity > 100/hour; range: 48 – 193
  - 12 of 35: Plan new runway by 2010; capacity benefits of 20 – 50%, with exceptions
  - Capacity benefits due to ATM: small (0–10%) except for some cases (e.g., SFO)
- Only three non-US airports have a declared capacity of more than 100/hour (!) – 4(?) more within next 5-10 years
- 16 major European airports (including practically all the busiest ones) received more requests for slots than they could handle for summer of 2007
- Slot coordination system “hides” problem outside the US

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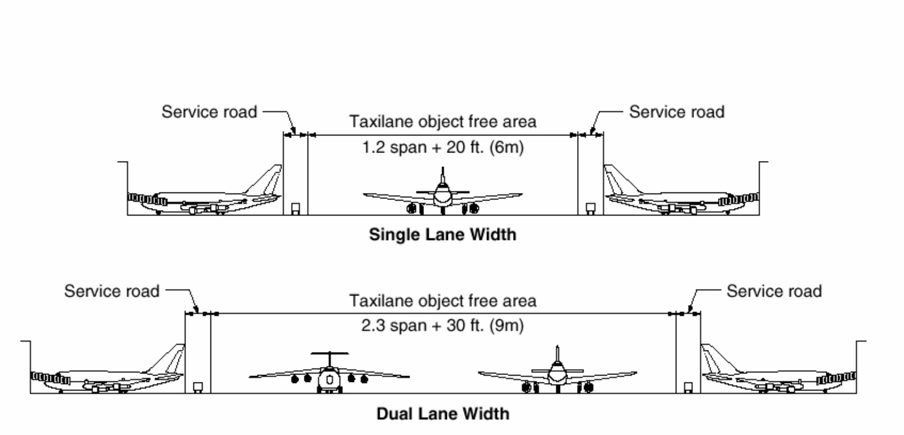
## Capacity of Taxiways

- The capacity of the taxiway system is rarely, if ever, the capacity bottleneck of major airports
- However, some specific parts of the taxiway system may consistently act as “hot spots” (points of congestion), especially at older, limited-area airports
- Local geometry and traffic flows determine the location of these hot spots
- The blocking of groups of stands by a single lane passage is one of the most common examples of such taxiway hot spots

# Single lane vs. dual lane access to stands



# Capacity of Aprons

- Often a tough problem!
- Different stands can accommodate different sizes of aircraft
- Remote vs. contact stands
- Shared use vs. exclusive use (airlines, handlers)
- Dependence among neighboring stands
- Static capacity: No. of aircraft that can be parked simultaneously at the stands. (Easy!)
- Dynamic capacity: No. of aircraft that can be accommodated per hour. (Can be difficult to compute.)

# Stand Blocking Time (SBT)

- Scheduled occupancy time (SOT) [20 minutes to 4 hours, except for overnight stays]
- Positioning time (PT) [3 – 10 mins]
- Buffer time (BT) [up to 1+ hour at some locations]

$$SBT = SOT + PT + BT$$

# A Simple Case

- Assume *n* stands; all can accommodate all aircraft sizes
- Subdivide aircraft into *K* relatively homogeneous classes w.r.t. *SBT*

$$E[SBT] = \sum_{i=1}^{K} p_i \cdot SBT_i$$

- Dynamic capacity = $n / E[SBT]$