

Capacity Management, Congestion and Demand Management

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M.Sc. Program

Airport Planning and Management

Module 12

March 2015

Objective and Topics

- **Objective:**
  – To summarize fundamental concepts regarding (a) the management of airport capacity and demand and (b) the relationship between capacity, demand and delays
- **Topics:**
  – Demand variability at major airports
  – Capacity of airfield (runways, taxiways, aprons)
  – Capacity of landside elements
  – Measures of delay; the relationships that generate delay
  – Current approach to demand management
  – Market-based approaches to demand management

Outline

- Variability of Demand
- Airside Capacity and Its Variability
  - Runway Systems
  - Taxiways and Aprons
  - Passenger Terminals
- Delays
  - Proper Measurement
  - Non-linearity
  - Landside vs. Airside
- Demand Management: Schedule Coordination
- Demand Management: Market-Based Schemes

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Airport Capacity Management: General Framework

- Capacity management refers to the steps that an airport must take in order to offer sufficient capacity to match demand and provide an adequate Level of Service (LOS)

- Demand management refers to interventions aimed at modifying demand; such interventions may be necessary if available capacity is not sufficient to ensure adequate LOS

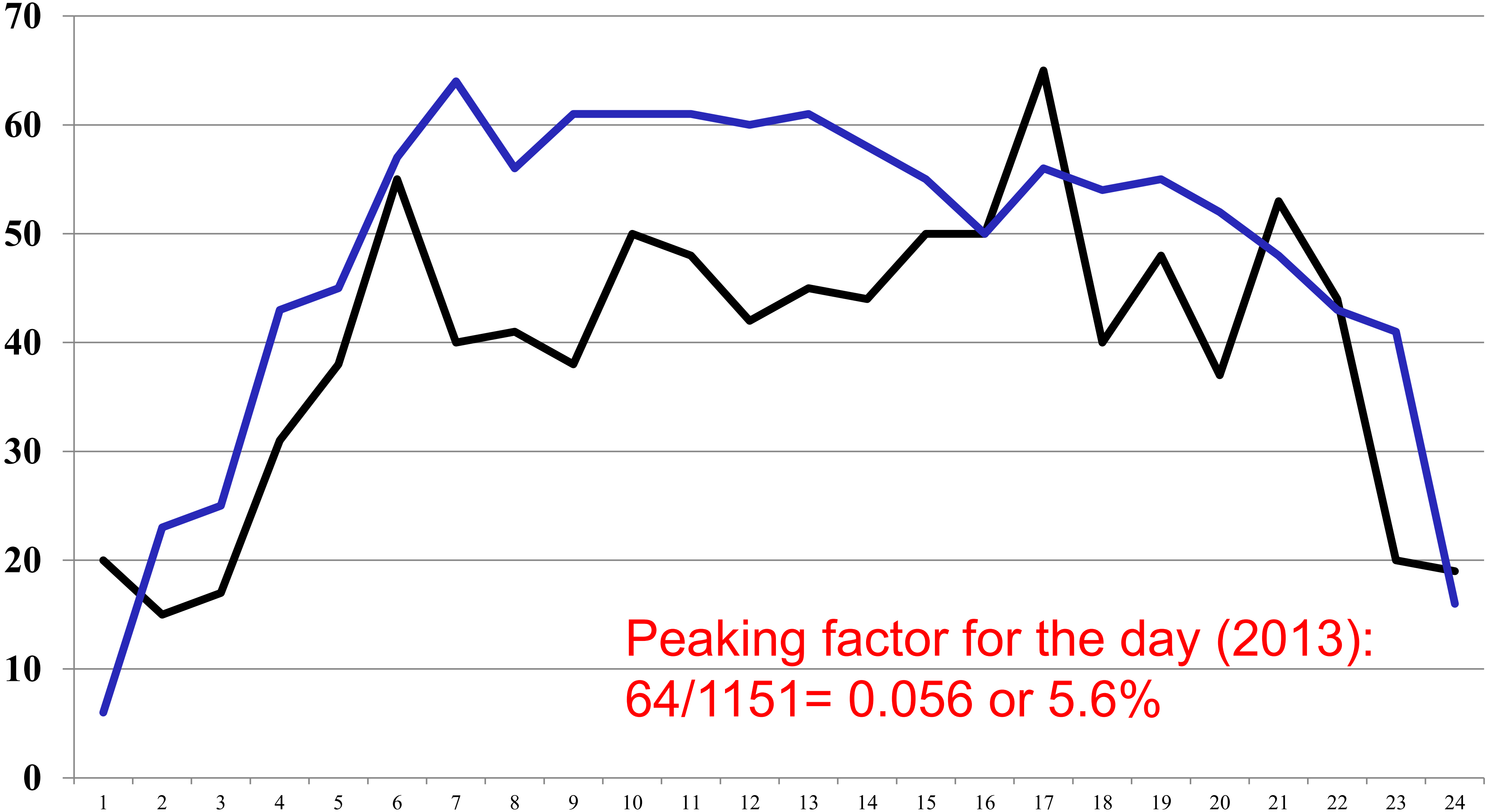
- To provide and manage capacity, it is necessary to understand well the characteristics of both demand and capacity on both airside and landside

- The issues and the measures of LOS on airside and on landside are quite different; will be considered separately

Variability of Airport Demand: Time-of-Day

- All airports experience time-of-day variability in demand, because of a number of reasons
  - Curfews (typically due to noise restrictions)
  - Preference of travelers for certain times of the day (especially true for business travel)
  - “Natural” times for flying on certain long-haul routes (e.g., most flights from Eastern United States to Europe depart between 4 PM and 11 PM)
- A few extremely congested airports (LHR, FRA, LGA) have “flat” demand profiles during the times they are operating, because of capacity constraints
- At all airports, the composition of demand (arrivals vs. departures, domestic vs. international, short-haul vs. long-haul, business vs. leisure) also varies by time-of-day

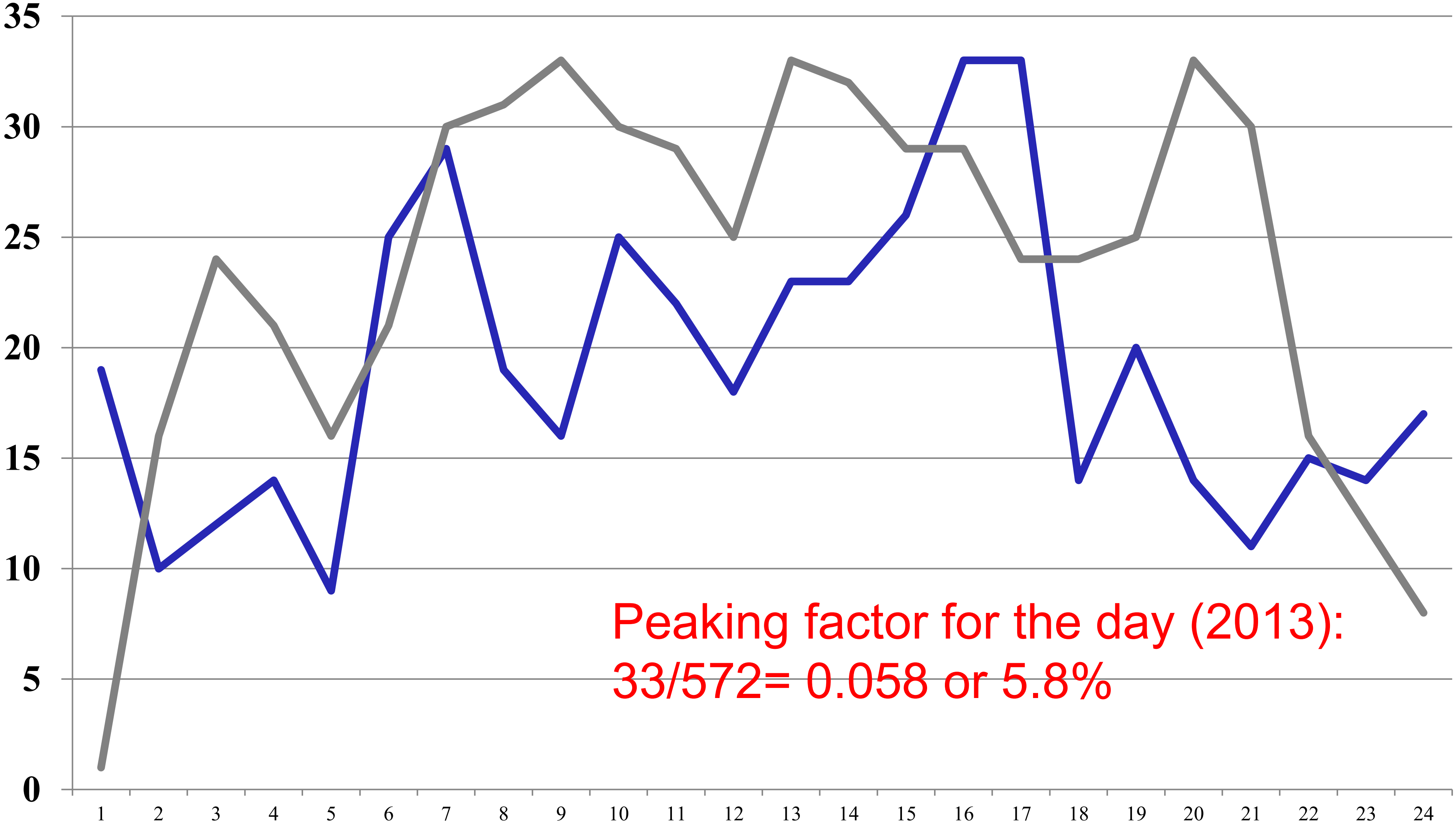
IST Total Demand: 2013 vs. 2011



Total: 2011: 950 movts; 2013: 1151 movts (+21%) [LHR=1350]

Peak hour: 2011: 65 movts; 2013: 64 movts (-1%)

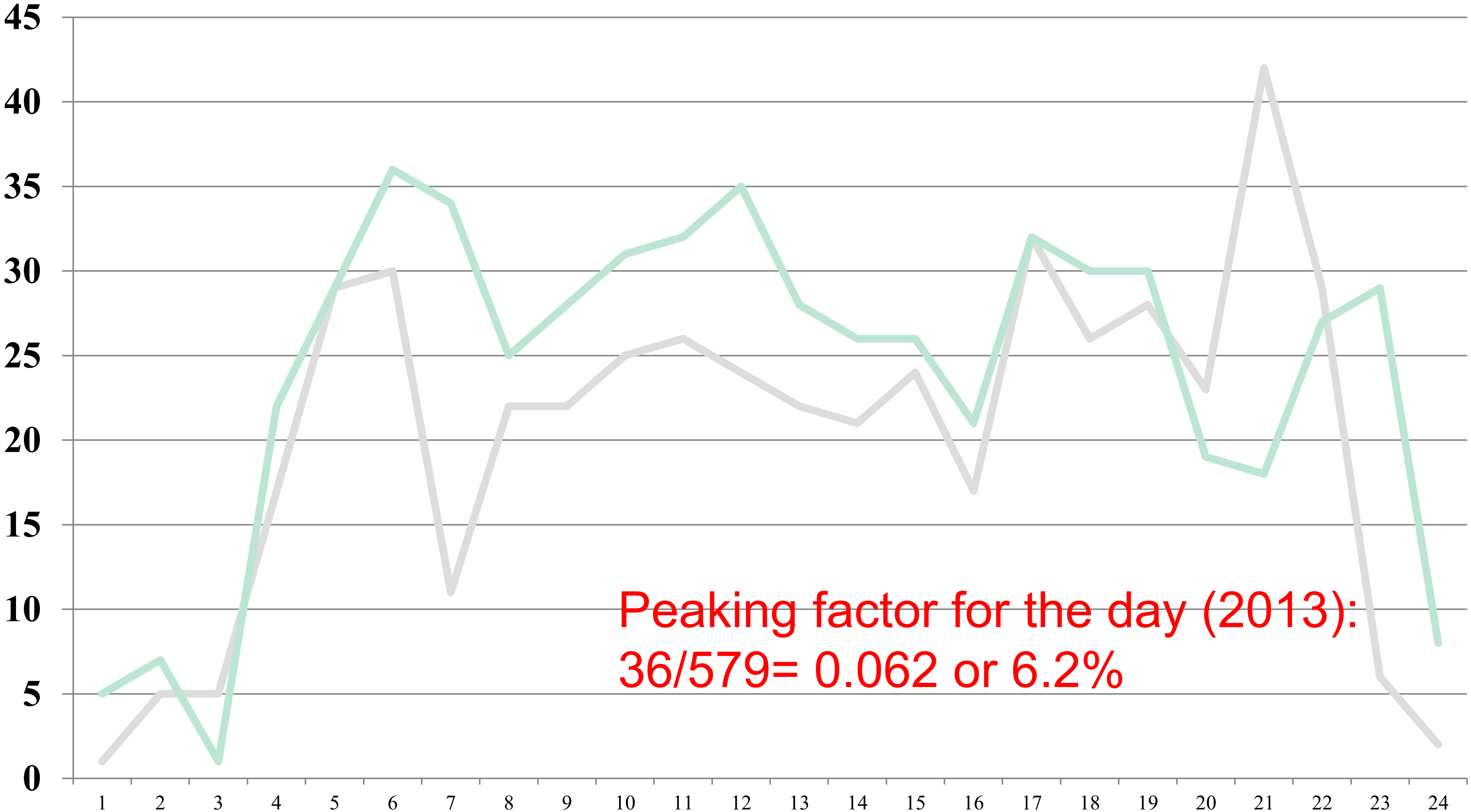
IST Arrivals Demand: 2013 vs. 2011



Totals: 2011: 461 arrs; 2013: 572 arrs (+24%)

Peak hour: 2011: 33 arrs; 2013: 33 arrs (0%)

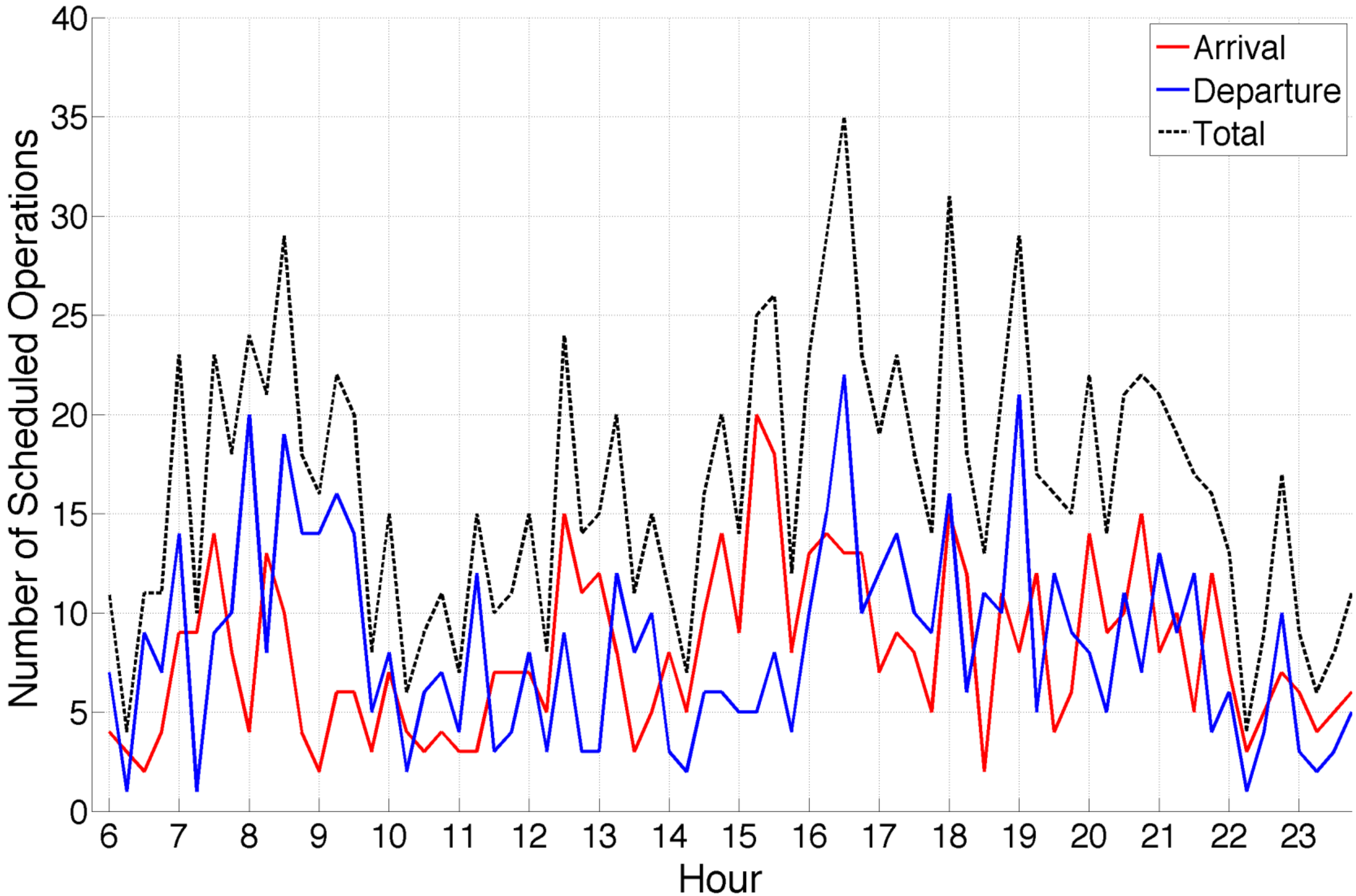
IST Departures Demand: 2013 vs. 2011



Totals: 2011: 489 deps; 2013: 579 deps (+18%)

Peak hour: 2011: 42 deps; 2013: 36 deps (-14%)

NY JFK: Scheduled Movements per 15 Minutes



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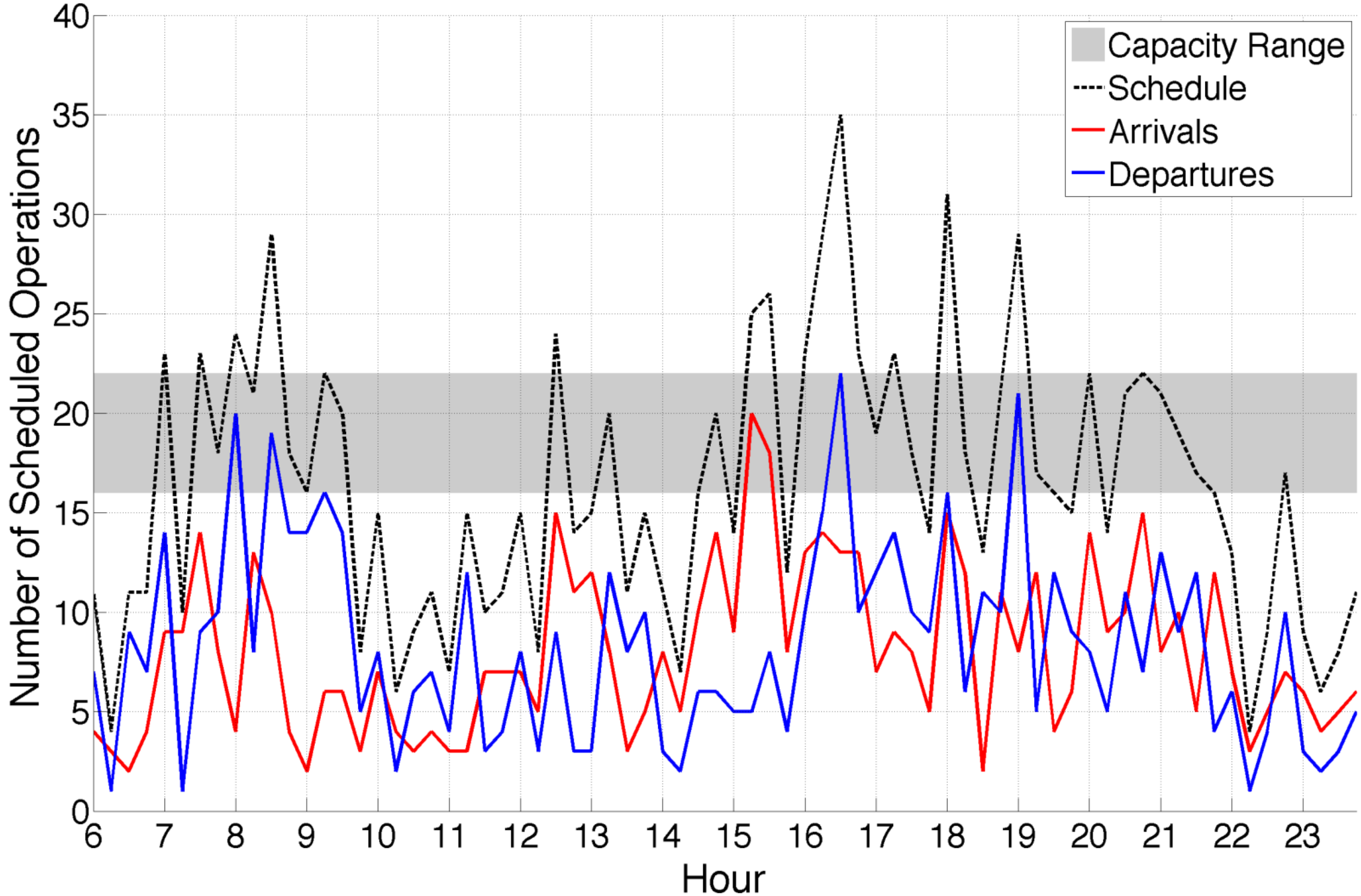
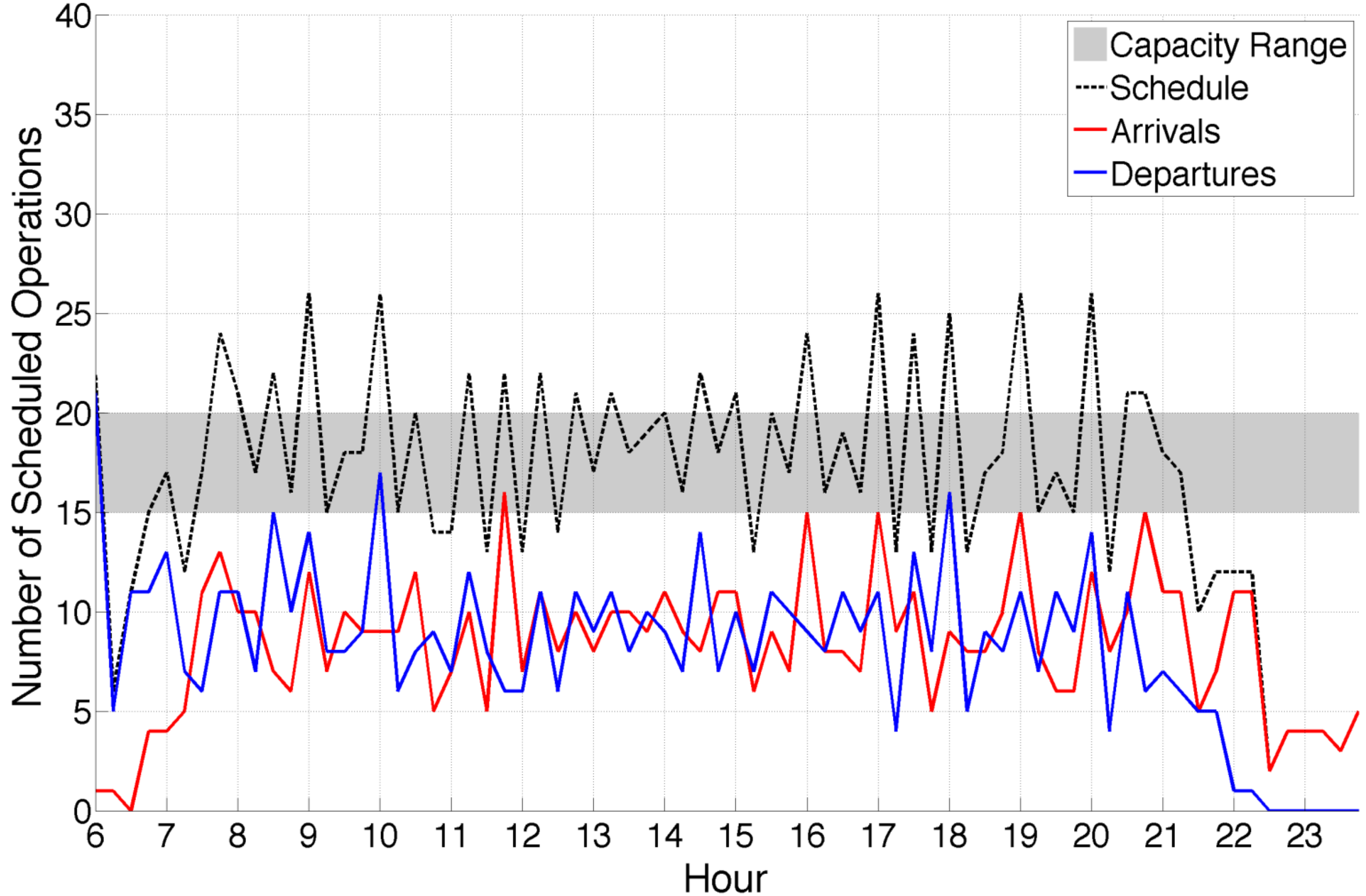


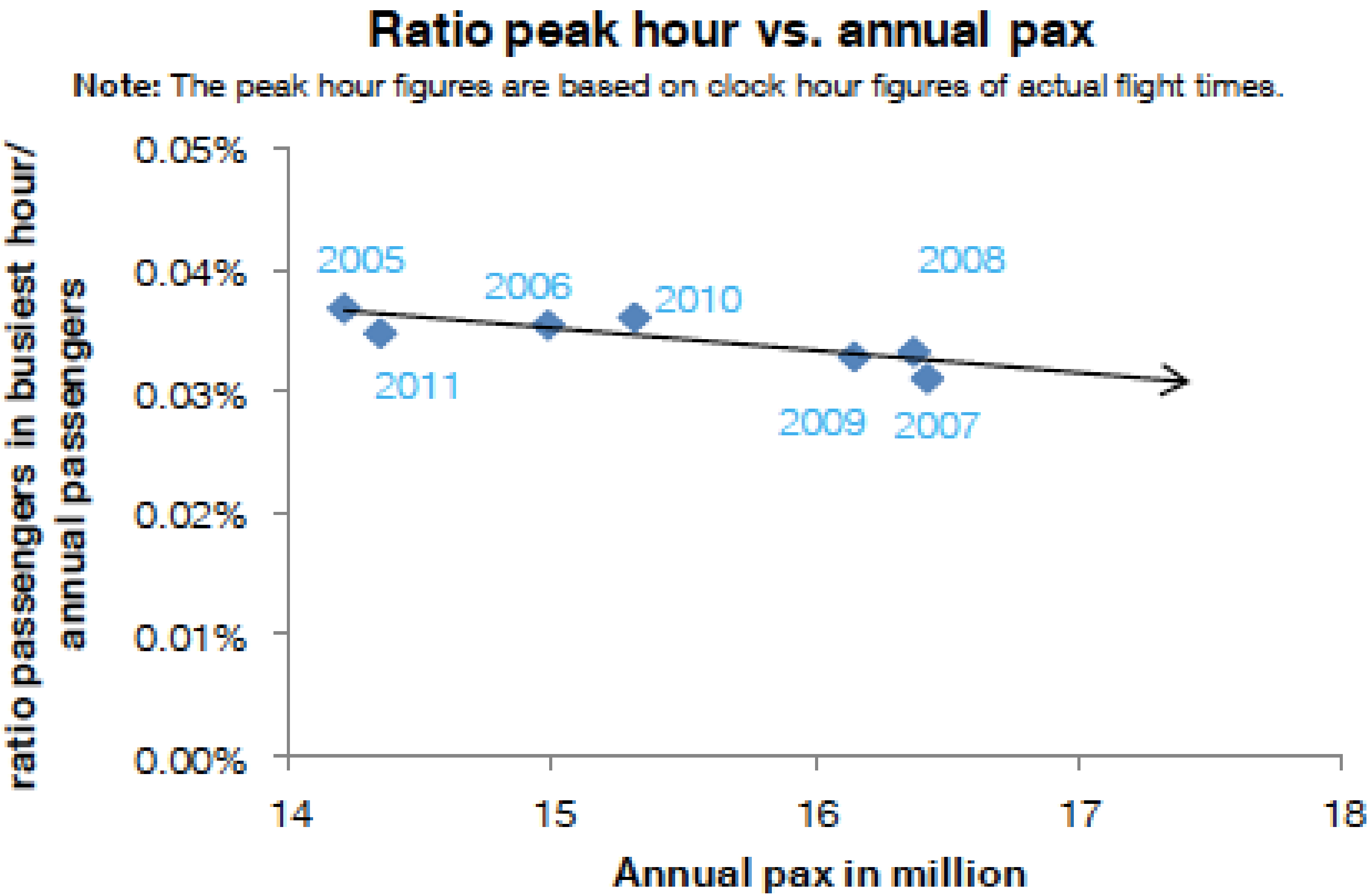
NY LaGuardia (LGA): Scheduled Movements per 15 Minutes



Variability of Airport Demand

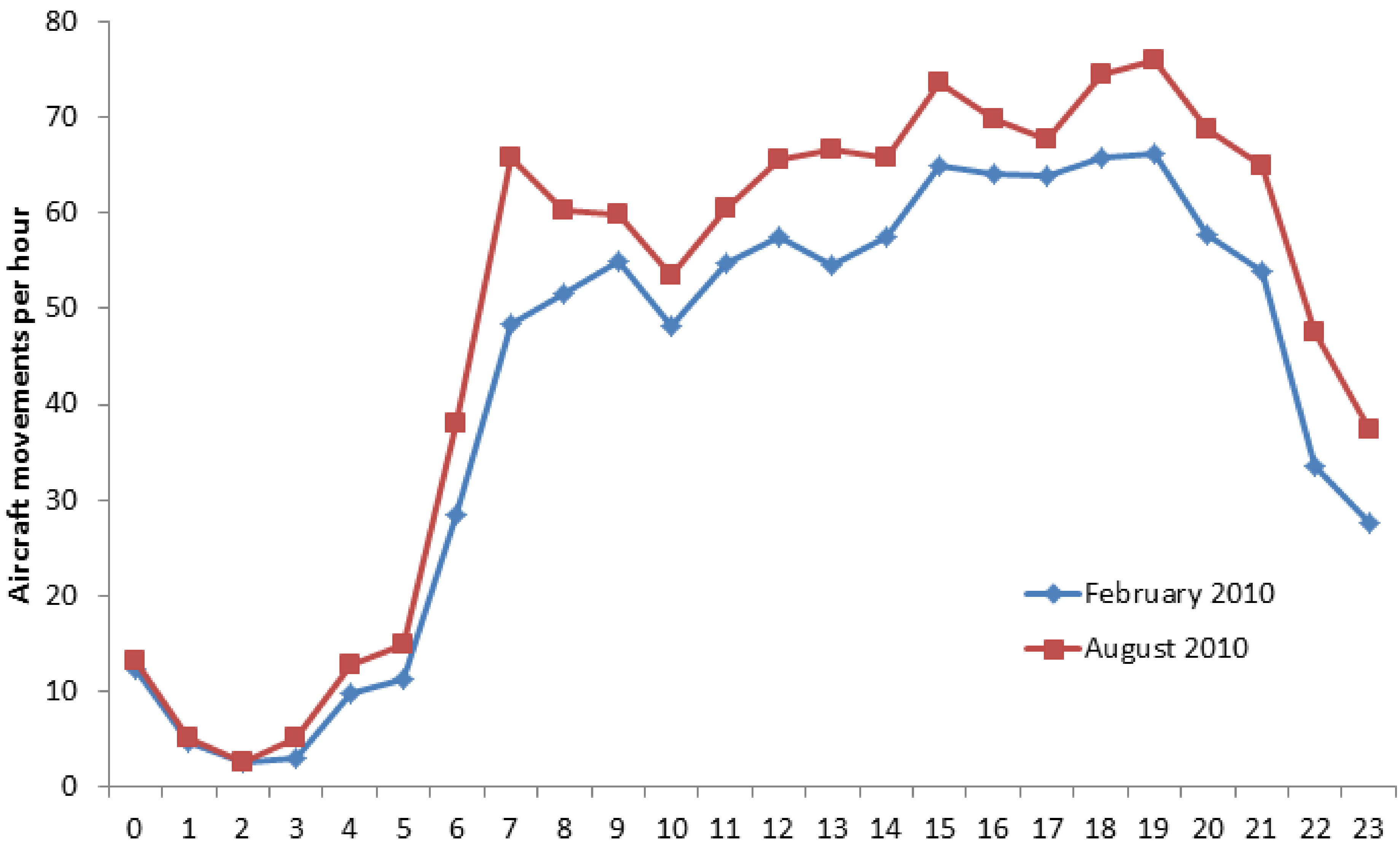
- Significant variability in demand may also exist with respect to:
  - Day of the week (e.g., in the US Saturday is the lowest day, Sunday is second lowest, while weekdays are similar to one another and have the highest demand)
  - Month and season (e.g., summer vs. winter, high and low months, influence of religious or other holidays)
  - Special events (e.g., sports, expos, etc.)
- ***Peaking patterns and demand variability can be very consistent at airports over many years***

Athens: Pax in Peak Hours of the Year as % of Annual Pax

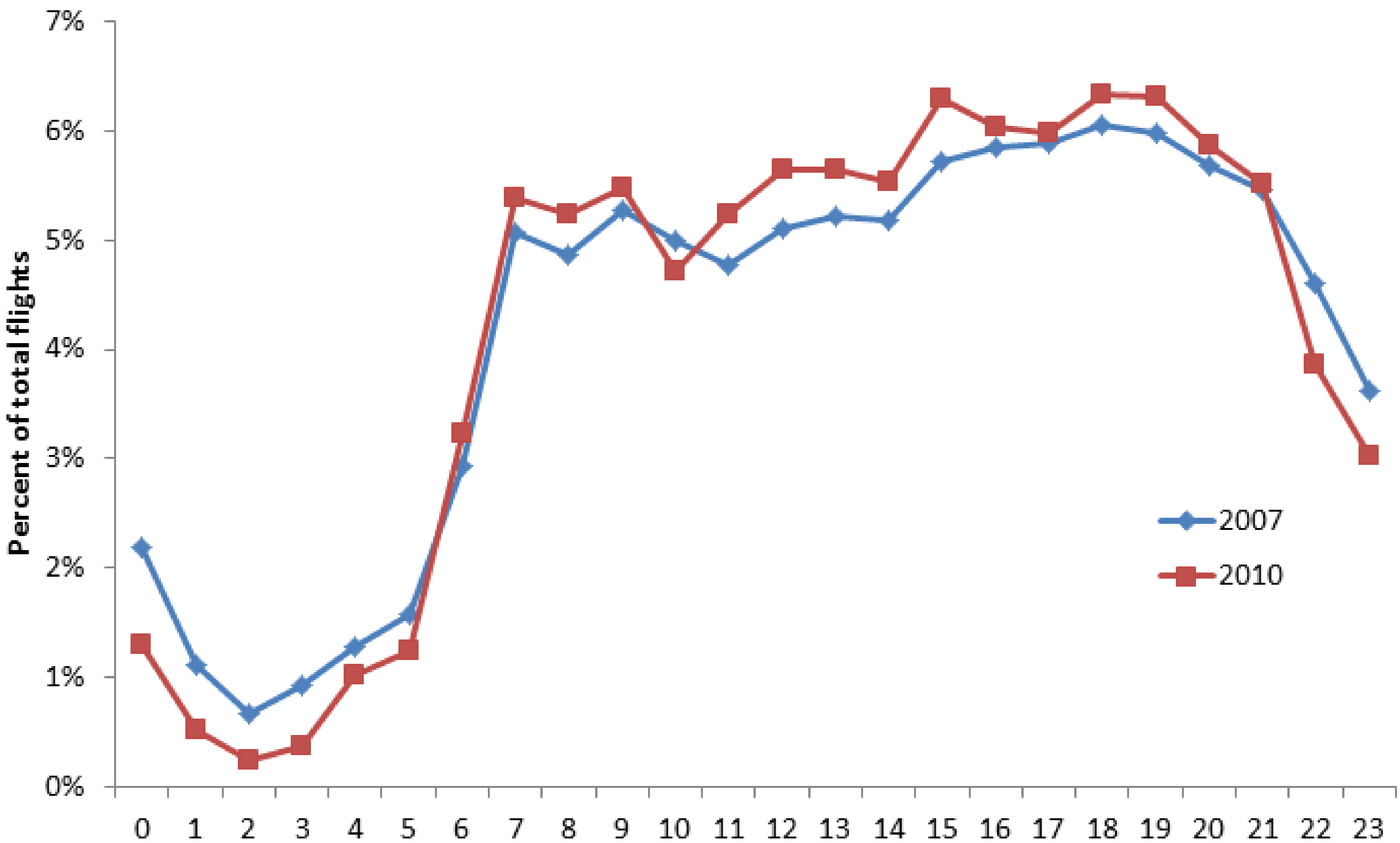


Source: AIA (2012)

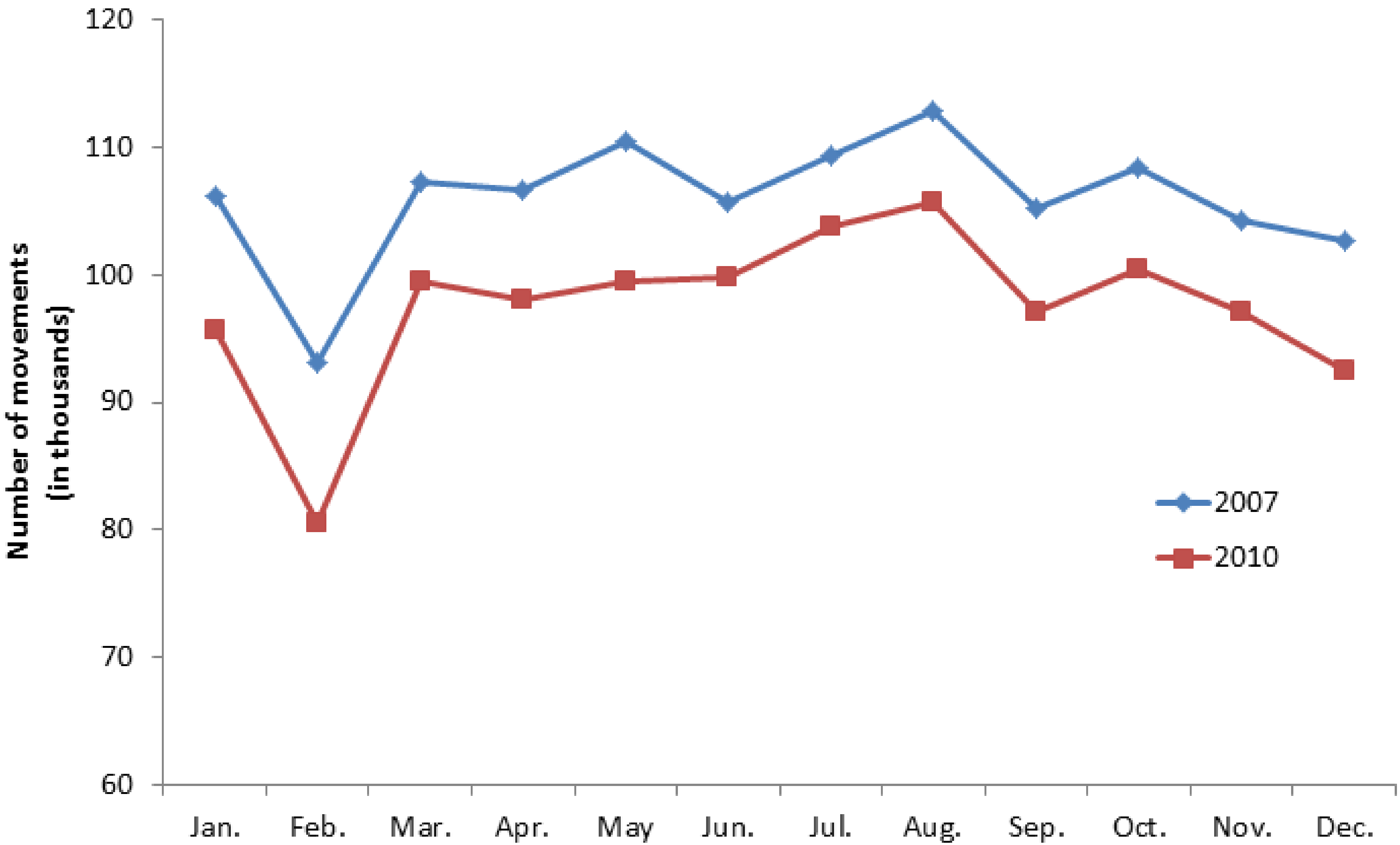
Daily Demand Profile: Newark Aircraft Movements



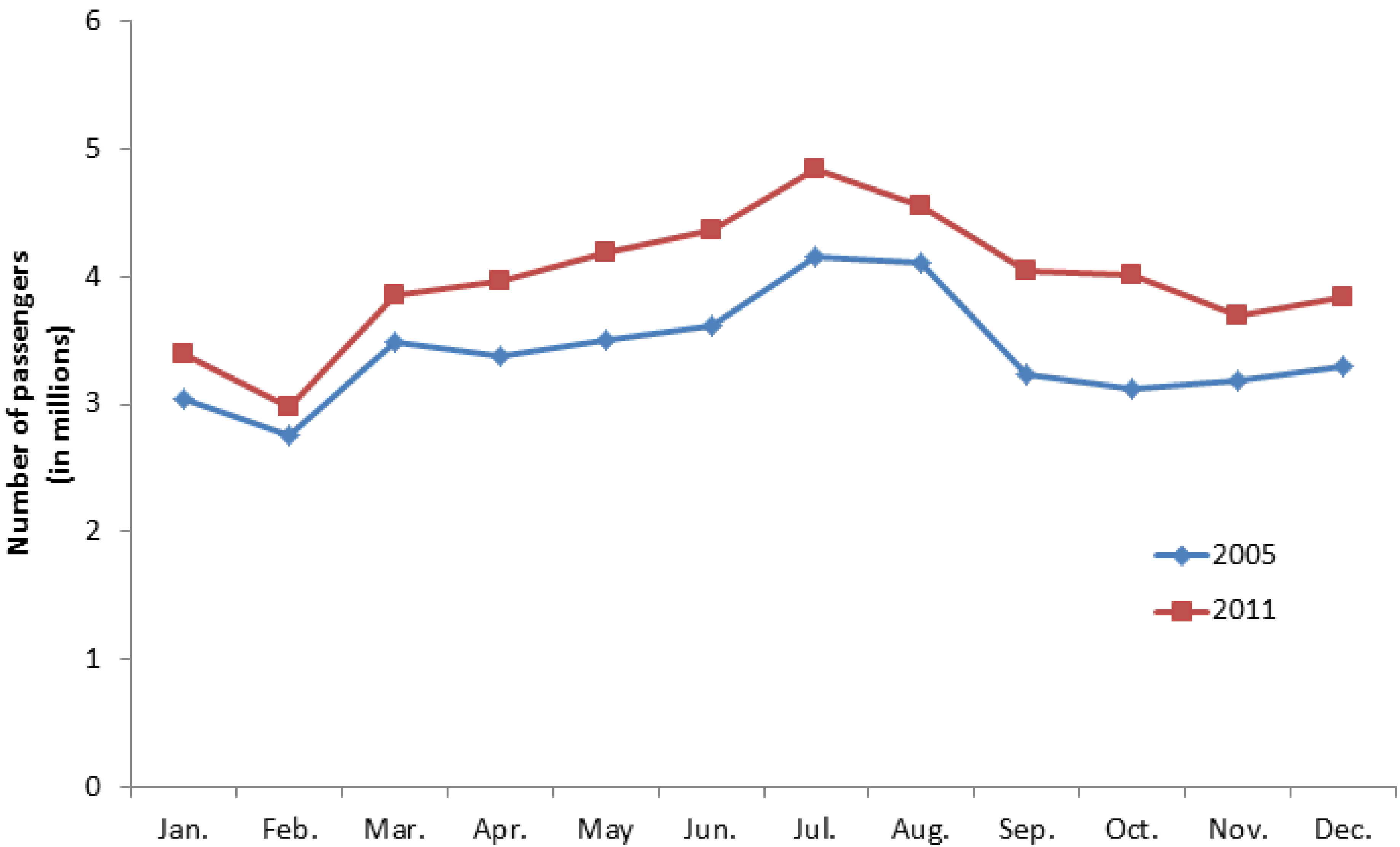
Daily Demand Profile: Newark Aircraft Movements (% of Daily Movements)



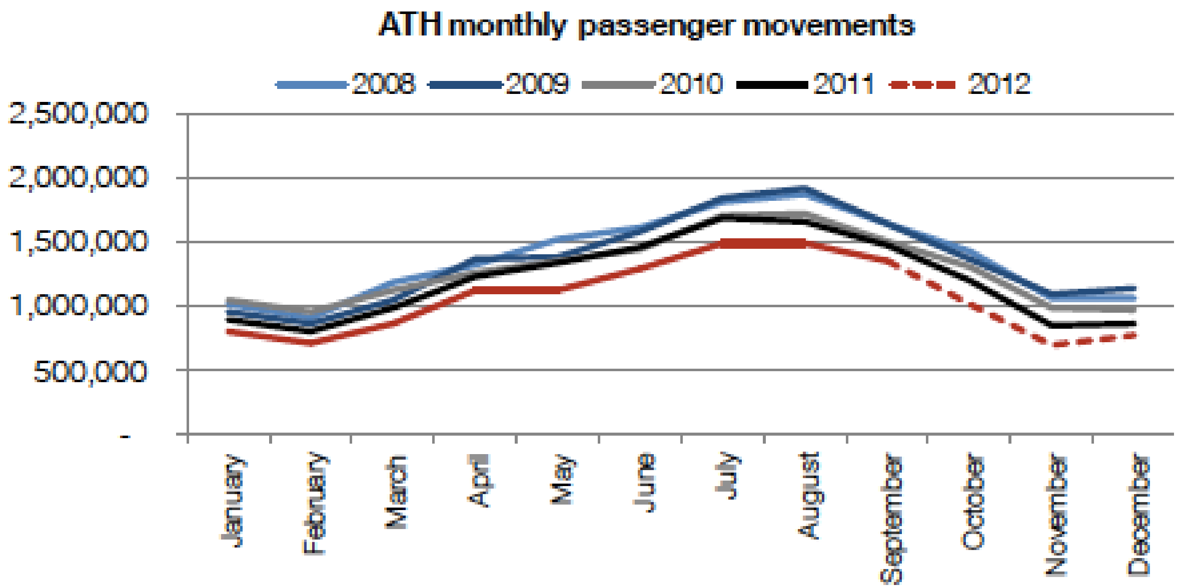
Stability of Monthly Patterns: Total Movements at the 3 New York Airports



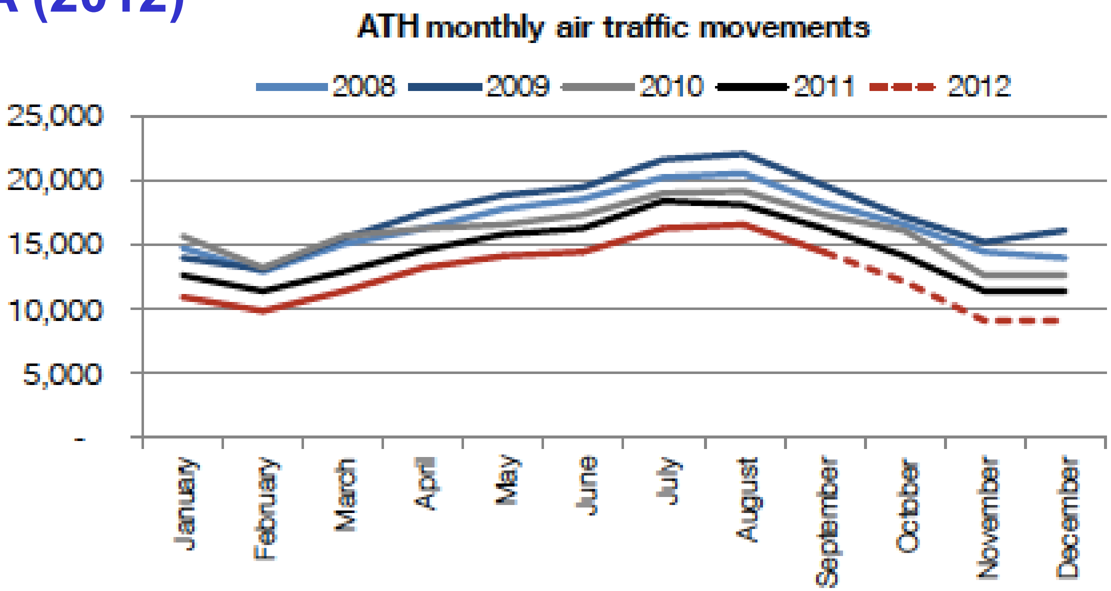
Stability of Monthly Patterns: No. of Passengers at NY JFK



Monthly Pax and Movements: Athens, 2008-2012



Source: AIA (2012)



Detailed Records

- Very important: Airport operators should
  - Collect and maintain detailed historical records of operations
  - Perform statistical analyses with the data
  - Perform data mining to identify significant patterns and trends
- Large databases developed by air navigation service providers (ANSP) and airlines are becoming increasingly common
  - often available to airport operators and sometimes to researchers or the general public

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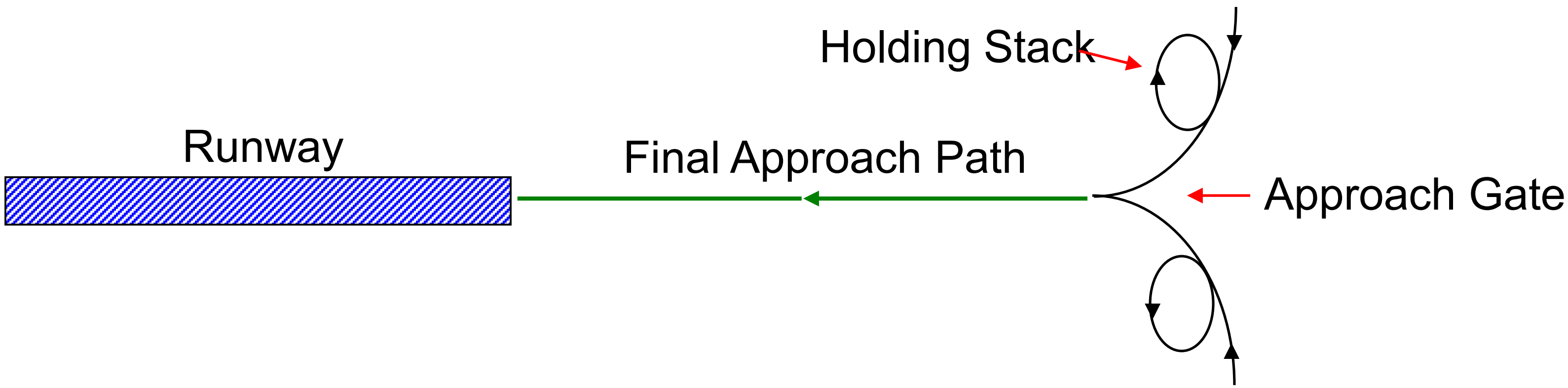
Capacity: An Important Initial Point

- Airside capacities can be computed with reasonable accuracy because of the presence of well-defined “rules of the road” (separation requirements, single occupancies, etc.)

- Landside capacities are much less well-defined because they depend on what Level of Service (LOS) one is willing to accept, behavioral characteristics, physical layout of facilities, etc.

- Implications about validity of comparisons across airports

The Principal Bottleneck



- The runway systems of the world's busiest airports act usually as the principal bottlenecks of the air transport system's infrastructure
- While other components of infrastructure may also occasionally act as bottlenecks, the capacity of runway systems is the **most "resistant to expansion"**

Variability of Airport Capacity: Airside

- Airside capacity (≈ runway capacity) depends on runway configuration in use, which, in turn, depends on weather conditions and wind
  - At many airports, where weather is variable airside capacity can also be highly variable and difficult to predict even a few hours in advance

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 air traffic management (ATM) rules, assuming continuous aircraft demand.

- *Declared Capacity* [tied to *Level of Service* (LOS)]

  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 stand/gate capacity, passenger terminal capacity, etc.

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

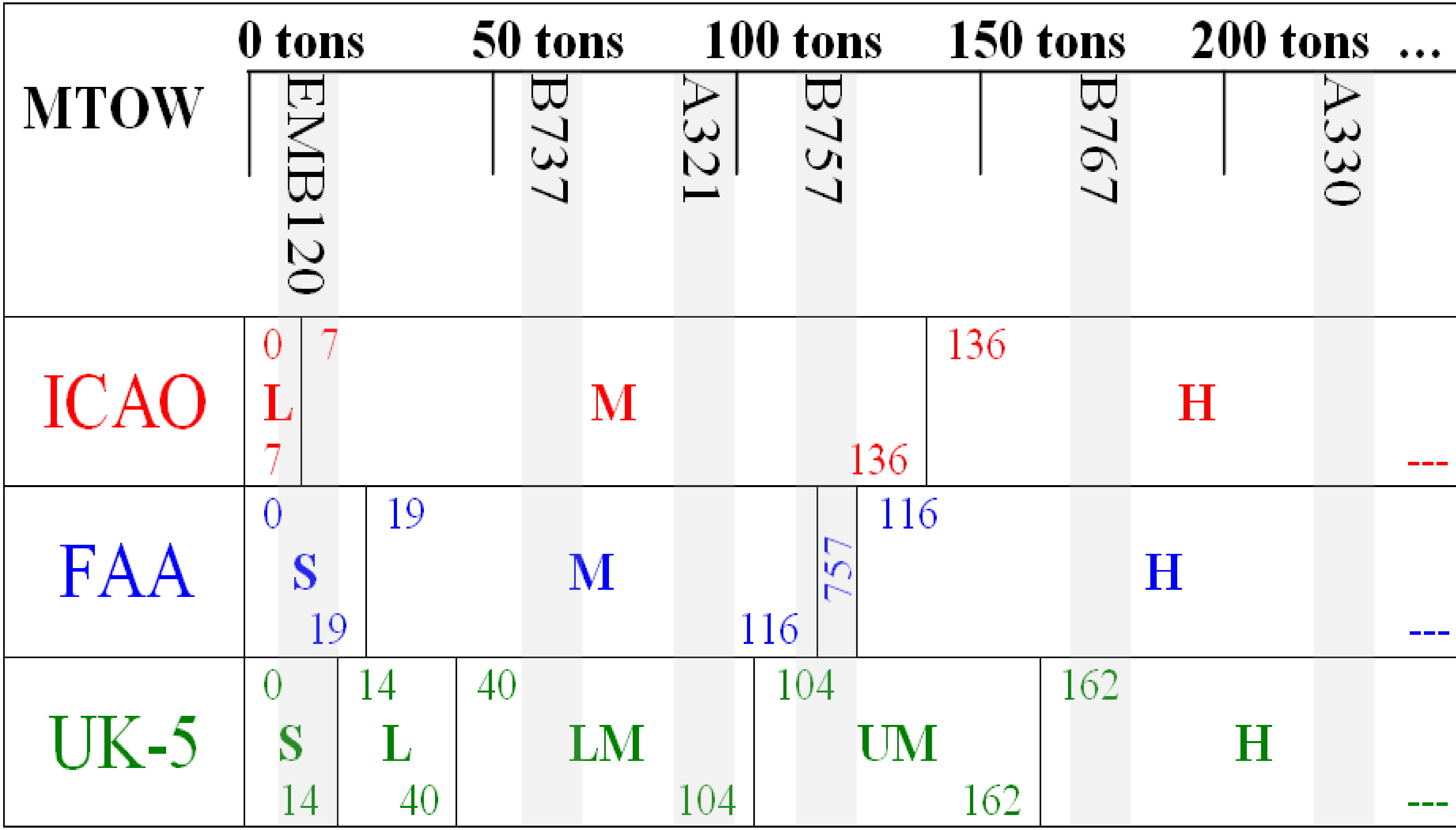
Factors Affecting Runway Capacity

- 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

Role of ATM Separation Requirements

- Runway (and airfield) capacities are constrained by ATM separation requirements
- Typically aircraft are separated into a small number (4 or 5) of classes according to their maximum takeoff weight (MTOW)
- Example: ICAO classification
  - Super Heavy (SH): Airbus 380 [560 tons], Boeing 747-8
  - Heavy (H): 136 tons ≤ MTOW [and <SH]
  - Medium (M): 7 tons ≤ MTOW < 136 tons
  - Light (L): MTOW < 7 tons
- 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 M requires 5 nautical miles of separation on final approach”

Aircraft Classes for Terminal Area ATM Purposes



"Super Heavy": A380 (560 tons), B747-8 (448 tons)

ICAO Recommended Separations*: Arrival - Arrival

	TRAILING A/C			
LEADING A/C	Super Heavy	Heavy	Medium	Light
Super Heavy	4	6	7	8
Heavy	4	4	5	6
Medium	3	3	3	5
Light	3	3	3	3

* Separations shown in n. miles (1 n.mile =1.852 km)

- **In addition, the leading aircraft in each pair must be safely out of the runway before the trailing aircraft can touch down on the runway**

ICAO Recommended Separations*: Departure - Departure

	TRAILING A/C			
LEADING A/C	Super Heavy	Heavy	Medium	Light
Super Heavy	150	150	180	180
Heavy	90	90	120	120
Medium	90	90	90	90
Light	90	90	90	90

*** Approximate separations in seconds (vary according to national practices)**

Numerical Example: Inputs

Aircraft Characteristics			
Type	Mix (%)	Approach Speed (knots)	Runway Occupancy Times (sec)
Heavy (1)	20	140	60
Medium (2)	50	120	55
Light (3)	30	100	50

Single Runway; Arrivals only

Length of Final Approach = 5 n. miles

Separation Requirements

	Trailing Aircraft			
Leading Aircraft		1	2	3
	1	4 n.m.	5 n.m.	6 n.m.
	2	3 n. m.	3 n.m.	4 n.m.
	3	3 n.m.	3 n.m.	3 n.m.

Numerical Example [2]

Aircraft of type *i* is followed by aircraft of type *j*

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

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

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

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

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:

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

Numerically:

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

↑ **E(t) = 124 seconds**

- Max throughput/saturation capacity (typically stated as no. of aircraft per hour):

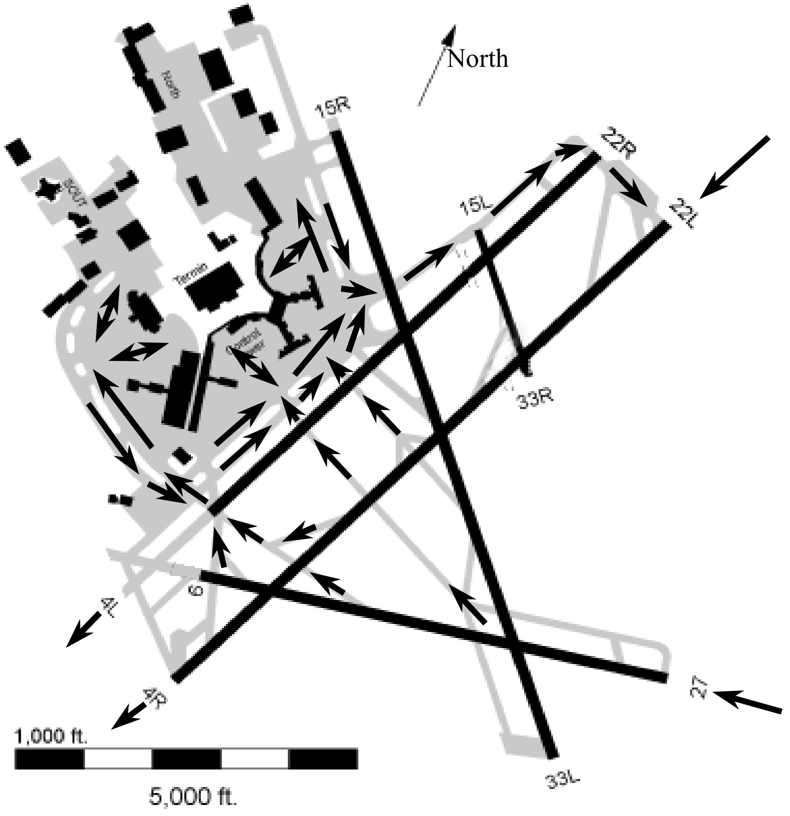
$$\textbf{Saturation Capacity} = \frac{3600\,\text{seconds}}{124\,\text{seconds}} = \textbf{29 aircraft}$$

The Concept of the “Runway Configuration”

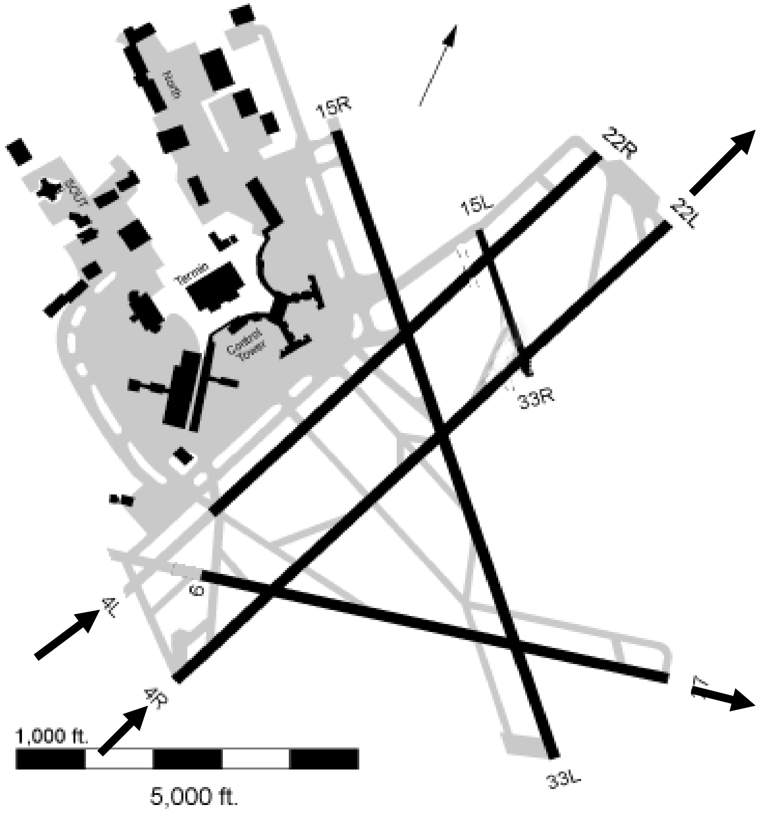
- Multi-runway airports can operate in any one of many possible “configurations”.
- Each configuration is described by:
  - The set of runways which are active
  - The type of operations (arrivals only, departures only, or mixed) assigned to each of the active runways
- Example: A common configuration at IST consists of “05 for arrivals, 35L for departures” (denoted as “05|35L”)
- Weather and wind direction and strength play a major role in the selection of a configuration – occasionally allowing a single choice only
- But air traffic managers often have the option of selecting among many alternative configurations (e.g., in calm winds)

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

27-22L | 22R-22L



4R-4L | 4R-4L-9



Parallel Runways (IFR)

Separation between runway centerlines	Arrival/ arrival	Departure/ departure	Arrival/ departure	Departure/ arrival
Closely-spaced 700/1200 – 2500 ft (213/366 – 762 m)	As in single runway	As in single runway	Arrival touches down	Departure is clear of runway
Medium-spaced 2500 – 5000* ft (762 – 1525* m)	1.5 nmi (diagonal)	Indep' nt	Indep' nt	Indep' nt
Independent > 5000* ft (> 1525* m)	Indep' nt	Indep' nt	Indep' nt	Indep' nt

* 3400 ft (1035 m) or 4300 ft (1310 m) are alternative limits; 3000 ft (915 m) stated as feasible by ICAO and FAA, subject to conditions

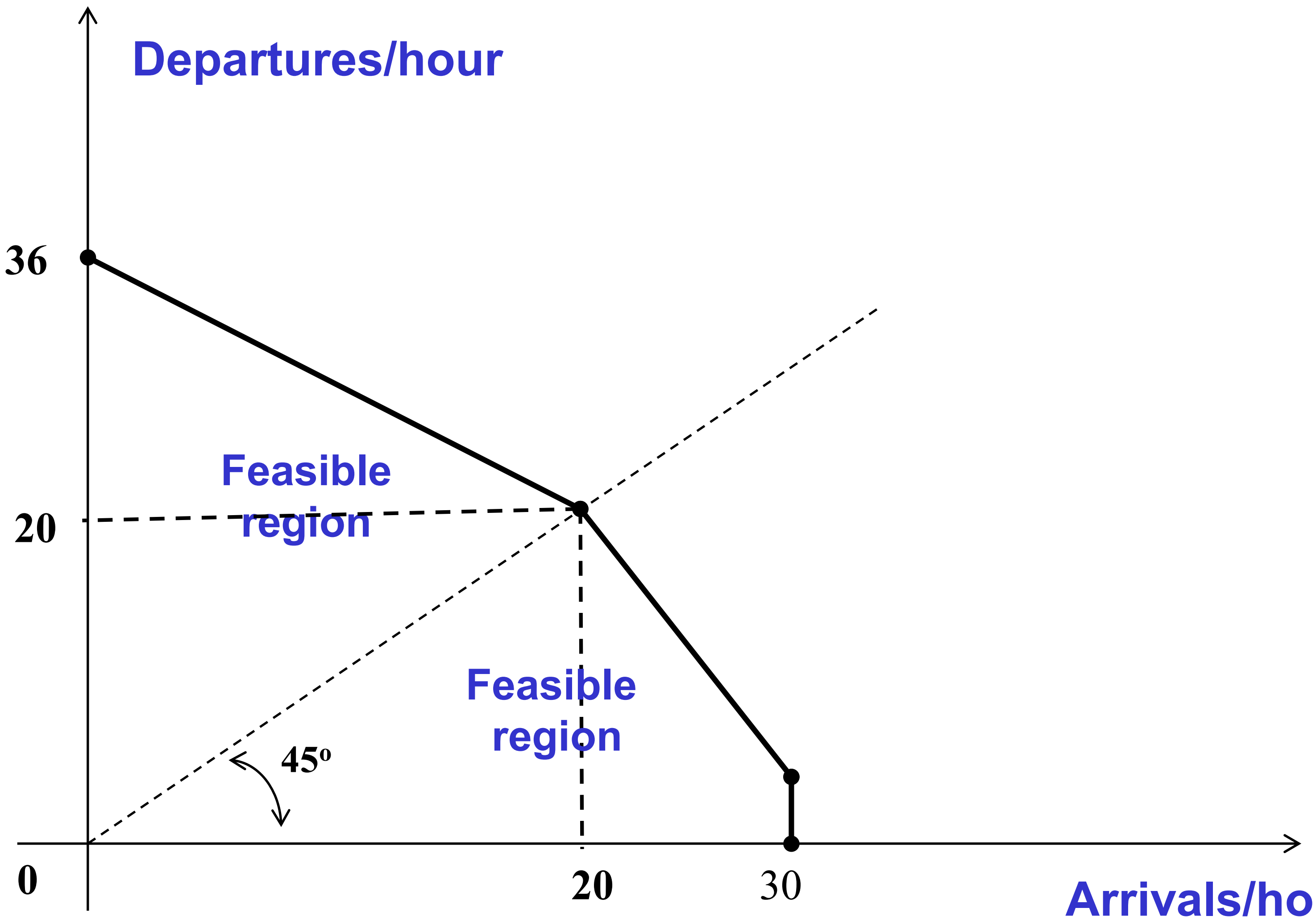
LBPIA: Single-Runway and Dedicated Two-Runway Capacities

Type of Operation	Example Runway Configuration	IMC	VMC
Single Runway, Mixed Operations	Arr 05, Dep 05	48	56
Dedicated Dependent East/West Operations	Arr 06R, Dep 06L	60	70
Dedicated Independent North/South Parallel Operations	Arr 15R, Dep 15L	63	65
	Arr 33L, Dep 33R	68	75
Dedicated Independent East/West Parallel Operations	Arr 05, Dep 06L	80	82
	Arr 23, Dep 24L	80	82

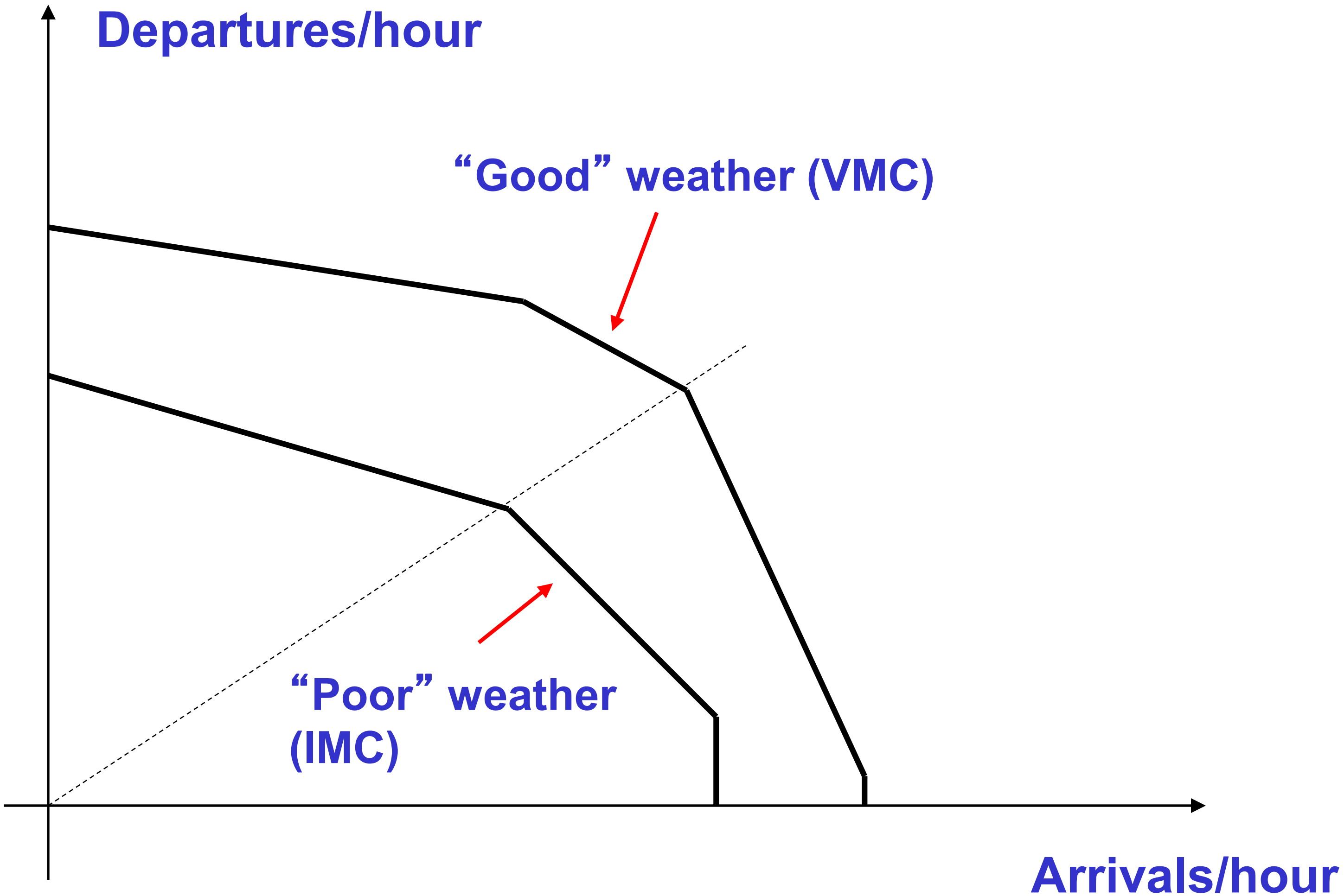
Summarizing Runway System Capacity

- Capacity envelopes: For any given runway configuration, the capacity envelope shows the number of arrivals and departures that can be performed per “unit of time” (one hour or 15 minutes or other) for all possible “mixes” of arrivals and departures
- Capacity coverage charts: For a specified long period of time (one year, one month) capacity coverage charts show how much total capacity is available at the airport for what percentage of time

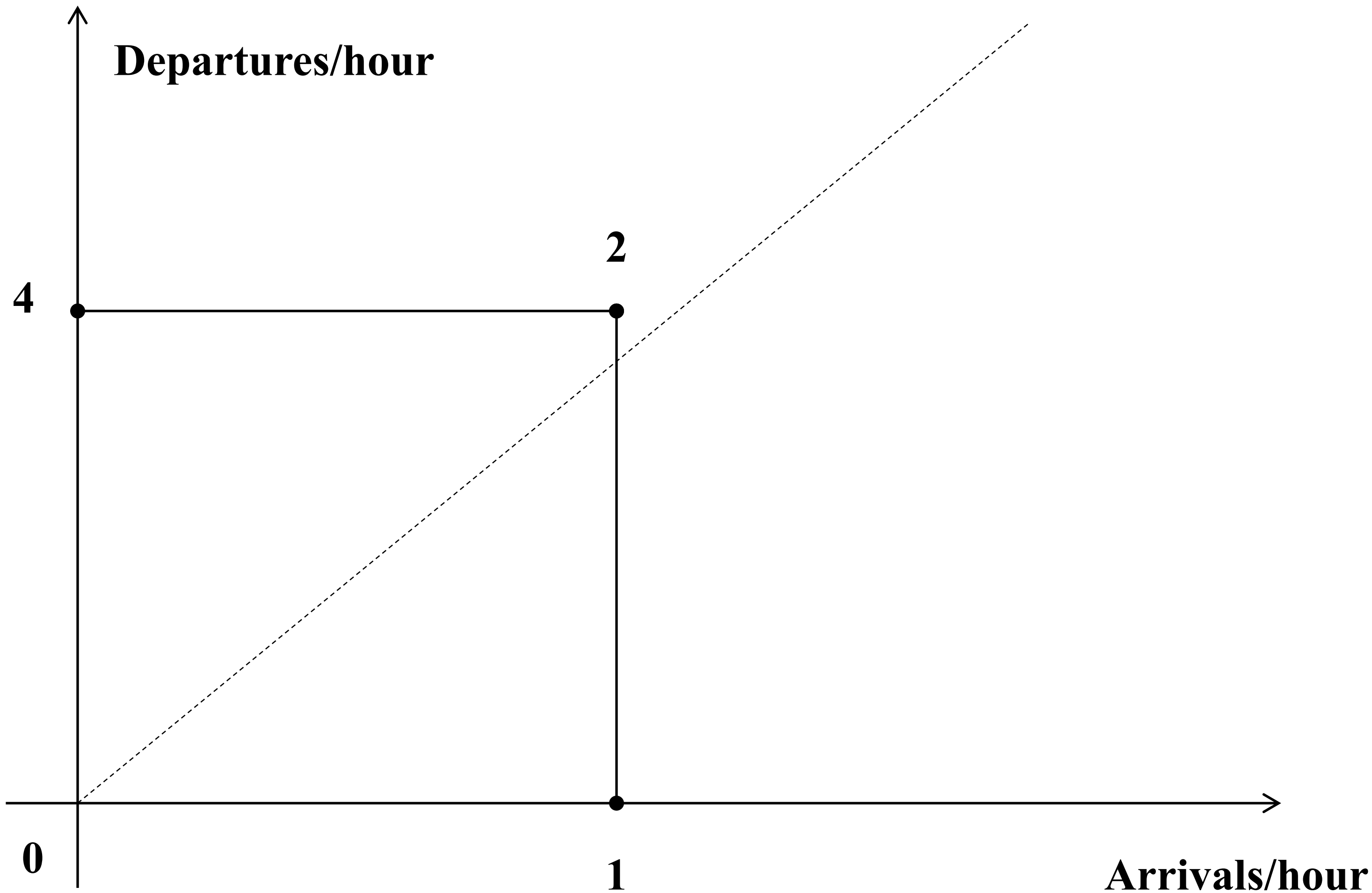
Typical capacity envelope ("Pareto envelope") for a single runway



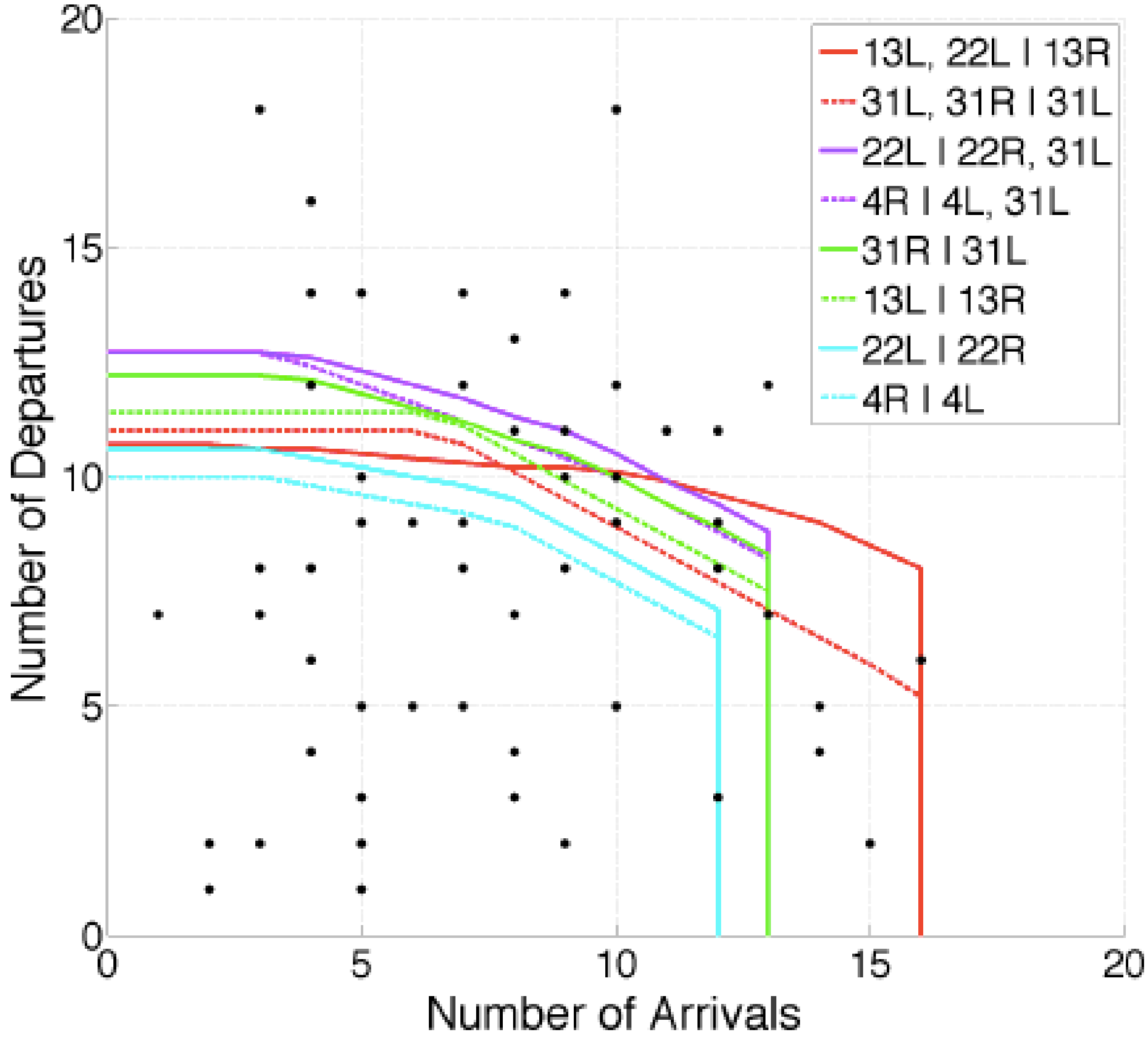
VMC vs. IMC Envelopes



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



Capacity Envelopes and Demand: JFK



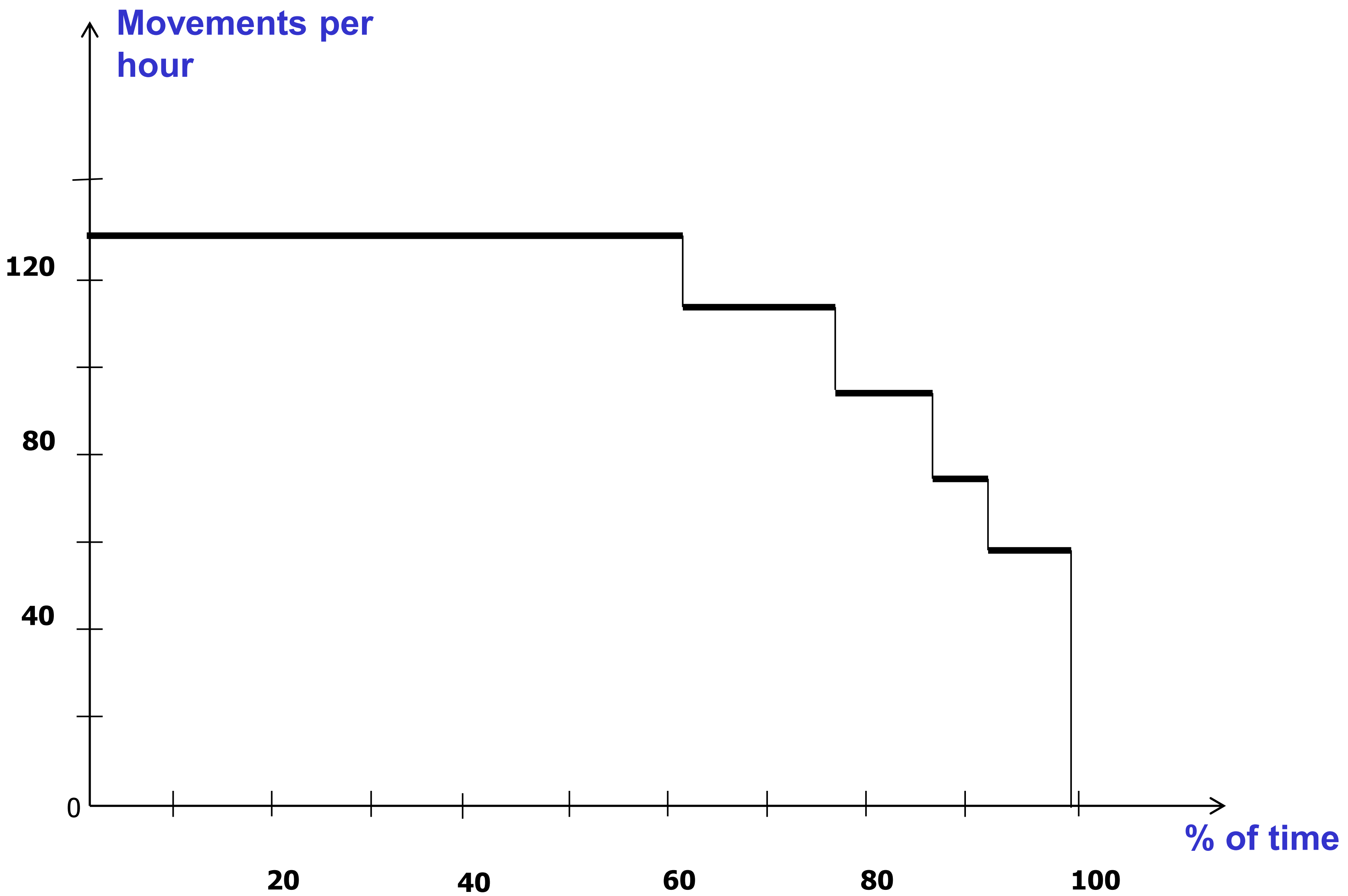
Shown on scale of “arrivals and departures per 15 minutes”

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



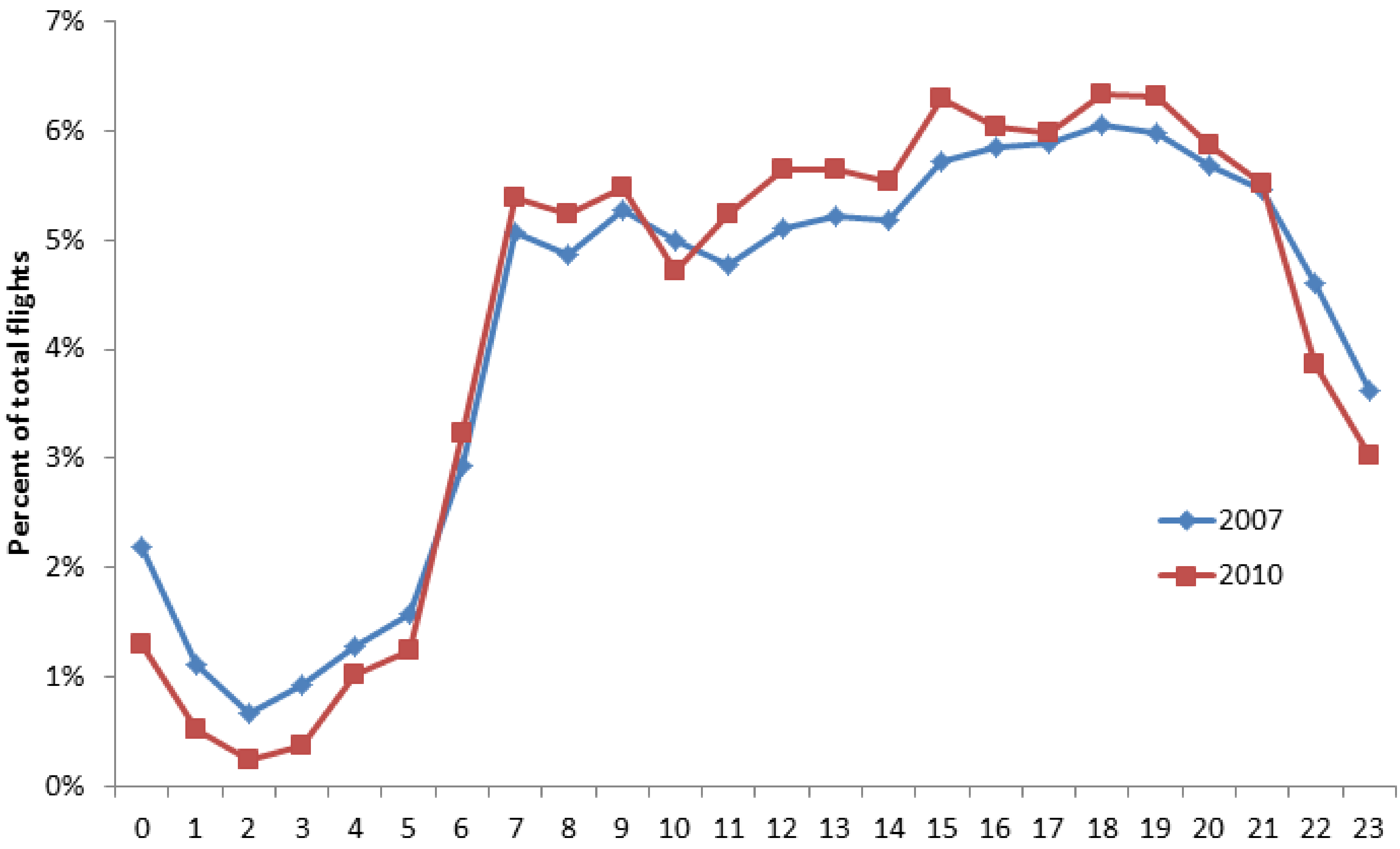
Range of Airfield Saturation Capacities

- The saturation capacity of a single runway varies greatly among airports, depending on ATM rules and performance, weather conditions, traffic mix, operations mix and other factors identified earlier
- At major commercial airports, in developed countries, the typical range per runway in good weather conditions is
  - 25 – 44 arrivals per hour for arrivals-only operations
  - 30 – 55 departures per hour for departures-only ops
  - 30 – 56 movements per hour for mixed ops
- Depending on the number of runways and the airport's geometric configuration, total airfield capacity of major commercial airports ranges from 30 per hour to 260+ per hour

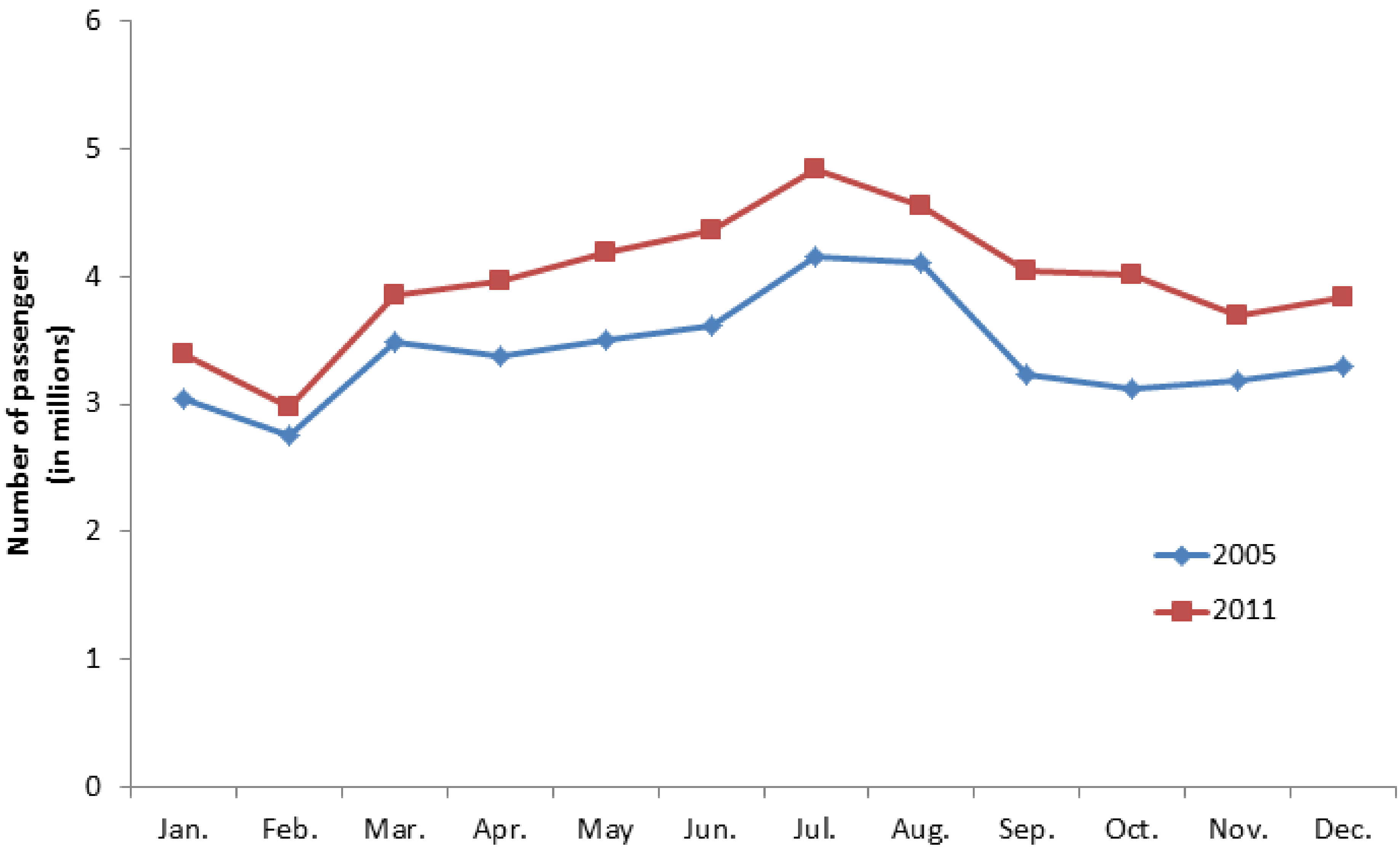
Annual Airside Capacity

- = The number of aircraft movements that can be handled at a reasonable level of service in one year
- Vaguely defined, but very important for planning purposes
- Runway system is typically the limiting element
- Estimation of annual capacity must consider:
  - Typical hourly (saturation) capacity
  - Pattern of airport use during a day (largely determined by type of airport demand and by geographical location)
  - Acceptable level of delay during busy hours
  - Seasonal and day-of-the-week peaking patterns of demand

Daily Demand Profile: Newark Aircraft Movements (% of Daily Movements)



Stability of Monthly Patterns: No. of Passengers at NY JFK



Annual Airside Capacity: Boston Example

1. Typical hourly runway capacity = 115 per hour

   Compute: A = 115 x 24 x 365 = 1,007,400

2. Equivalent of ~16–17 hours of strong activity per day.

   Compute: 1,007,400 x (16/24) = 671,600

3. ~85% utilization in busy hours to ensure delays are tolerable

   Compute: 671,600 x 0.85 = 570,860

4. Summer season days have about 15% more movements than winter season days

   (570,860 / 2) + (570,860 / 2)x(1/ 1.15) ≅ 534,000

This is a *rough estimate* of the ultimate capacity of Logan airport, absent any further capacity increase

- **Note: the annual capacity amounts to only about 50% of A**

Increasing Runway Capacity

- At high levels of utilization, even small increases in the capacity of the runway system can have a large impact on air traffic delays
- This is the motivation behind many of the current efforts of airport operators and of ANSPs (e.g., NextGen and SESAR)
  - Reducing, even marginally, separation requirements (e.g., at many US and several European airports)
  - Improved precision in separations, especially on arrival
  - Sequencing of landing aircraft to minimize the use of wake vortex separations (e.g., LHR, Denver, Dallas/Ft. Worth)
  - Intersection departures to reduce separations between departures (e.g., Munich, LHR)
  - Time-based inter-arrival separations in headwinds (LHR)
  - Re-definition of aircraft classes (RECAT)

IFR Separation Requirements: Single Runway (USA)

Arrival-Arrival:

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

Trailing aircraft

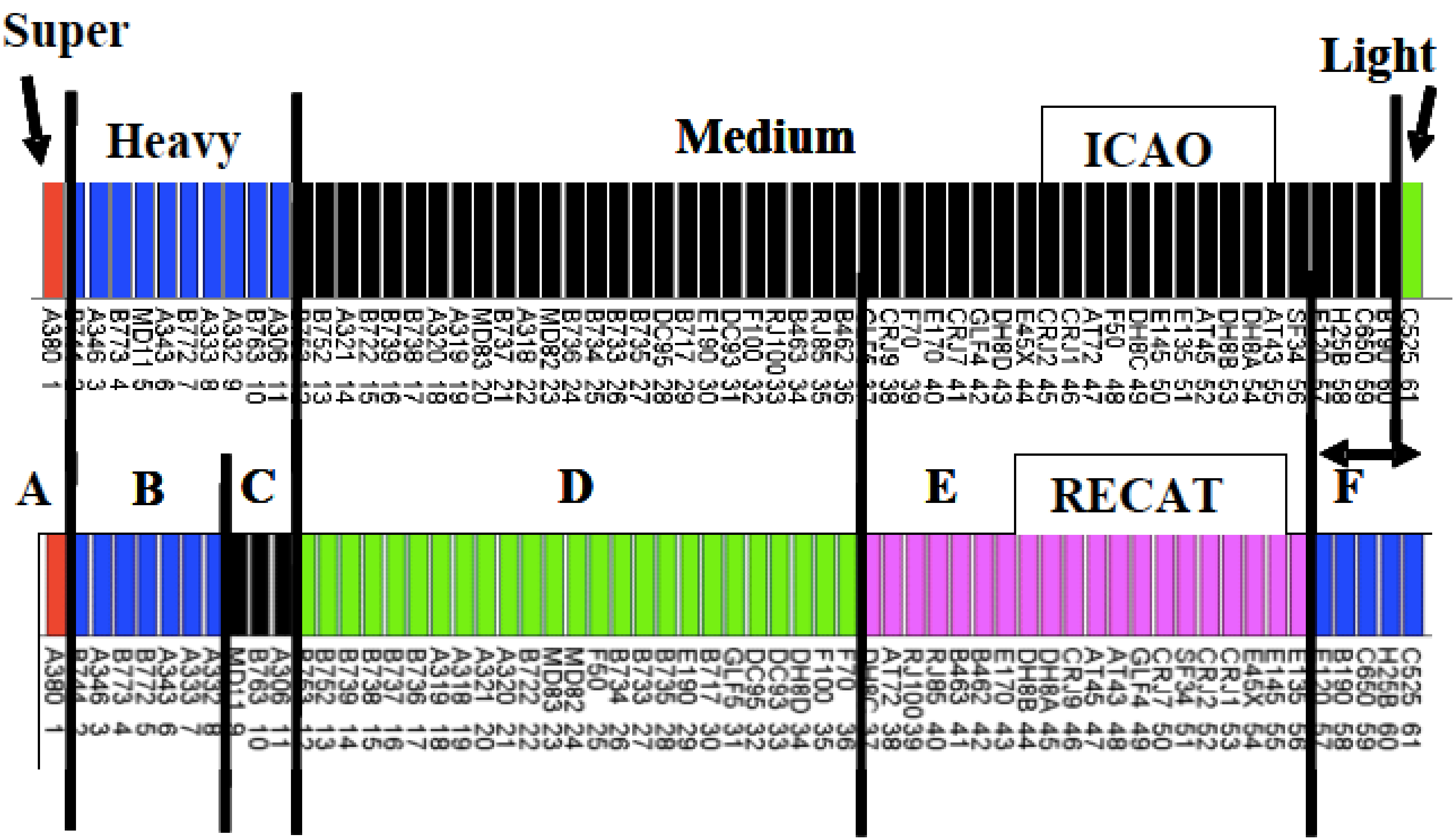
Leading aircraft

	H	L or B757	S
H	4	5	6*
B757	4	4	5*
L	2.5	2.5	4*
S	2.5	2.5	2.5

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

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

Current ICAO vs. Proposed RECAT Classes



Need for More Capacity

- ATM innovations will result in only limited increases in *runway system* capacity at the busiest airports [e.g., +10% – 20%(??) over 20 years]
- Quantum increases in capacity can only come from new airports or new runways at existing airports
- Practically no new primary airports planned in North America and Western Europe; several in Asia (India, China, Middle East)
- New runways are planned at a very few busy airports in Europe and US and at many major airports in Asia

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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
- Much more common problem: long taxiing times (15+ minutes) associated with surface movements, as the airfields and runway systems of busiest airports become ever more expansive and complex

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Capacity of Aprons/Stands

- 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) [30 minutes to 4 hours, except for overnight stays]
- Positioning time (PT) [5 – 20 min for in-and-out]
- Buffer time (BT) [can be more than 1 hour at some locations]

$$SBT = SOT + PT + BT$$

No. of aircraft served by a single gate rarely exceeds 6 – 7 per day and can be significantly less for gates serving long-range flights

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- Delays
  - Proper Measurement
  - Non-linearity
  - Landside vs. Airside
- Demand Management: Schedule Coordination
- Demand Management: Market-Based Schemes

General Observations

- Because of the absence of clear "rules of the road", capacities of terminal buildings (or of some of their components) are often estimated on the basis of space availability standards that are associated (rather arbitrarily) with various Levels of Service
- This simplistic approach does not account for fundamental issues such as:
  - Behavioral characteristics (e.g., how do people allocate their pre-departure time)
  - Space configuration (e.g., points where people tend to concentrate, lines of vision, etc.)

Design Peak Days and Design Peak Hours

- Airfields and passenger terminals are designed for "design peak days" (DPD) and "design peak hours" (DPH) associated with selected annual traffic levels
- The DPD and DPH loads are estimated in terms of aircraft movements (for airfields) and of arriving and departing passengers (for terminals and landside facilities)
- Numerous definitions of DPD (and DPH)
  - 20th or 30th or 40th busiest day of year
  - Average day of peak month
  - 90th or 95th percentile busiest day of year
- Common characteristic of all definitions: not busiest day (or hour) of the year, but "reasonably close" to it
- Practical rule: It makes little difference which definition one chooses, as long as it is consistent with the above concept

Level of Service (LOS)

- A verbal description of Quality of Service in terms of Ease of Flow and Delays
- Six standard categories:

LOS / Comfort	Flows	Delays
A – Excellent	Free	None
B - High	Stable	Very Few
C - Good	Stable	Acceptable
D – Adequate	Unstable	Passable
E – Inadequate	Unstable	Unacceptable
F – Unacceptable	--- System Breakdown ---	

- System Managers, Designers should Specify LOS
  - Level C is recommended minimum
  - Level D is tolerable for peak periods

Level of Service Standards: Space (sq. m. per occupant)

	A	B	C	D	E	F
Wait and circulate with bags	2.7	2.3	1.9	1.5	1.0	?
Wait and circulate w/o bags	2.0	1.8	1.6	1.4	1.2	?
Wait with bags	1.8	1.6	1.4	1.2	1.0	?
Wait without bags	1.4	1.2	1.0	0.8	0.6	?

Source: IATA Airport Development Reference Manual, 8th ed., 1995

NOTE: No guidelines exist concerning delays at the various parts of the terminal

LOS Standards: Passageways

Passengers per meter of effective width per minute (PPM)

Type of Passageway	Speed of Walking	Level of Service					
		A	B	C	D	E	F
Corridor	Regular	10	12.5	20	28	37	More
Stairway	Slower	8	10	12.5	20	28	More

[Source: Modified from Fruin (1971)]

Space Required

- Space Required, sq. meters =

  (Load, persons/hour)x(Standard, sq.m./person)x(Dwell time, hours)

- Example:

  What space is required at LOS C for passport inspection of 2000 passengers per hour when maximum dwell is 20 minutes?

Space Required = 2000x1x(1/3) = 667 sq. m.

Refinements to the LOS Standards

- IATA Airport Development Reference Manual, 9th ed., 2004 has refined the 1995 LOS standards
- Depending on the type of space being considered, the LOS standards are now also sensitive to
  - The presence of carts in the space
  - The number of bags (many or few) typically carried by passengers occupying the space
- For passageways (such as corridors and stairways), allowances are also made for ergonomics; for example, for 2-way passenger flows: 1.5 m extra is required to account for “edge effects” (0.5 m from each side of the corridor and another 0.5 m between the two flows)
- IATA Airport Development Reference Manual, 10th ed., 2014 has introduced flexibility in the guidelines so that local considerations can be taken into account

In Truth…

- Unfortunately, an approach that relies on average space availability guidelines to determine the capacity of terminals or to design terminals is usually totally inadequate
- Often leads to big mistakes and oversized or undersized passenger terminals
- Approach does not consider
  - The presence of several different stakeholders, each with its own priorities
  - The possibility of creating "hot spots" because of the behavioral characteristics of terminal's users
  - The potential for modifying passenger behavior with proper signage and information
- **Every design of a passenger terminal must be driven by local considerations**

Stakeholders in Passenger Building Design/Planning

- Airport operator
- Airlines
- Passengers
- Government (security, immigration, customs..)
- Commercial vendors and non-aeronautical service providers
- Different stakeholders attach different values and priorities to the various attributes of a terminal
- “Efficient” vs. “shopping mall” debate

Evaluation Measures for Passenger Terminals

- Direct:
  - Capacity
  - Time-in-system
  - Waiting time
  - Space requirements
  - Facility requirements
  - Walking distances

- Indirect:
  - Non-aeronautical revenues
  - Operating costs
  - Staffing requirements
  - Flexibility
  - Security
  - Ambience / image
  - Signalization/orientation

Connecting traffic, dwell time, discretionary time

- Hubbing airports must serve large numbers of connecting passengers instead of just originating and terminating ones
- Connecting passengers often have long dwell times at airports (space needed) and take advantage of commercial services there
- Dwell times of departing passengers are also becoming longer, primarily due to security requirements
- Large investments in infrastructure required
- Influencing the magnitude and allocation of dwell time and of "discretionary" time has become critical for airports

Outline

- Variability of Demand
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Delay / Congestion on Airside

- Delay is one of the two key measures of performance on airside; the other is environmental impact
- Delay affects airline costs in major ways:
  - Direct costs: labor, fuel, maintenance, depreciation
  - Level of service perceived by passengers
  - Disruption of daily schedules
  - Need for additional resources (staff, aircraft, etc) to permit schedule recovery
  - Long-term loss of goodwill, loss of demand (diversion to other modes, alternatives to travel)
- Similar negative impacts on passengers
  - Direct cost of lost time
  - High cost of trip disruptions
  - Change of travel strategies, more time spent traveling
- Negative impacts on environment and safety

Cost of Air Traffic Delays in US, 2007

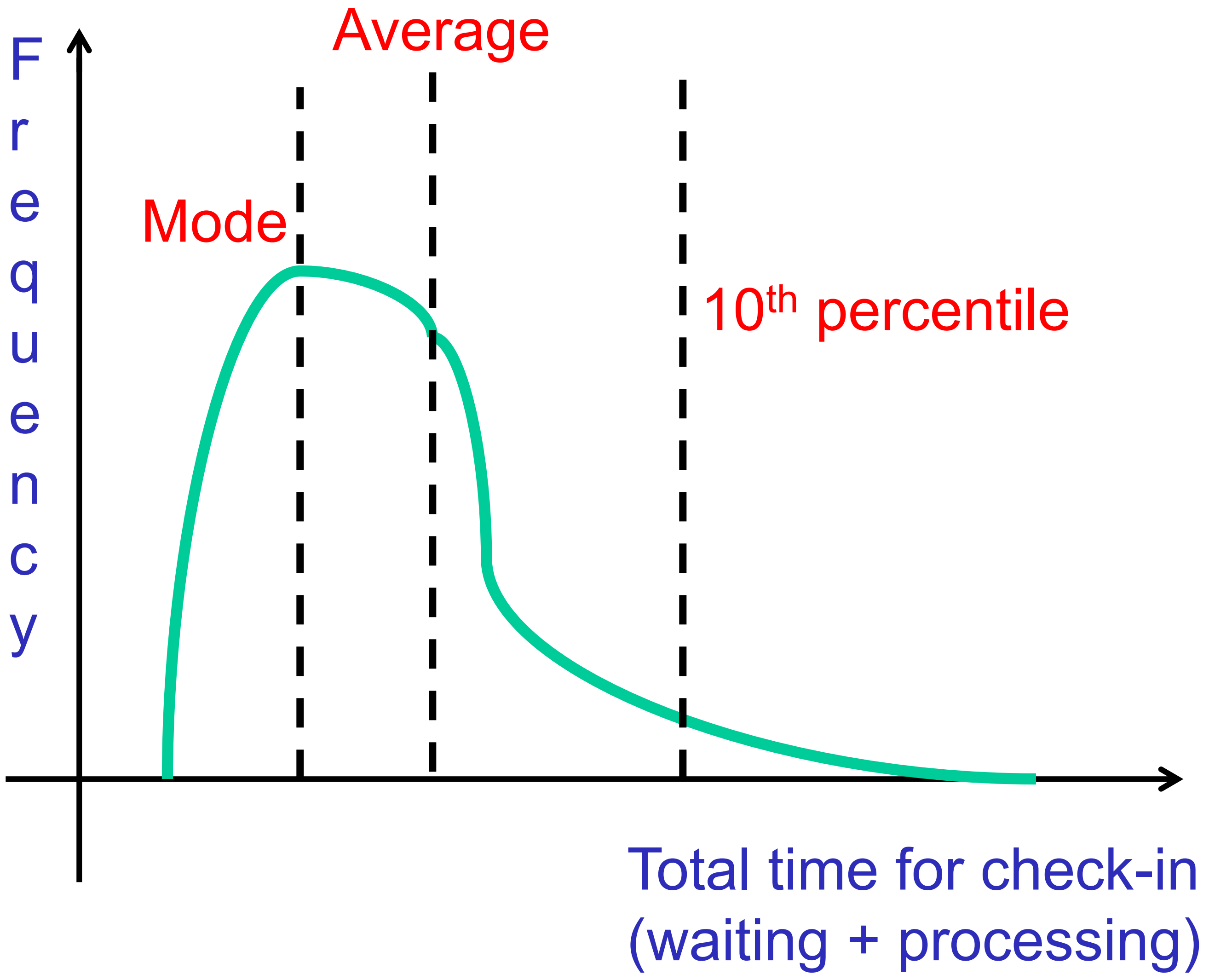
Cost Component	**Cost (billion dollars)**
Cost to Airlines	8.3
Cost to Passengers	16.1
Cost of Lost Demand	7.9
Total Direct Cost	32.3
Indirect Impact on GDP	4.0
Total Cost Impact	36.3

Source: *Total Delay Impact Study: A Comprehensive Assessment of the Costs and Impacts of Flight Delay in the United States*, NEXTOR 2010

Delay / Congestion on Landside

- Delay is also one of the principal measures of performance on landside
- But, because landside performance has so many different aspects and is evaluated by several types of “stakeholders”, many other measures must also be used
- In contrast to space-related standards, there are no international guidelines on what is “reasonable” delay and what is “unacceptable” delay on airside
  - Different airports and airlines have different standards in this respect (and many have no standards at all)

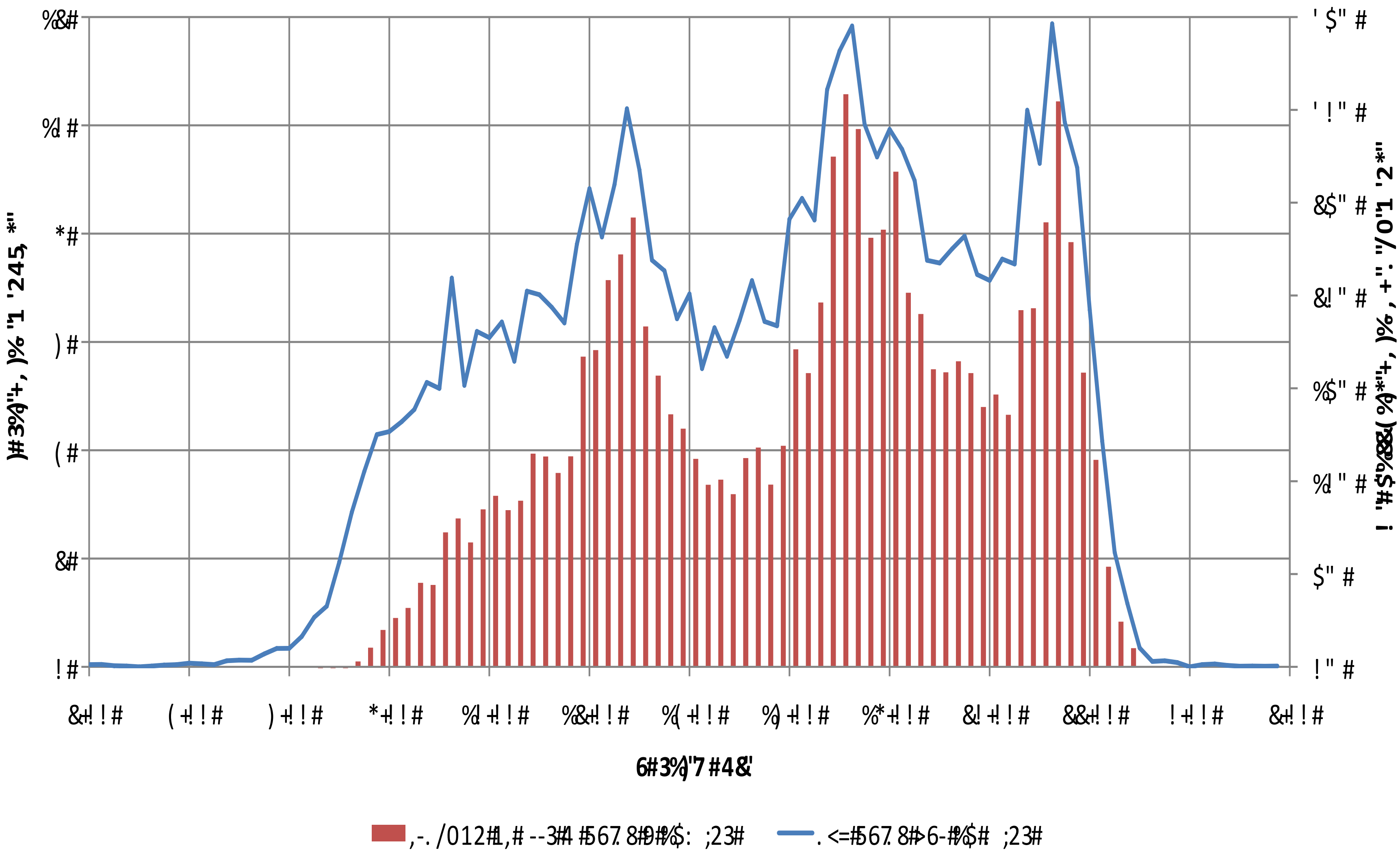
Sketch of a Distribution of Time for Check-in



Measuring and Assessing Delay

- Delay-related performance at an airport must be assessed from several perspectives:
  - **"Average"** (expected value)
  - **"Spread" / "uncertainty"** (standard deviation)
  - **"Extreme cases" / "outliers"** (X-percentile of distribution, where X=10 or 5 or 1)
  - **"Most frequent"** (mode of distribution)
- Typically we are concerned about
  - Delay over the entire period under consideration, as well as
  - Delay during peak demand periods (peak hours, peak days, peak month, special days

Runway Delay Statistics for a Typical Day at FRA



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Behavior of Queuing Systems in the "Long Run"

- The "utilization ratio", ρ, measures the intensity of use of a queuing system:

$$\rho = \frac{average\ demand\ rate}{average\ service\ rate} = \frac{"demand"}{"capacity"} = \frac{\lambda}{\mu}$$

- A queuing system cannot be operated in the long run with a utilization ratio which exceeds 1; the longer such a system is operated, the longer the queue length and waiting time will be.
- **But delays may occur even when $\rho < 1$ due to time-variability of demand and to probabilistic fluctuations of demand and capacity; these delays can be very large when ρ is close to 1.**

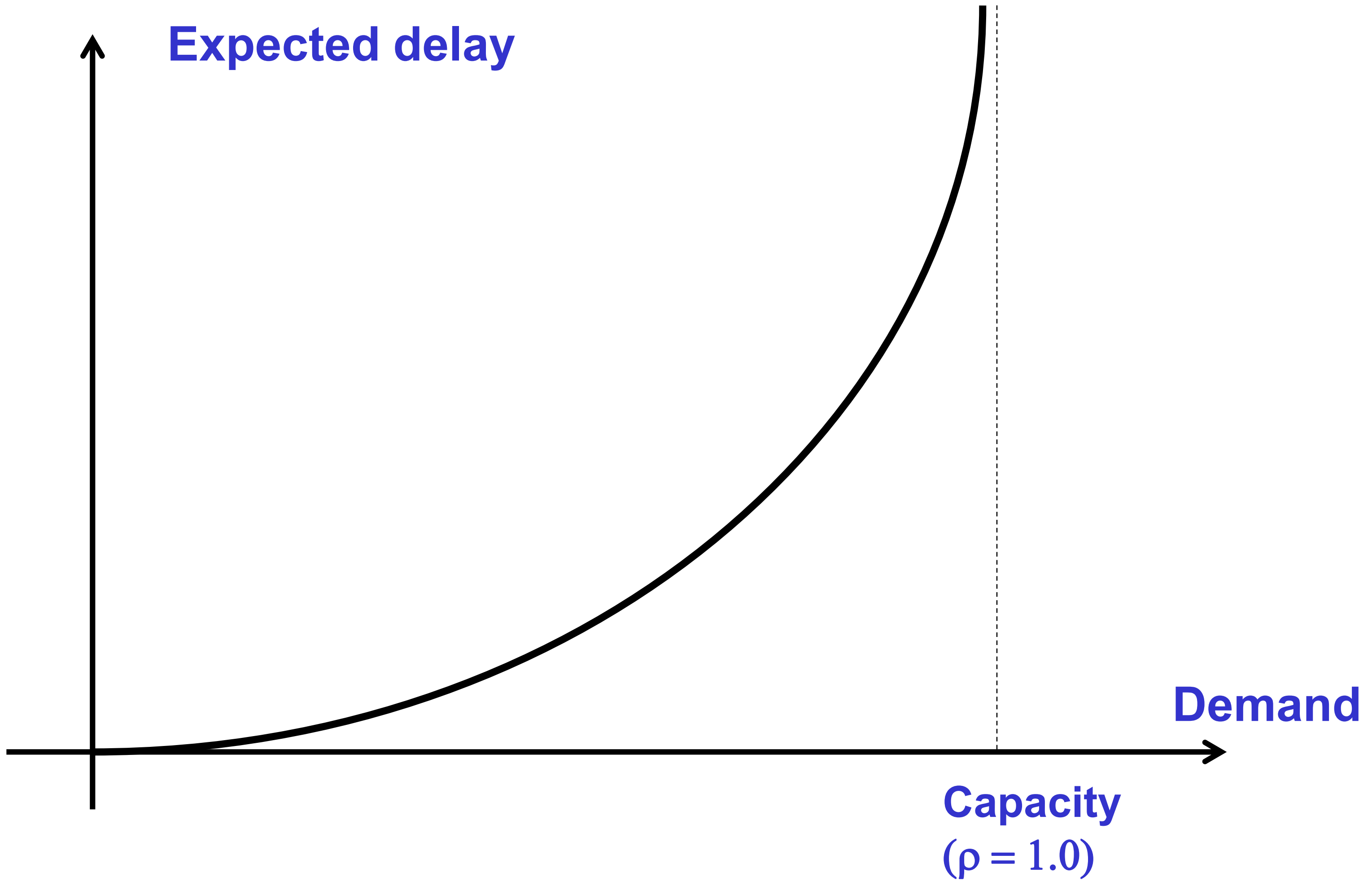
Behavior of Queuing Systems in the "Long Run"[2]

- In the "long run", the average queue length and average delay in a queuing system are proportional to:

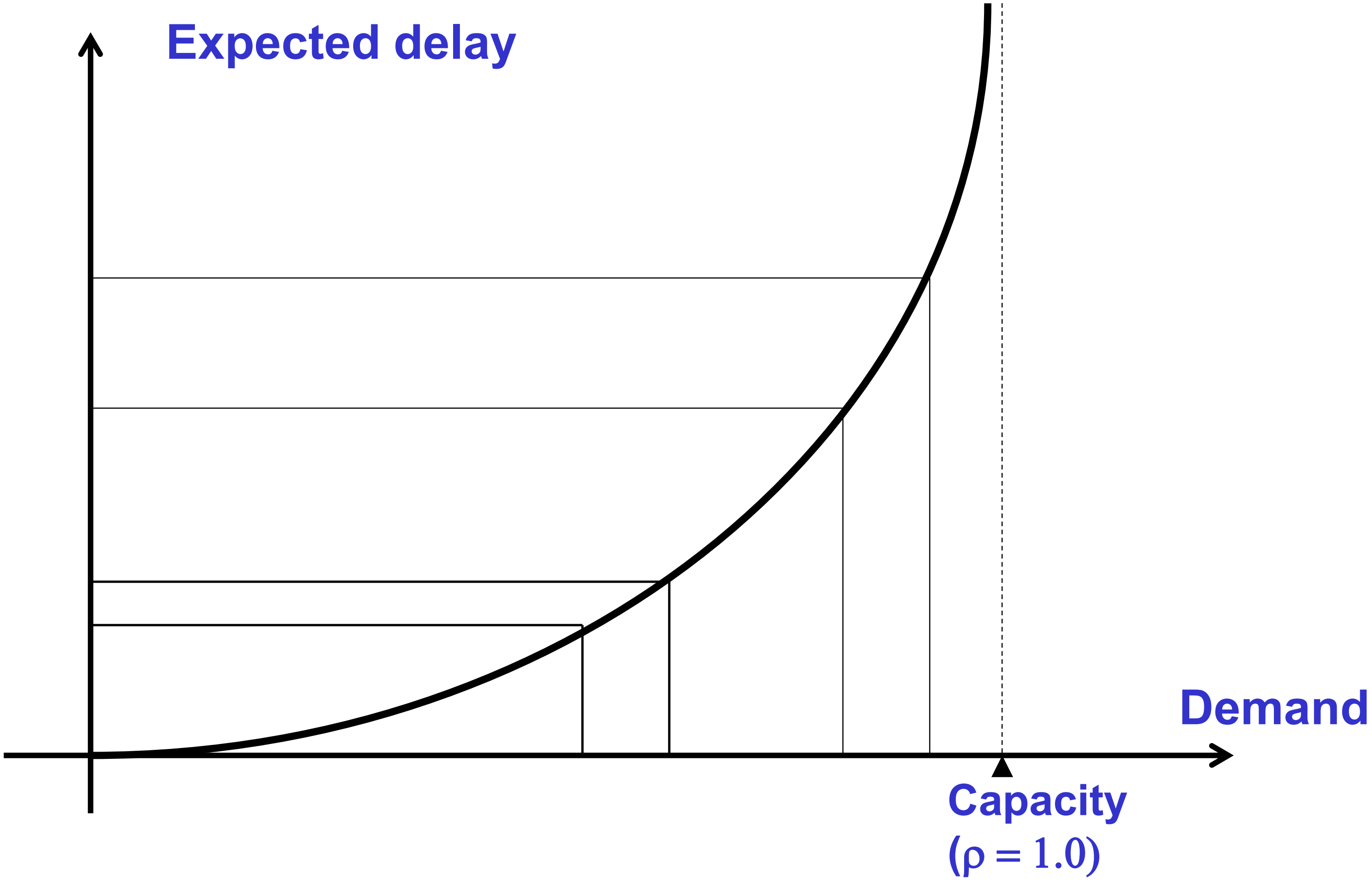
$$\frac{1}{1-\rho}$$

- Thus, as the demand rate approaches the service rate (or as $\rho \to 1$, or as "demand approaches capacity") the average queue length and average delay increase rapidly
- The "proportionality constant" increases with the variability of demand inter-arrival times and of service times

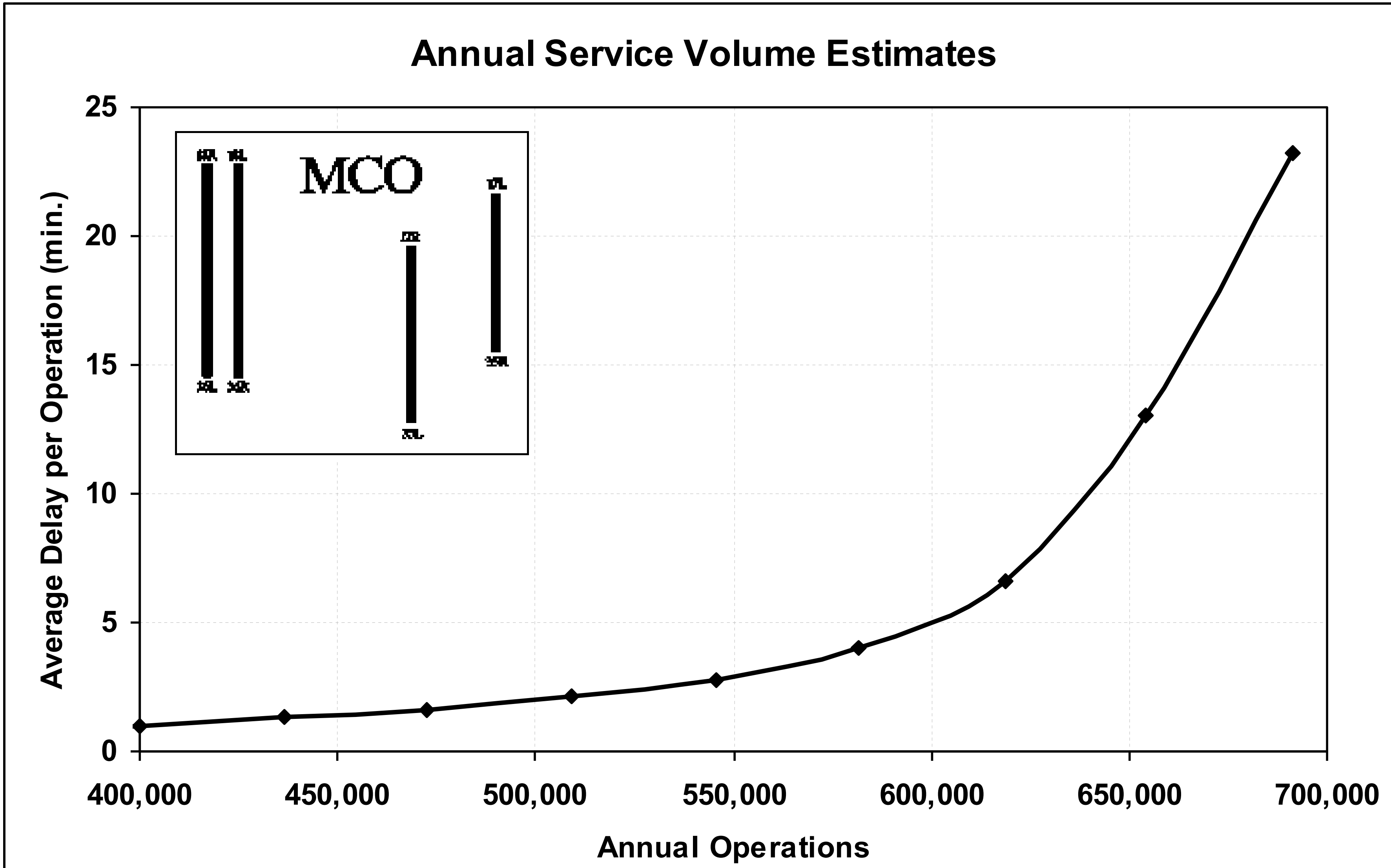
Delay vs. Demand and Capacity



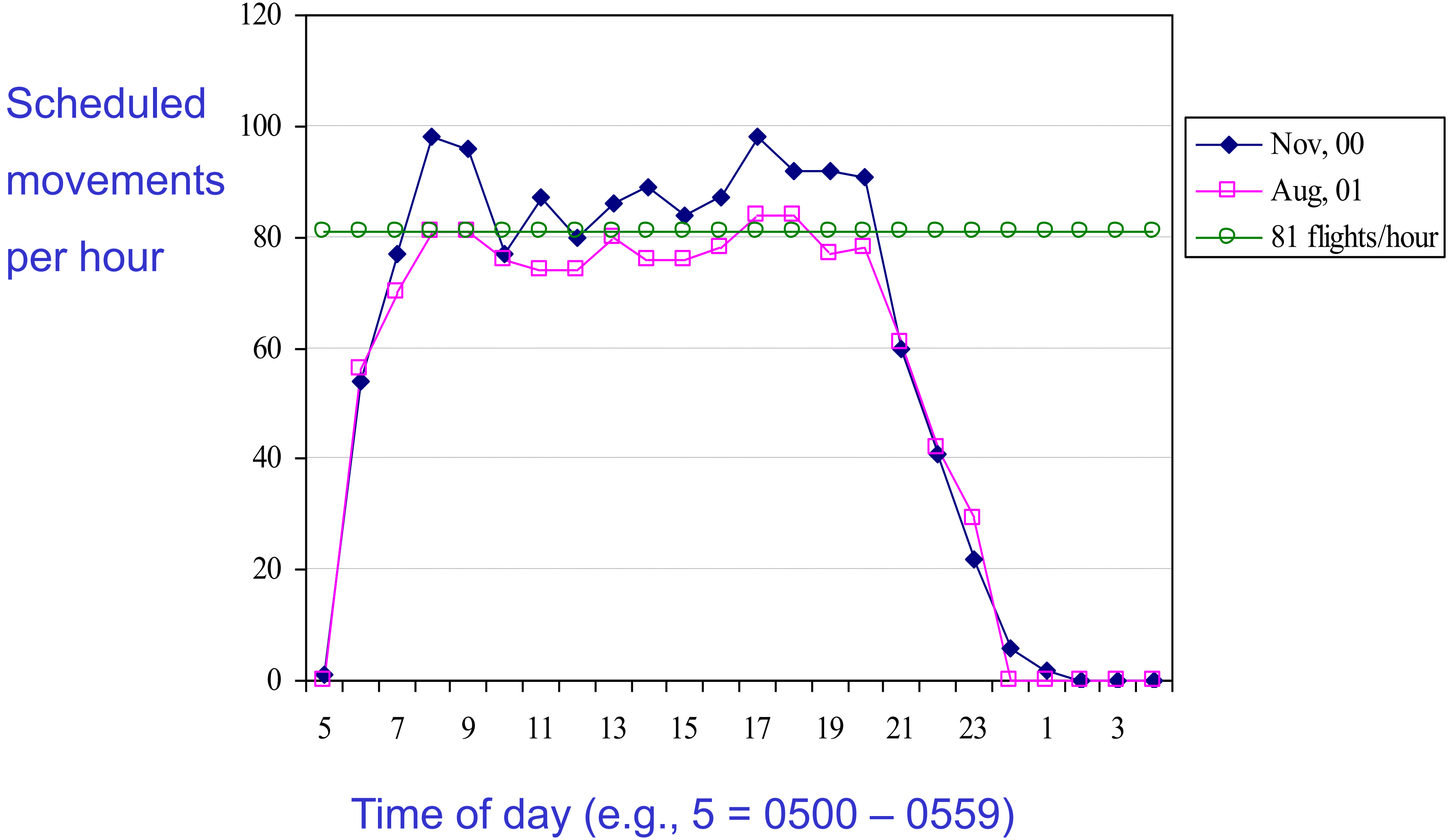
High Sensitivity of Delay at High Levels of Utilization



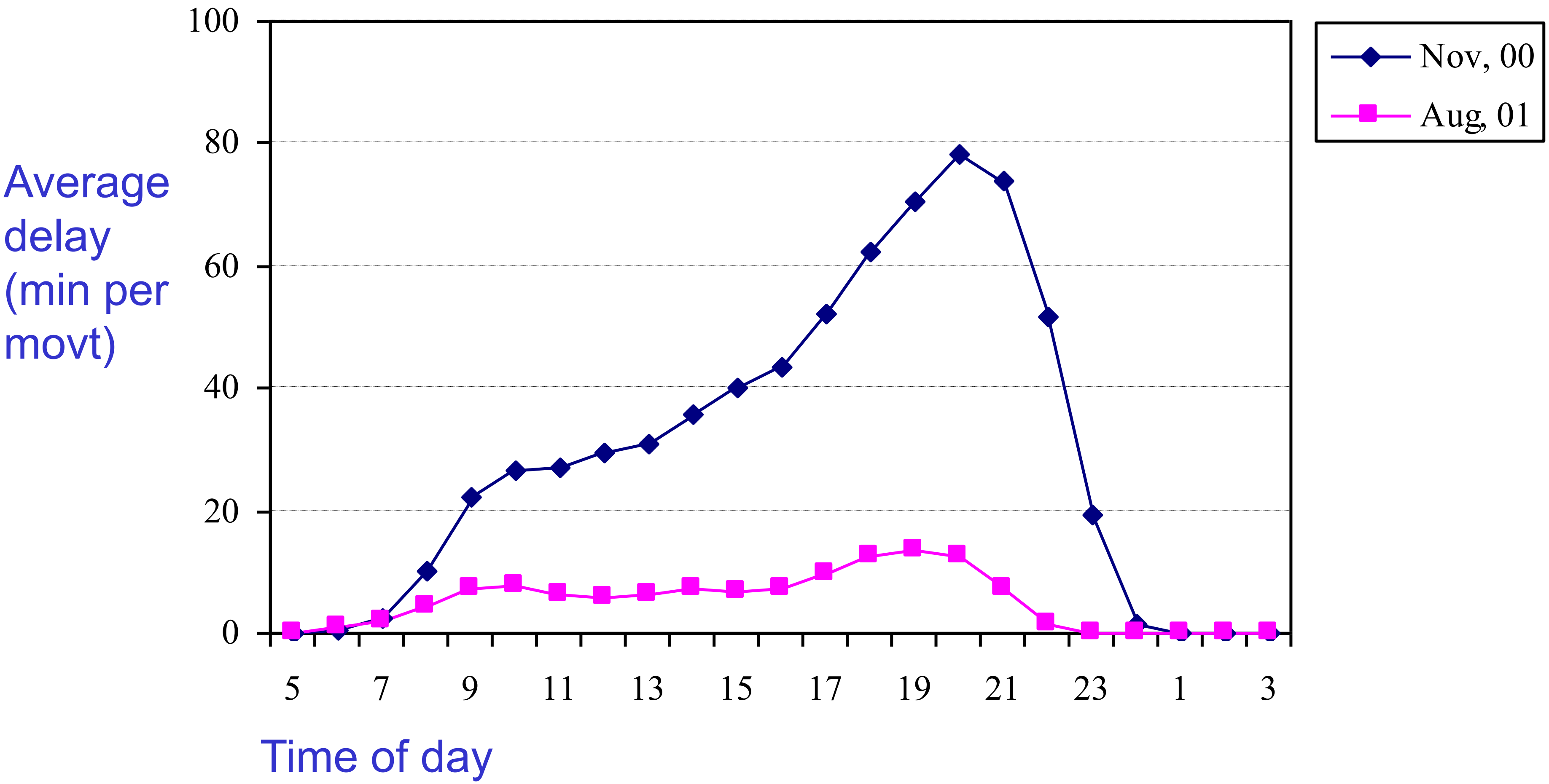
Delay vs. Annual Operations at Orlando Airport (MCO)



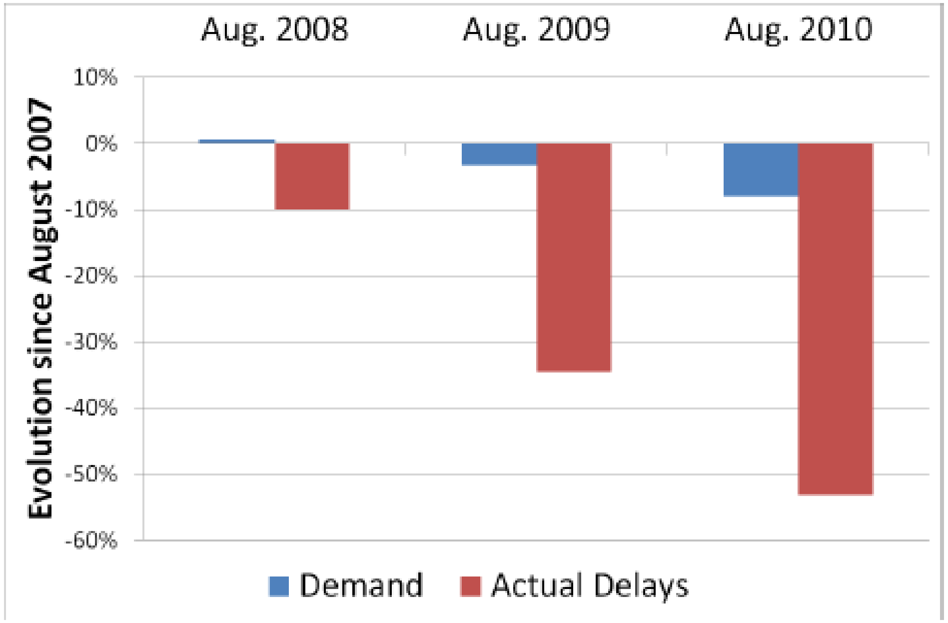
Scheduled aircraft movements at LGA before and after 2001 slot lottery



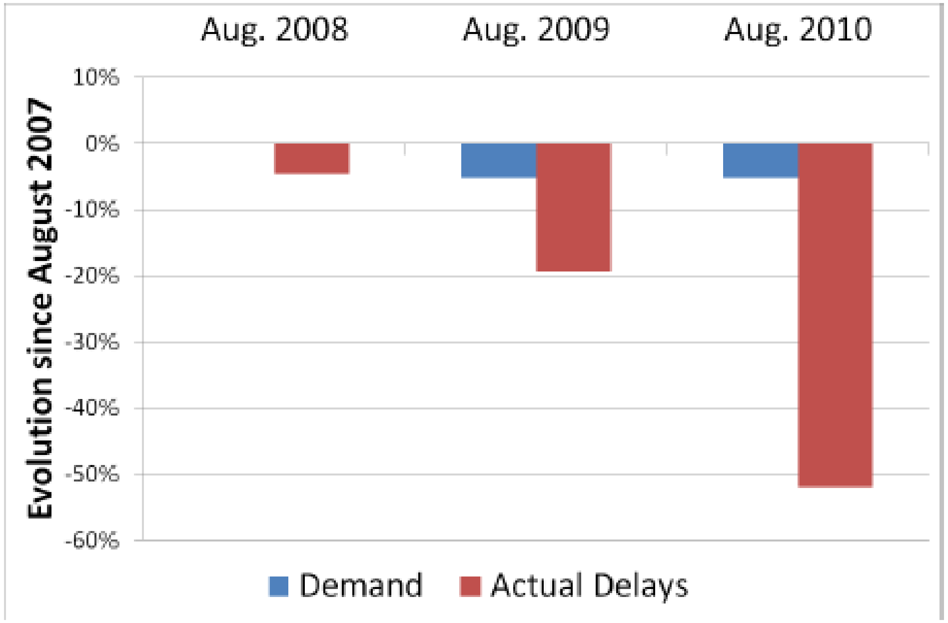
Estimated average delay at LGA before and after slot lottery in 2001



Evolution of NY Delays (2007 – 2010)



(a) JFK



(b) EWR

	JFK		EWR	
Month in 2010	**July**	**August**	**July**	**August**
Demand	-6.84%	-8.02%	-3.37%	-5.16%
Actual Delays	-46.90%	-53.15%	-32.93%	-52.02%
Model-Predicted Delays	-48.69%	-51.30%	-36.14%	-41.56%

Jacquillat, 2012

Variability of Queues

- The variability of delay also builds up rapidly as demand approaches capacity.
- In “steady state,” the standard deviation --a measure of variability -- of delay and of queue length is also proportional to:

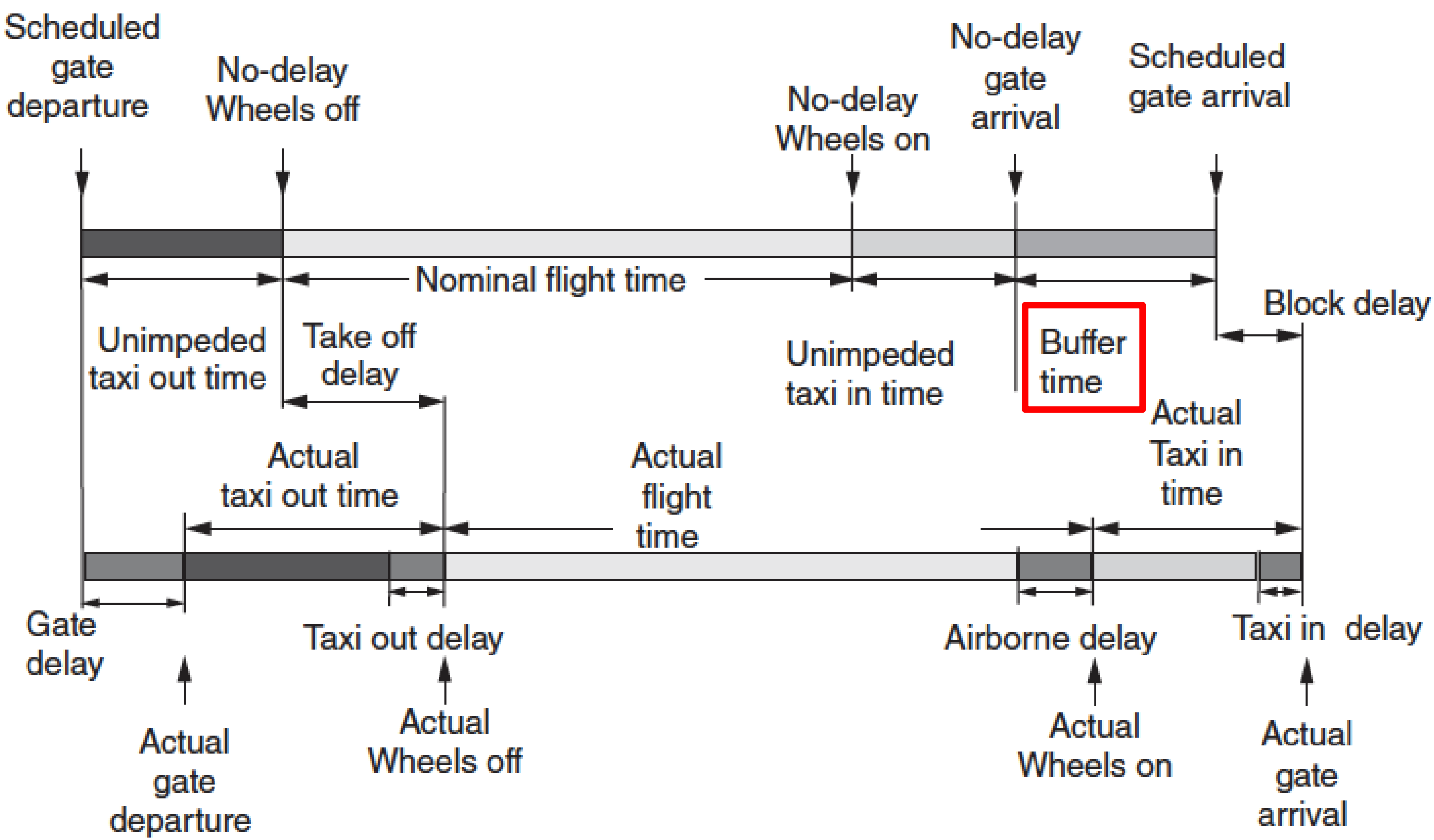
$$\frac{1}{1-\rho}$$

- A large standard deviation implies unpredictability of delays from day to day and low reliability of schedules

Two Types of Delay Measurement

- Two types of delay measures; cause of much confusion:
  - "True" delay: the difference between the actual time it took to complete a flight (or a flight segment) and an estimate of the time ("nominal time") that would be required in the absence of delay
  - Delay relative to schedule
- In much of the world, a flight is counted as "late" if it arrives or departs (at gate) more than 15 minutes later than scheduled [note this is delay relative to schedule]
- In recognition of habitual "true" delays, airlines have been lengthening ("padding") the scheduled duration of flights
  - improve "on-time arrival" statistics
  - improve reliability and realism of their schedules
- Thus, airline scheduled flight durations include a delay allowance: a flight that arrives on schedule may in truth have been significantly delayed!

Understanding the Measurement of a Flight's Delay



True Delay = Buffer Time + Block Delay

Measuring and Attributing Delay

- It is difficult to use field data to measure and attribute delay when congestion is severe
- Tightly inter-connected, complex system
- Users react dynamically to delays (feedback effects, flight cancellations)
- Geographical spreading (no single location for measurement), temporal propagation and secondary effects
- Delay-free, nominal travel times are not readily available
- Causality is unclear

Tools for Estimating Delays Theoretically

- The estimation of delays at an airport is usually sufficiently complex to require use of computer-based models
  - Dynamic queuing models: solve numerically the equations describing system behavior over time
  - Simulation models (e.g., TAAM, SIMMOD)
- For very rough approximations, simplified models may sometimes be useful
  - Simple (“steady-state”) queuing models
  - Cumulative diagrams
- *Note:* Field data on air traffic delays increasingly available, getting better in quality (e.g., ASPM, CODA)

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Delay / Congestion on Landside

- Delay is also one of the most important measures of performance on landside
- But, because airside performance (i) affects many "stakeholders" and (ii) impacts people
  - Many other measures must also be used
- It is also true that, in contrast to space-related standards, there are no international guidelines on what is "reasonable" delay and what is "unacceptable" delay on airside
  - Different airports and airlines have different standards in this respect (and many have no standards at all)

A Poor Performance Measure

- Many airports and airlines specify quality-of-service requirements of the form:

  "Average time to complete service S equal to X minutes, maximum time equal to Y minutes"

  – Example: S=check-in, X=10, Y=20
- But, "maximum time" requirements make no sense; extreme cases should be quantified by means of probabilities (or "frequency of occurrence")

  – Example: 95% of passengers should be able to complete check-in in 20 minutes or less
- The length of queues should also be a concern and should be limited in a similar way

LHR: Quality Control Program

- A program to control quality of service at LHR, called the Service Quality Rebate Scheme (SQRS) was introduced by the regulatory Civil Aviation Authority
- Identifies the service standards that airlines and passengers should expect from Heathrow in return for the regulatory charges they paid.
- If performance falls below a certain level, Heathrow must repay a proportion of charges levied back to the airlines.
- SQRS provides an incentive to the airport operator to meet the specified standards of service quality
- Rebate payments are made monthly to airlines
- Maximum amount of rebates is 7% of airport charges
- Rebates are paid on performance in each individual terminal

Example of Proper Measures and Targets

- London Heathrow, Terminal 5
- Central security queue: Measures of performance

1. Percent of time that queue requires less than 5 minutes
   - Target: 95%
   - Actual figure for January 2015: 96.54%
2. Percent of time that queue requires less than 10 minutes
   - Target: 99%
   - Actual figure for January 2015: 99.88%

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Demand Management Fundamentals

- Demand management measures may be taken when expected demand at an airport will habitually exceed available capacity
- Airport capacity expansion should be the principal means of accommodating growth of demand
- Demand management should be used to address:
  - short- and medium-term problems
  - long-term problems when capacity expansion:
    - becomes unreasonably expensive; or
    - is constrained by challenging political, social or environmental barriers
- Demand management is generally practiced today through "schedule coordination", essentially a reservation system for access to congested airports

The Concept of Schedule Coordination

- Slots are "permissions to use a runway and airport infrastructure on a specific date and time for an arrival or departure"
- Schedule Coordination "rations" scarce capacity among airlines so as to achieve high utilization of airport while keeping delays at reasonable levels
  - "smoothens peaks and valleys" in daily demand
  - keeps demand below a target level specified by the airport's "declared capacity"
- Important to estimate declared capacity accurately and to understand the relationship and tradeoffs between number of flights served and delay

Declared Capacities – Brussels, 2009

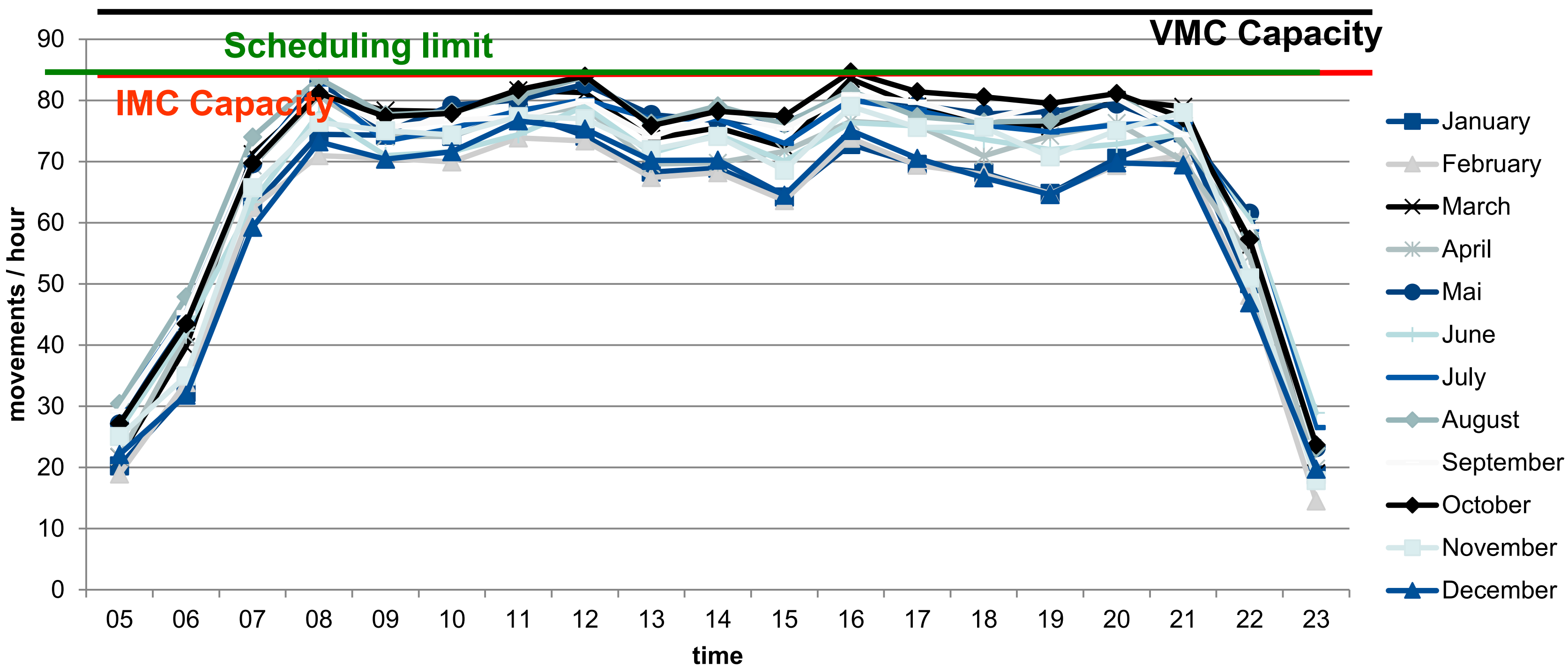
times / period		05 min			10 min			30 min			60 min		
from	until	arr	dep	total	arr	dep	total	arr	dep	total	arr	dep	total
00.00	05.55	5	5	8	9	9	9	16	16	16	30	30	30
06.00	06.55	5	5	9	10	9	13	24	27	35	35	40	45
07.00	22.55	6	5	10	10	9	15	30	27	40	48	44	74
23.00	23.55	5	5	8	9	9	9	16	16	16	30	30	30

Source: Morisset, 2010

Determining Declared Capacity

- No standard methodology for determining declared capacity (= the number of "slots" available at an airport)
  - some sophisticated approaches with detailed simulations and extensive consultation with stakeholders
  - many *ad hoc*, "back-of-the-envelope" approaches with limited inputs and "politicized" considerations
- Declared capacities are typically set with reference to IMC capacity of the airport:
  - Lower than IMC capacity in most cases (MUCH lower in some)
  - Very close to (and sometimes slightly above) estimated IMC capacities at some of the busiest airports (e.g., Heathrow, Frankfurt, Gatwick, Munich)
  - Terminal building capacity may also be a constraint

FRA – Average daily schedule by month (2007)



- Evenly distributed demand profile from 07:00 to 21:00
- Hourly demand peaks at 84-movement hourly slot limit

IATA Schedule Coordination Process

- Level 1 ("non-coordinated")
- Level 2 ("schedules facilitated") (~ 120 airports)
- Level 3 ("fully coordinated")
  - ~ 170 airports (~100 in Europe, practically all busiest ones outside US)
  - Coordinator appointed by appropriate authority, usually assisted by a coordination committee
  - IATA Schedule Coordination Conferences (SCC); in June and November for subsequent season
  - Attended by ~300 air carriers, coordinated airport reps, schedule coordinators, etc.

Level 3 and Level 2 Airports (Feb 2015)

Region	Level 3	Level 2
Asia Pacific	36	16
Europe	100	74
Middle East and Africa	11	12
North Asia	13	2
Americas	7	12
Total	167	116

Source: IATA

IATA Schedule Coordination Process [2]

- Carriers must submit slot requests 27 days before SCC
- During SCC and post -SCC, coordinators resolve conflicts, finalize schedules
- ***Historical precedent is over-riding criterion***
- Carriers may change use of slots or exchange slots
- **Use-it-or-lose-it clause (80% use required)**
- **New entrants are allocated up to 50% of "free" slots**
- ***Restrictive definition of "new entrant"***
  - ***Maximum of 4 slots in a day after being awarded new slots***
- Other allocation criteria: size and type of market, length of period of operation, curfews, etc.
  - "Transparent" slot buying/selling permitted in some EU countries (authorized as an option by EU Commission in 2008)

LHR Slots: Summer 2015

Runway Scheduling Limits Summer 2015

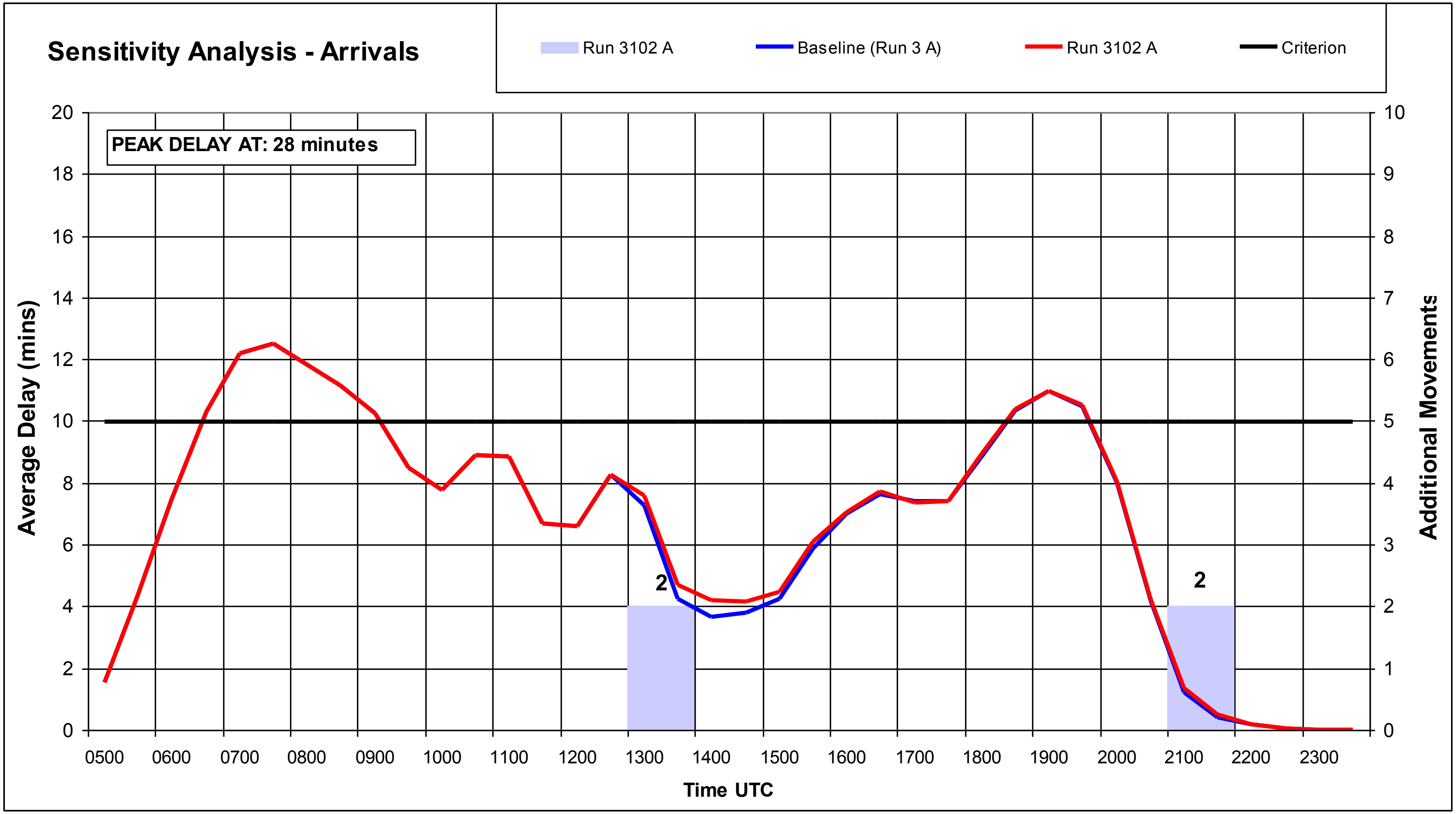
Arrivals																			
Hour (UTC)	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**Average**	**Total**
Summer 2014	38	39	37	40	40	41	40	43	43	41	41	44	44	43	38	44	20	39.8	676
Capacity change	+1							+1	-1	+1		+1				-1	+3		
Summer 2015	39	39	37	40	40	41	40	44	42	42	41	45	44	43	38	43	23	40.1	681

Departures																			
Hour (UTC)	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**Average**	**Total**
Summer 2014	25	46	43	43	41	42	41	44	44	44	42	43	44	44	38	38	30	40.7	692
Capacity change				+1	+1				+1		+1			-1	+2				
Summer 2015	25	46	43	44	42	42	41	44	45	44	43	43	44	43	40	38	30	41	697

Air Transport Movement Cap
Weekly Planning Limit: 9,620

Summer 2009: Arrs. 676, Deps. 691; Weekly, 9524
Annual Limit: 480,000 movements (Terminal 5 agreement)

Example: Sensitivity of Delay at LHR



Source: Manager, Slot Coordination, Airport Coordination UK

Passenger Limits: LHR, Summer 2015

Terminal	A/D	Constraint	Time Period (GMT)	Lower Limit	Initial Coordination Limit	Upper Limit
T1	D	International 1 Hour	0000 - 2359	200	**500**	1000
		International 3 Hour	0000 - 2359	1000	**1200**	2000
	A	International 1 Hour	0000 - 2359	250	**500**	1100
		International 2 Hour	0000 - 2359	500	**1000**	2200
T2	D	Combined 1 Hour	0000 - 2359	2500	**2800**	3500
		Combined 3 Hour	0000 - 2359	6000	**6800**	9000
	A	International & CTA 1 Hour	0000 - 2359		**2600**	3900
		International & CTA 2 Hour	0000 - 2359		**5100**	6500
		Domestic 1 Hour	0000 - 2359		**400**	600
T3 – S15 live	D	International 1 Hour	0000 - 2359	1700	**2000**	4000
		International 3 Hour	0000 - 1559	4200	**5000**	9000
			1600 - 2359	4000	**4200**	9000
	A	International 1 Hour	0000 - 2359	3000	**3500**	4000
T3 – "end game"**	D	International 1 Hour	0000 - 2359	2700	**3000**	4000
		International 3 Hour	0000 - 2359	5800	**7000**	9000
	A	International 1 Hour	0000 - 2359	3000	**3500**	4000
T4	D	International 1 Hour	0000 - 2359		**1650**	2500
		International 3 Hour	0000 - 2359		**3750**	5500
	A	International 1 Hour	0000 - 2359	1400	**1800**	2500
		International 2 Hour	0000 - 2359	2800	**3200**	4300
T5	D	Combined 1 Hour	0000 - 2359		**4500**	5000
	A	International 1 Hour	0000 - 2359		**3750**	4500
		Domestic 1 Hour	0000 - 2359		**950**	1150

Assumed Load Factors: LHR, Summer 2015

Summer 15	T1 International	T1 International	T2 Domestic	T2 CTA & International	T2 Combined	T3 International		T4 International		T5 Domestic	T5 International	T5 Combined
Day of Week	A	D	A	A	D	A	D	A	D	A	A	D
1	88%	81%	82%	87%	86%	88%	91%	86%	86%	90%	87%	86%
2	86%	82%	72%	85%	84%	88%	87%	86%	84%	88%	86%	85%
3	85%	81%	70%	84%	85%	86%	89%	83%	85%	87%	85%	84%
4	87%	85%	72%	85%	86%	87%	89%	85%	85%	87%	88%	86%
5	88%	86%	75%	86%	89%	90%	91%	87%	87%	87%	90%	88%
6	89%	86%	77%	89%	91%	90%	92%	86%	88%	91%	89%	89%
7	91%	85%	80%	87%	88%	90%	90%	89%	88%	88%	89%	89%

Stand Limits: LHR, Summer 2015

Total Physical Stand Supply - For Information Only, this is not the S15 Declared Stands

Summer 15										
Apron	F	E	E (747-400)	E (777-200)	D (767-300)	D (757)	C (A321)	C (A319)	B	TOTAL
T1	0	0	0	1	1	3	5	0	0	**10**
T2	10	10	0	3	0	0	13	0	0	**36**
T3	9	19	5	3	2	3	3	0	0	**44**
T4	6	12	7	1	3	0	4	1	0	**34**
T5	15	15	10	0	4	0	15	1	0	**60**
Total exc. Cargo	**40**	**56**	**22**	**8**	**10**	**6**	**40**	**2**	**0**	**184**
CARGO	0	3	3	0	0	0	0	0	0	**6**
Total inc. Cargo	**40**	**59**	**25**	**8**	**10**	**6**	**40**	**2**	**0**	**190**

Slot Availability at LHR: The Limits!

ARRIVALS							
HOUR	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0600	0	0	0	0	0	1	0
0700	0	0	0	0	0	0	1
0800	0	0	0	0	0	0	3
0900	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0
1100	0	0	0	0	0	1	1
1200	0	0	0	0	0	0	1
1300	0	0	0	0	0	1	1
1400	2	1	2	0	3	0	4
1500	0	1	1	0	0	0	0
1600	0	0	0	0	0	0	0
1700	0	0	0	1	0	0	0
1800	0	0	0	0	0	0	0
1900	0	0	0	0	0	2	0
2000	0	0	0	0	0	3	0
2100	0	0	0	0	0	15	1
2200	4	3	1	2	2	12	3

DEPARTURES							
HOUR	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0600	0	0	0	0	0	3	12
0700	0	0	0	0	0	0	9
0800	0	0	0	0	0	0	0
0900	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0
1100	0	0	0	0	0	0	0
1200	0	0	0	0	0	0	0
1300	0	0	0	0	0	0	0
1400	0	0	0	0	0	0	0
1500	0	0	0	0	0	0	0
1600	0	0	0	0	0	0	0
1700	0	0	0	0	0	0	0
1800	0	0	0	0	0	0	0
1900	0	0	0	0	0	0	0
2000	0	0	0	0	0	4	0
2100	8	1	1	0	0	12	0
2200	0	2	2	1	0	5	0

Source: Manager, Slot Coordination, Airport Coordination UK for Summer, 2001

IATA: Partial List of Badly Congested Airports (2014)

Region	IATA Code	Name	RUNWAYS Aircraft Movements	Growth Rate	Capacity limit reached	TERMINAL Passengers in Millions	Growth Rate	Capacity limit reached
Asia Pacific	CGK	Jakarta	398,985	4.9%	2021	60.1	4.1%	FULL
	HND	Tokyo Haneda	403,242	3.1%	2018	68.9	3.2%	2035
	BKK	Bangkok	301,747	-4.8%	2023	51.4	-3.1%	FULL
North Asia	PEK	Beijing	567,759	1.9%	2019	83.7	2.2%	FULL
	SHA	Shanghai	243,916	3.8%	2021	35.6	5.2%	2016
	HKG	Honk Kong	382,782	5.7%	2016	59.6	6.3%	FULL
Europe	AMS	Amsterdam	440,057	0.5%	2021	52.6	3.0%	2018
	IST	Istanbul	406,317	11.5%	2017	51.3	13.7%	2017
	LHR	London Heathrow	471,938	-0.7%	FULL	72.4	3.3%	2026
Latin America	BOG	Bogota	322,546	1.0%	2020	25.0	14.2%	FULL
	GRU	Sao Paulo	284,191	3.8%	2020	36.2	11.4%	2018
	MEX	Mexico	396,567	5.0%	2022	31.5	6.9%	2015
Middle East	DOH	Doha	205,744	7.7%	2026	23.4	9.8%	2018
	AUH	Abu Dhabi	135,213	11.2%	2023	16.5	12.4%	FULL
	DXB	Dubai	369,953	7.5%	2019	66.4	15.2%	2016
North America	YYZ	Toronto	431,323	-0.6%	2031	36.1	3.4%	2019
	EWR	Newark	419,850	1.4%	2018	35.0	2.9%	2031
	LGA	La Guardia	371,565	0.4%	2017	26.7	3.9%	2020

- Airports with full terminals: 90 in 2014; 223 in 2020
- Airports operating at 90% capacity of the runways: 6 in 2014; 63 in 2020
- Source: IATA (2014) *The Infrastructure Challenge,* courtesy of Joe Sulmona

Outline

- Variability of Demand
- Airside Capacity and Its Variability
  - Runway Systems
  - Taxiways and Aprons
  - Passenger Terminals
- Delays
  - Proper Measurement
  - Non-linearity
  - Landside vs. Airside
- Demand Management: Schedule Coordination
- **Demand Management: Market-Based Schemes**

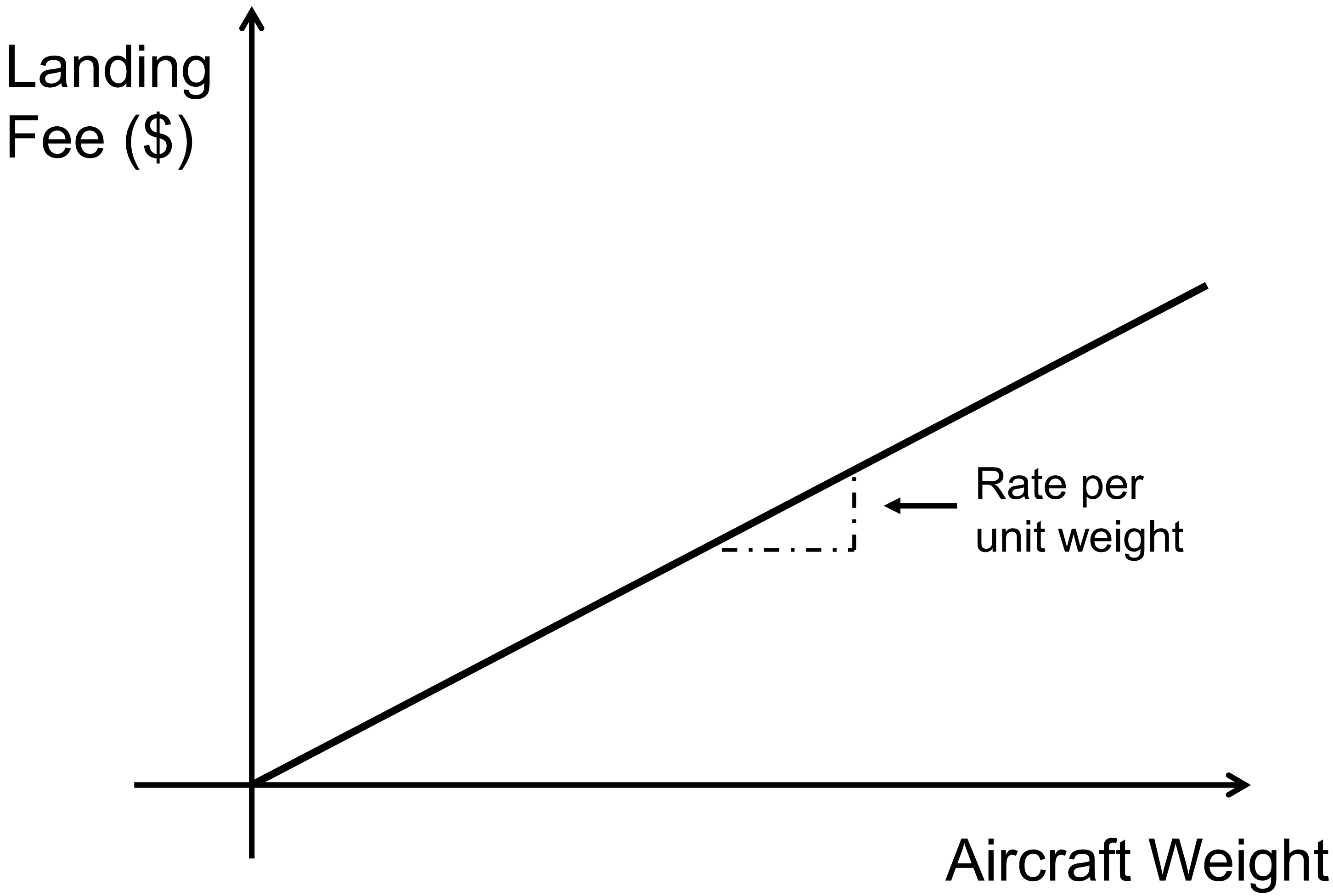
Outline

- Capacity of Runway Systems
- Capacity of Passenger Terminals
- Capacity of Taxiways and Aprons
- Delays: Non-linearity
- Demand Management: Schedule Coordination
- Demand Management: Market-Based Schemes

Criticisms of Slot Coordination

- Grandfathering allows no consideration of the economic value of a slot; an airline has no way of obtaining a slot to which it assigns high value
- By prioritizing punctuality, slot-coordinated airports may often be setting their declared capacity to smaller than optimum values, i.e., may be serving fewer than the optimum number of flights
- Heavy reliance on historical precedent in the allocation of slots and limitations on access by new entrants may inhibit competition
- May mask need for and economic value of additional capacity

Traditional Weight-Based Landing Fee



Congestion Pricing: A Key Observation

- The marginal congestion cost associated with an aircraft movement has 2 components:
  - Cost of delay to that movement (***internal*** cost)
  - Cost of additional delay to all other aircraft operators (***external*** cost)
    - At congested airports, this second component can be very large -- often much more than $1000 *per aircraft movement*

- *Congestion pricing aims at increasing the efficiency of resource utilization by forcing users to "internalize external costs" through the payment of a congestion toll*

Possible Forms of Congestion Pricing

Due to the many practical difficulties, the realistic possibilities for application of congestion pricing seem limited to charging *during peak periods*:

- A surcharge in addition to the weight-based landing fee
- A flat fee independent of aircraft weight (or variation thereof)
- A multiplier applied to the weight-based landing fee
- A landing fee equal to the larger of a specified minimum charge and of the weight-based landing fee

Landing Fees, BAA (2005)

	Heathrow		Gatwick		Stansted	
Aircraft weight (tons)	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak
MTOW ≤ 16	£ 590	£ 250	£ 385	£ 110	£ 95	£ 85
16<MTOW≤ 50	£ 590	£ 250	£ 385	£ 110	£ 142	£ 105
50 < MTOW	£ 590	£ 425	£385	£ 125	£ 231	£ 131
For MTOW > 250	£ 590	£ 425	£385	£ 125	£ 400	£ 400

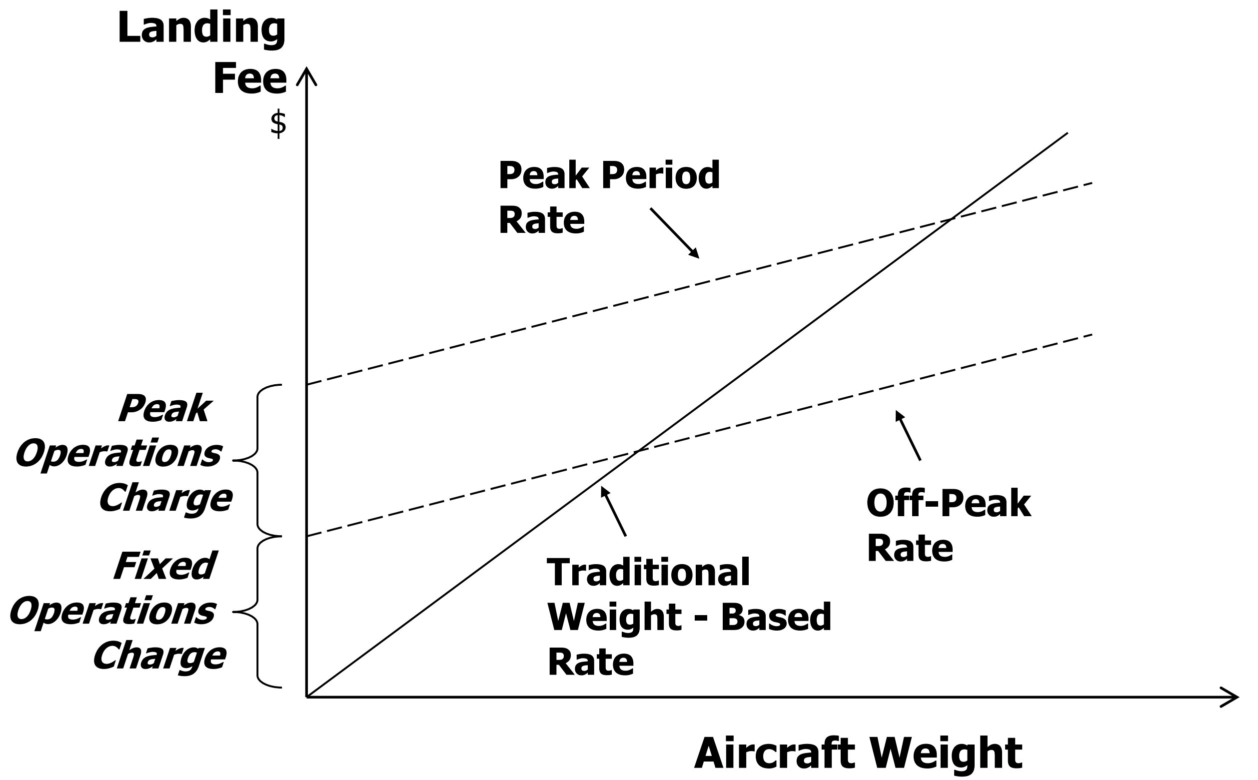
Apply to domestic and international flights

Note: “Peak” varies by airport (e.g., Heathrow peak: 07:00-9:59 and 17:00-18:59 GMT, April 1-Oct. 31)

Some Major Airport Fees, LHR (2015)

- Landing fee for Chapter 3 and 4 aircraft: £ 2,934 and £ 1,430, respectively, irrespective of weight. [*Note:* The fee is closely tied to "noise"; further adjustments are made for noise characteristics and for late night (00:30-03:30) operations.]
- Air navigation service fee: £ 80.53 + 1.08 per metric tonne of MTOW.
- Charge per departing passenger: £ 29.59 for European destinations; £ 41.54 for others.

Boston (1993): Proposed Landing Fee vs. Traditional Weight-Based Fee



Auctions

- A much-discussed approach for which there is no practical experience to date
- Possible Scenario:
  - Carriers submit sealed bids for any number of slots
  - All slots are auctioned simultaneously

- BUT: How to do this and address all the complexities remains an open question!

Complexity of Slot Auctions

- Value an airline derives from a slot depends on what other slots it obtains
  - Landings and takeoffs
  - Alternative times for a given flight
  - Slots for connecting flights
- Network effects are also important
  - A slot at a given time at airport A may be useless without a corresponding slot at airport B
- Hence, there is a *huge* number of combinations that each carrier may be interested in at *each* airport.
  - How does one prepare such bids and how does the auction administrator select the best bids?
- A follow-up market is also clearly needed to adjust auctioned slot allocations

Secondary Trading of Slots

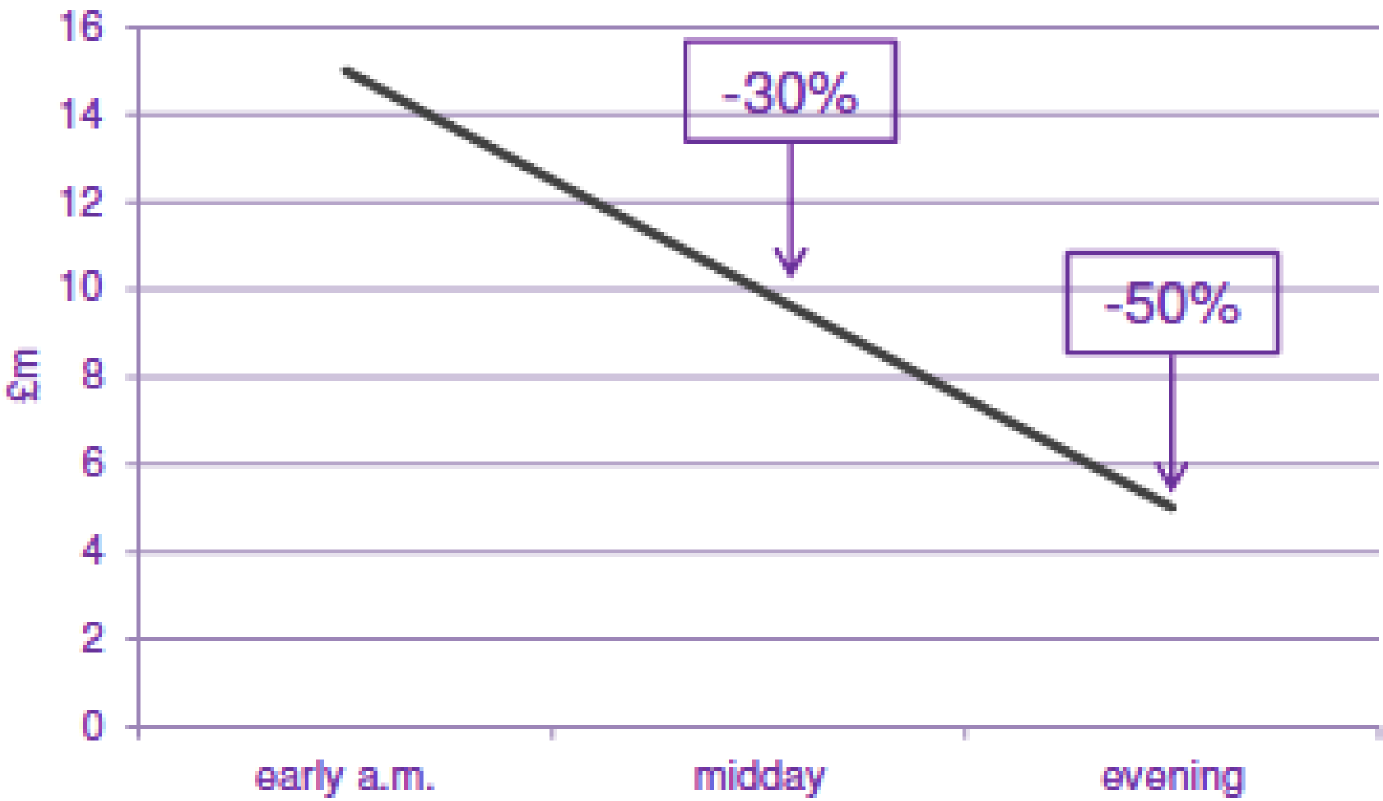
- Several countries now allow the trading of slots (purchasing, leasing) at Level 3 airports
- European Commission (2008): Leaves it up to Member States to permit or ban secondary trading of slots; such trading must "take place in a transparent manner".
- LHR rules:
  - The Coordinator must confirm feasibility of trade
  - Buyer purchases runway slot pair along with historical terminal and stand capacity (e.g., Code D aircraft with 150 seats in T3)
  - May "re-time" slot or change terminal subject to availability
  - Transactions are public, but price need not be disclosed
  - Once the slot has grandfather rights, it can be traded (must wait 2 years for new entrant slots)

Some Slot Prices from Secondary Trading

- Highest published price (until recently): $207 million for four daily pairs at LHR
- LHR: A non-daily slot pair may be worth up to £0.5 million for a single day
- LGA (New York) and DCA (Washington) slot pairs valued at about $5 million each
- Compensation may not be purely monetary (e.g., swap slots at other airports)
- Eligibility to acquire slots may be restricted
- February 2015: SAS sold two pairs of slots at LHR; a morning pair for $60 million and an afternoon pair for $22 million; now has 19 more available pairs at LHR

[Sources: Morrell, 2012; LHR Holdings, Ltd, 2012]

More on Slot Valuation



- Time of day is important; morning slots at LHR are the most valuable

[Sources: LHR Holdings, Ltd, 2012]

Future Trends: Demand Management

- Innovative slot allocation schemes with emphasis on more efficient use of slots (e.g., incentives for use of large aircraft, "specialized" airports with respect to traffic)

and/or

- Slot allocation schemes that include economic criteria and approaches:
  - Congestion pricing
  - Slot auctions
  - ("Secondary) slot trading

References

- de Neufville, R. and A. Odoni (2013) *Airport Systems: Planning, Design and Management*, 2nd Edition, McGraw-Hill Education. [Chapters 10, 11, 12, 15 and 16]
- ACRP – Airport Cooperative Research Program *Airport Passenger Terminal Planning and Design*, Report 25, vol. 1.
- ACRP – Airport Cooperative Research Program *Airport Passenger Terminal Planning and Design*, Report 25, vol. 2.

Questions? Comments?