Airport Capacity

CEE 4674 - Airport Planning and Design

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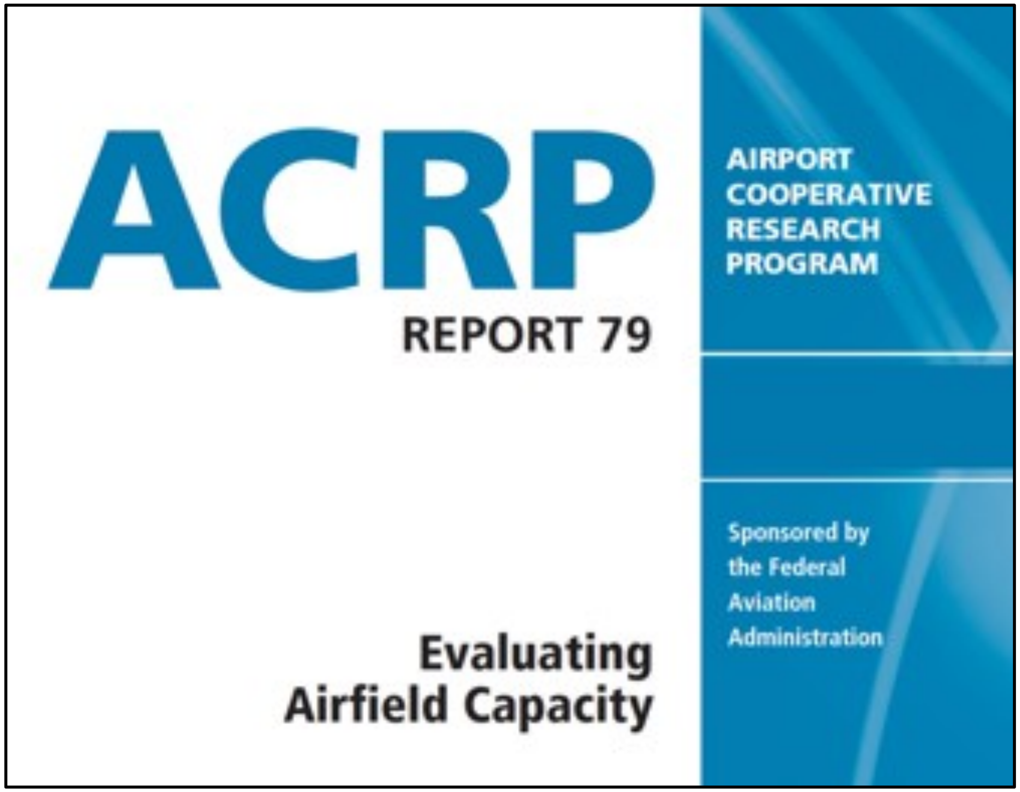
Fall 2023 (revisions)

Some References on this Topic

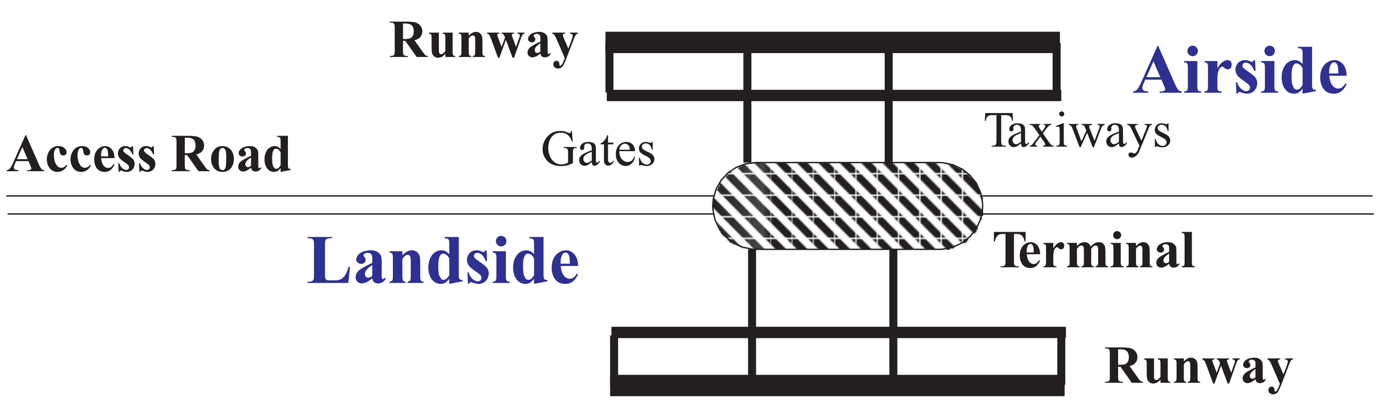


http://onlinepubs.trb.org/onlinepubs/acrp/acrp_rpt_079.pdf

- FAA, Airport Capacity http://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/22824
- Trani, A.A., Airport Capacity Notes http://128.173.204.63/courses/cee5614/cee5614_pub/Airport_capacity_intro_2012.pdf

Methodologies to Assess Airport Capacity

- The capacity of an airport is a complex issue.
- Several elements of the airport facility have to be examined.
  - Airside
  - Landside

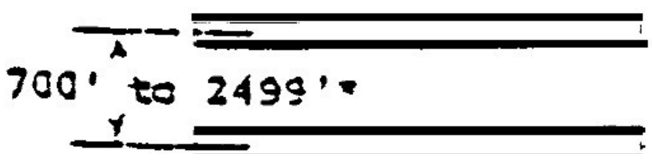


Methodologies to Study Airport Capacity/ Delay

- Analytic models
  - Easier and faster to execute
  - Good for preliminary airport/airspace planning (when demand function is uncertain)
  - Results are generally less accurate but appropriate
- Simulation-based models
  - Require more work to execute
  - Good for detailed assessment of existing facilities
  - Results are more accurate and microscopic in nature

Airfield Capacity

Airfield Capacity (AC 150/5060-5)

Runway-use Configuration	Mix Index %(C+3D)	Hourly Capacity Ops/Hr VFR	Hourly Capacity Ops/Hr IFR	Annual Service Volume Ops/Yr
	0 to 20	98	59	230,000
	21 to 50	74	57	195,000
	51 to 80	63	56	205,000
	81 to 120	55	53	210,000
	121 to 130	51	50	240,000
	0 to 20	197	59	355,000
	21 to 50	145	57	275,000
	51 to 80	121	56	260,000
	81 to 120	105	59	285,000
	121 to 180	94	60	340,000

Notes: Old data (1983)

Procedures have changed substantially (i.e., CRO, close parallel operations)

Time-Space Analysis

- A simple technique to assess runway and airspace capacity if the headway between aircraft is known
- The basic idea is to estimate an expected headway, *E(h)*, and then estimate capacity as the inverse of the expected headway

$$Capacity = {}^{1}/_{E(h)} \qquad (1)$$

$E(h)$ is expressed in time units (e.g., seconds)

Time-Space Analysis Nomenclature

δ_{ij} is the minimum separation matrix (nm)

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

δ is the minimum arrival-departure separation (nm)

ROT_i is the runway occupancy time for aircraft i (s)

σ_0 is the standard deviation of the in-trail delivery error (s)

V_i is the speed of aircraft *i* (lead aircraft) in knots

Time-Space Analysis Nomenclature

V_j is the trailing aircraft speed (knots)

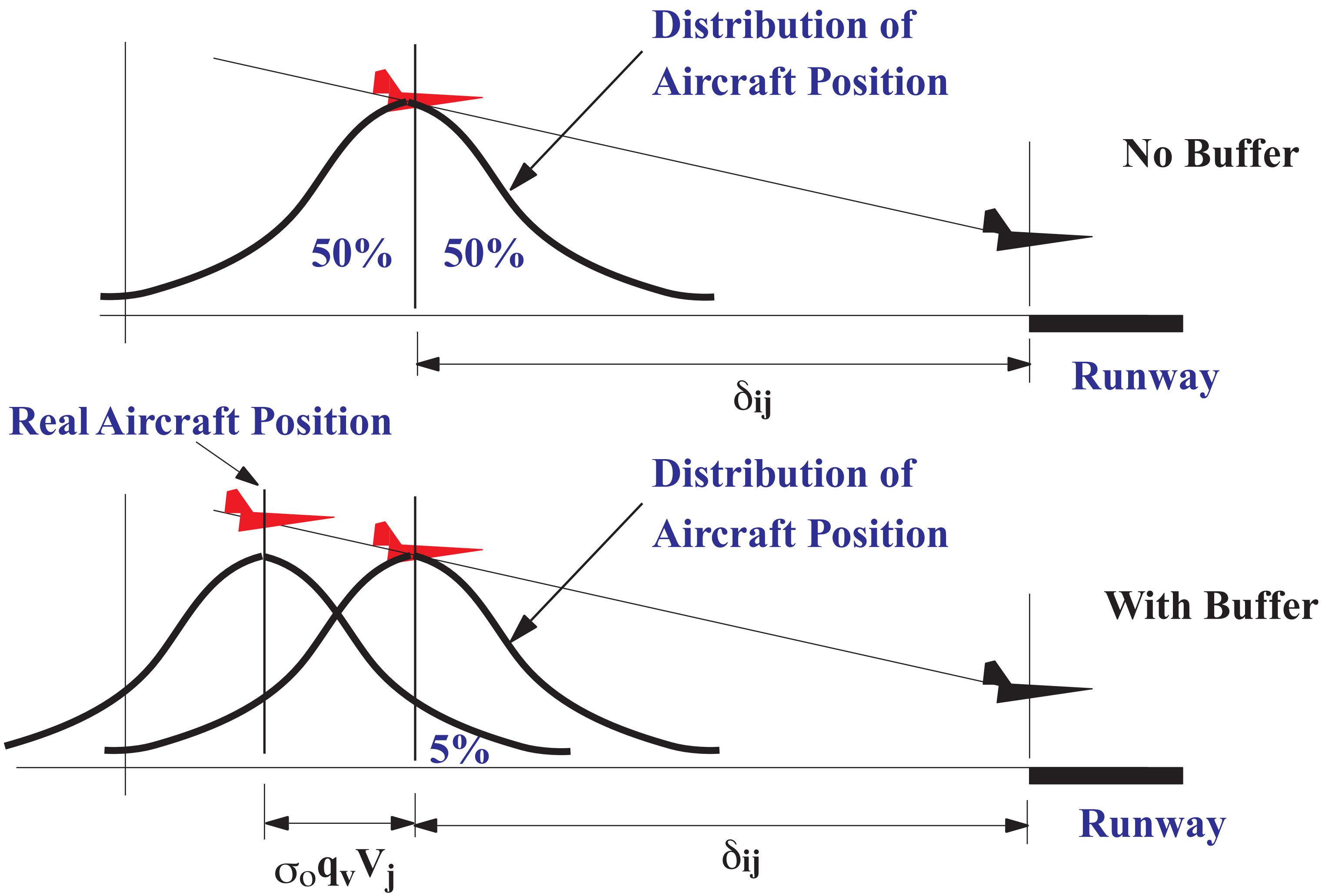
γ is the common approach length (nm)

B_{ij} is the buffer times matrix between successive aircraft (s)

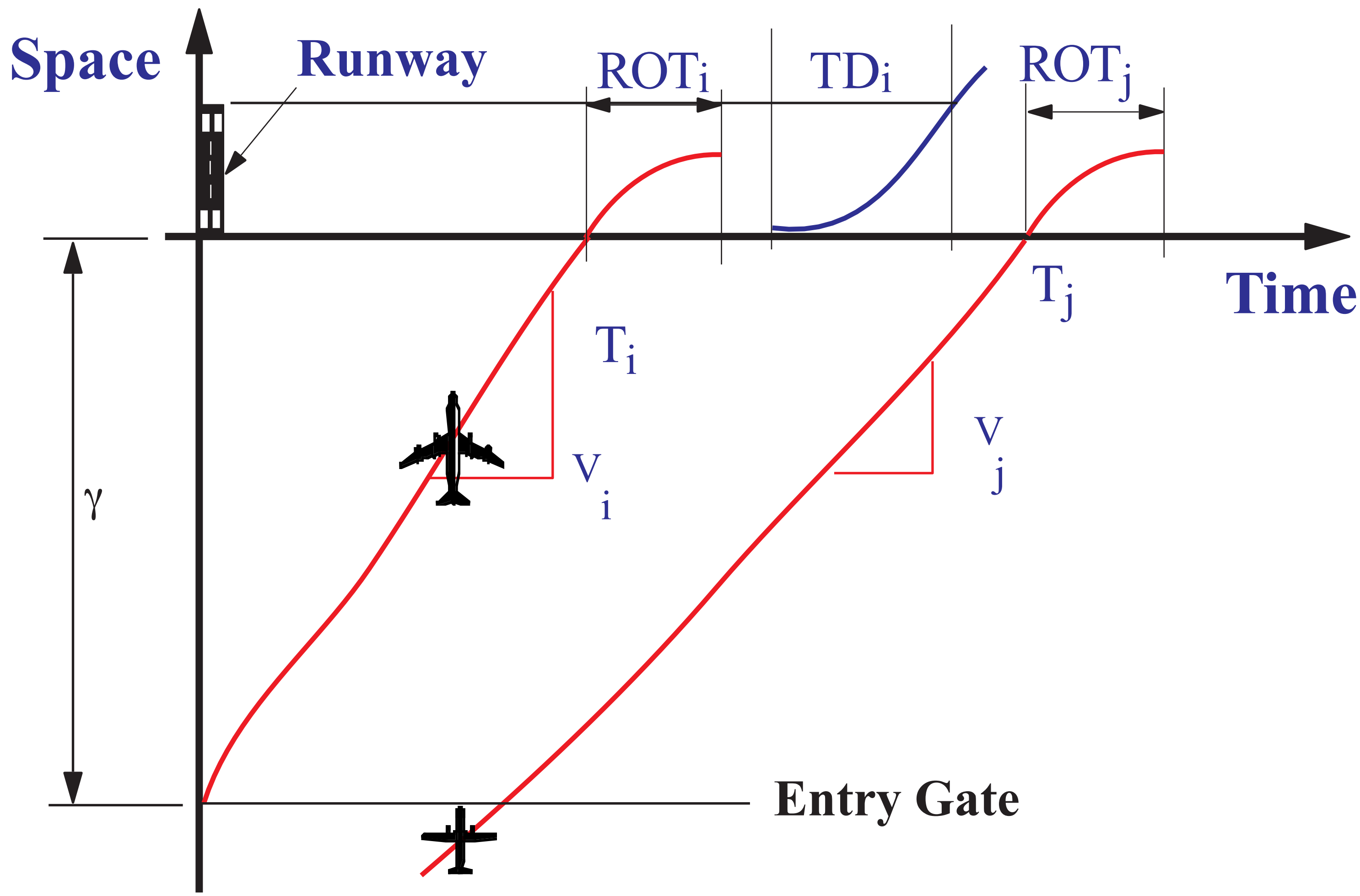
q_v is the value of the cumulative standard normal at probability of violation p_v

p_v is the probability of violation of the minimum separation criteria between two aircraft

Understanding Technical Position Errors



Approach and Landing Processes in Time-Space Diagram



Possible Outcomes of a Single Runway Time-Space Diagram

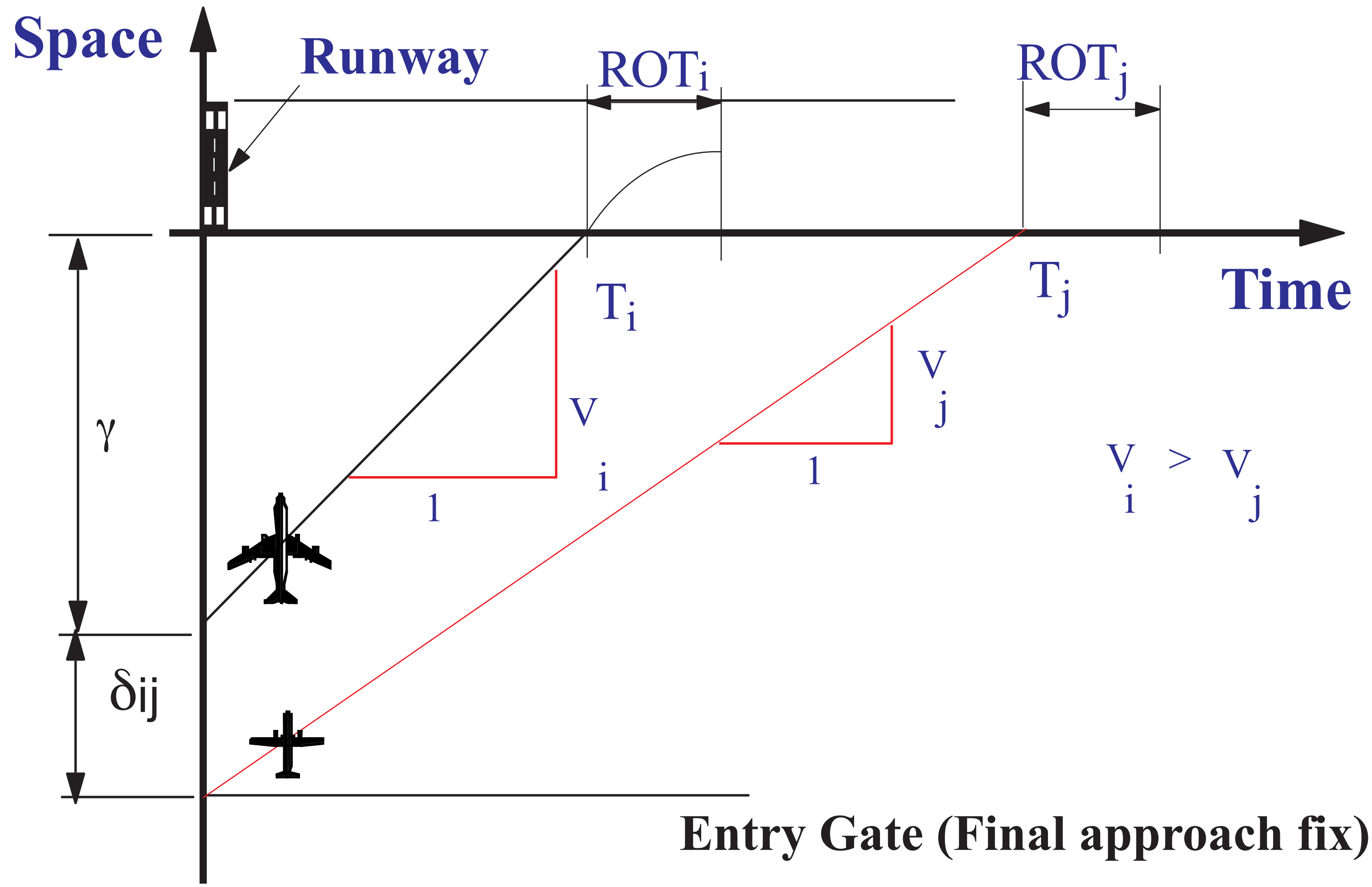
Aircraft approaching a runway arrive in a random pattern

Aircraft have different approach speeds

Two possible scenarios are observed:

- Opening Case - Instance when the approach speed of lead aircraft is higher than trailing aircraft ($V_i > V_j$)
- Closing case - Instance when the approach of the lead aircraft is less than that of the trailing aircraft ($V_i \leq V_j$)

Opening Case Diagram (Arrivals Only)



Opening Case (Equations)

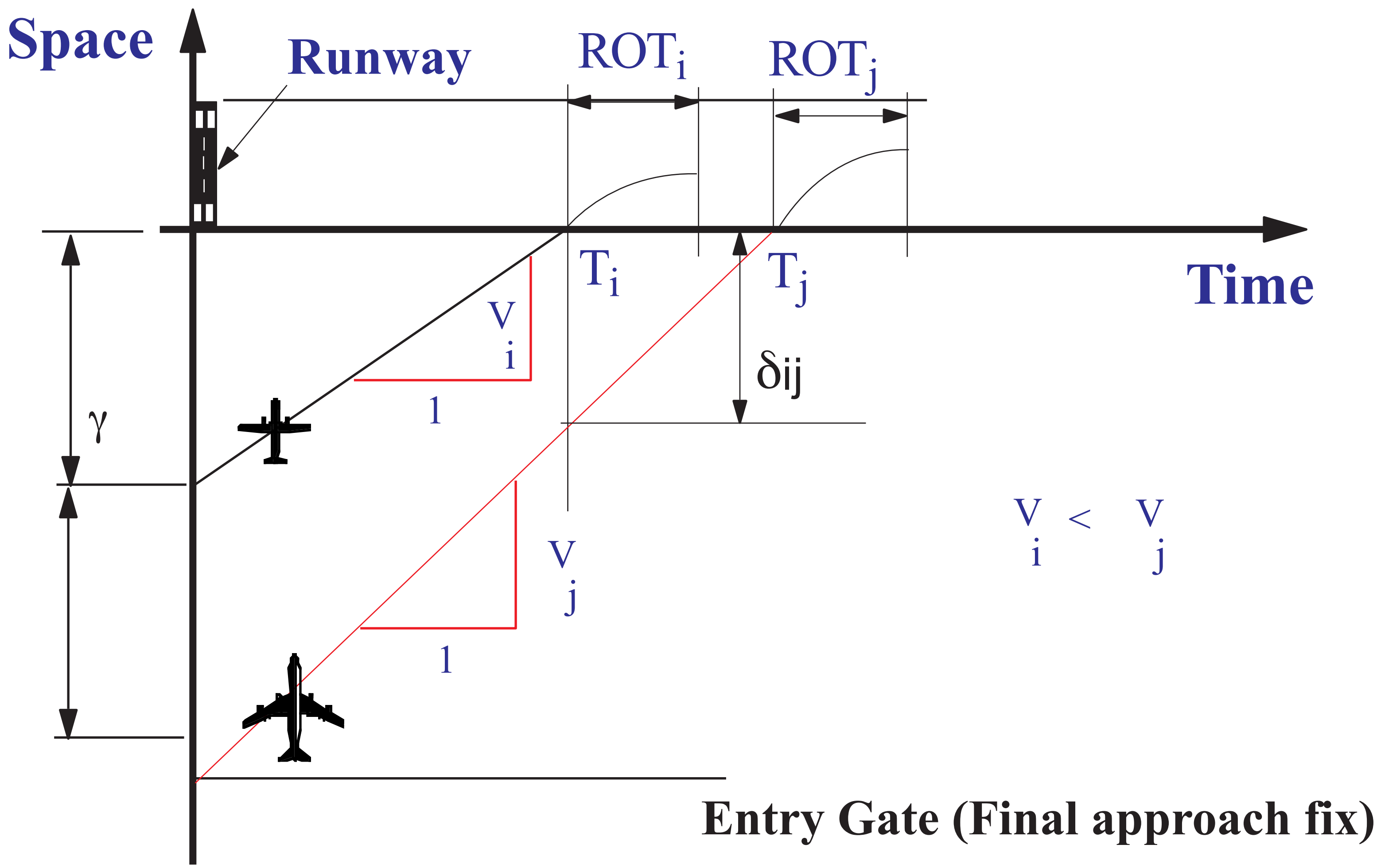
Error free headway, $T_{ij} = T_j - T_i$, (no pilot and ATC controller error) assuming control is exercised as the lead aircraft passes the entry gate,

$$T_{ij} = \frac{\delta^{ij}}{V_j} + \gamma\left(\frac{1}{V_j} - \frac{1}{V_i}\right) \tag{2}$$

Position error buffer time (with pilot and ATC controller error)

$$B_{ij} = \sigma_o q_v - \delta_{ij}\left(\frac{1}{V_j} - \frac{1}{V_i}\right) \text{ or zero if } B_{ij} < 0. \tag{3}$$

Closing Case Diagram (Arrivals Only)



Closing Case (Equations)

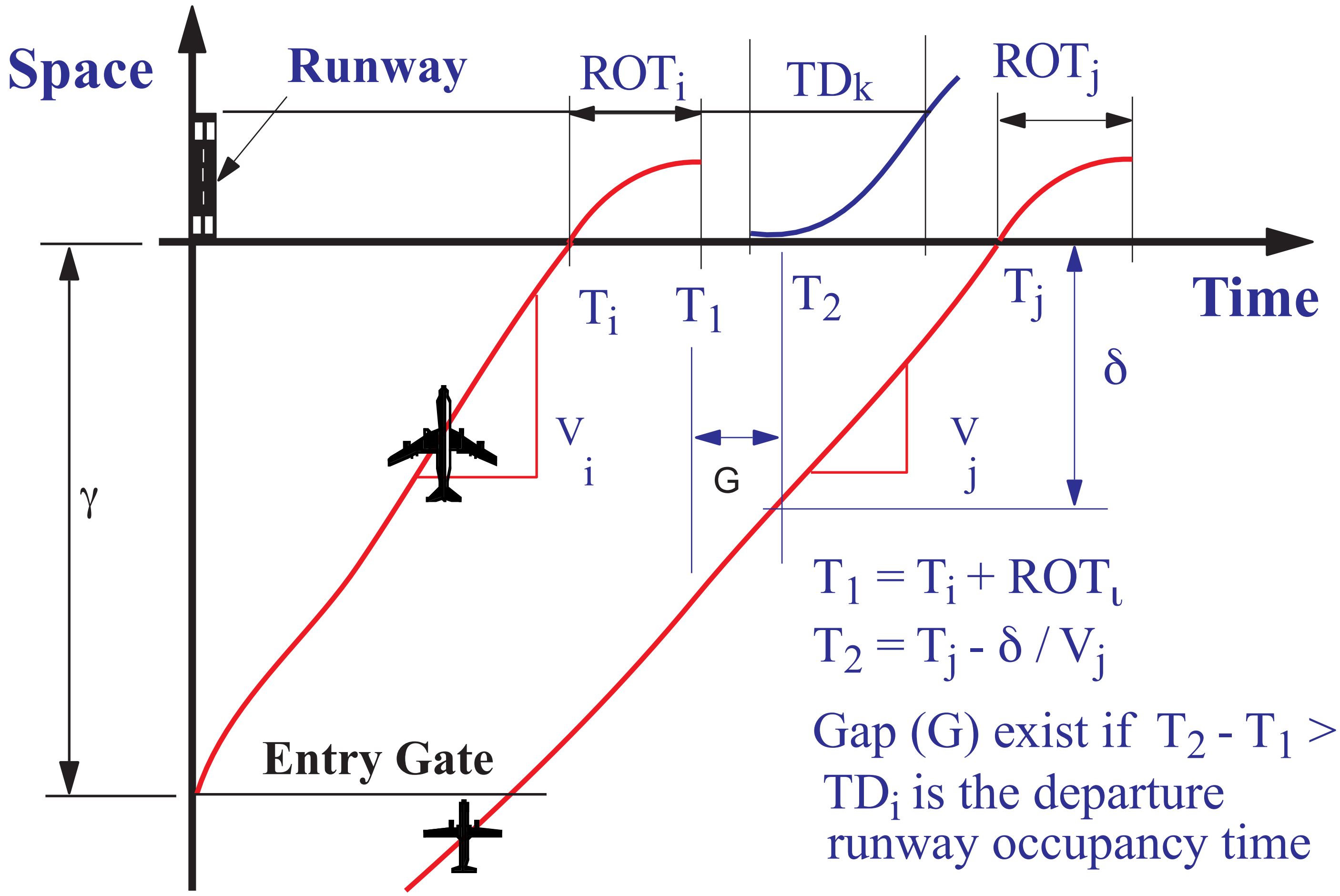
Error free headway, $T_{ij} = T_j - T_i$ (no pilot and ATC controller error) with the minimum separation enforced when the lead aircraft passes the runway threshold,

$$T_{ij} = \frac{\delta_{ij}}{V_j} \tag{4}$$

Position error buffer time (with pilot and ATC controller error) is,

$$B_{ij} = \sigma_o q_v \tag{5}$$

Mixed Runway Operations Diagram



$T_1 = T_i + ROT_i$

$T_2 = T_j - \delta / V_j$

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

TD_i is the departure runway occupancy time

$$E[T_{ij} + B_{ij}] = E[\delta / V_j] + E[ROT_i] + (n\text{-}1)\, E(TD_k) + E(\tau)$$

Mixed Runway Operations Notes

- The arriving aircraft leave natural gaps in the time space diagram
- When gaps (*G*) are long, ATC controllers can schedule one or more departures in the gap
- The size of the gaps depends on:
  - Runway occupancy time (for lead aircraft)
  - Runway occupancy time for departing aircraft
  - Minimum departure-departure headway (seconds)
  - Minimum arrival-departure separation (δ)

Example of Departure-Arrival Separation (δ)

Boeing 737-300 starts takeoff roll at time = 0
Picture taken at time ~ 18 seconds into the takeoff roll

Embraer 175 crosses the runway threshold ~40 seconds after Boeing 737-300 started its takeoff roll

Embraer 175 typical approach speed is 124 knots (see Appendix 1 of FAA AC 150/5300-13a)

Distance to threshold to cover 40 seconds is: 1.4 nautical miles!

source: A.A. Trani

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

Mixed Runway Operations (Gap Analysis)

- In the U.S. the current minimum separation between arrivals and departures (δ) is 2 nautical miles

Define:

- T_1 as the time when the lead aircraft completes the landing roll (i.e., exits the runway plane)
- T_2 as the time when the following arriving aircraft is (δ) from the runway threshold
- The gap (G) is the time difference between T_2 and T_1.

$$G = T_2 - T_1 \quad (6)$$

Mixed Runway Operations (Gap Analysis)

Note that,

$$T_1 = T_i + ROT_i \tag{7}$$

and

$$T_2 = T_j - \frac{\delta}{V_j} \tag{8}$$

then

$$G = T_j - \frac{\delta}{V_j} - (T_i + ROT_i) \tag{9}$$

Mixed Runway Operations (Gap Analysis)

$$G = (T_j - T_i) - \frac{\delta}{V_j} - ROT_i \qquad (10)$$

- Note that, $(T_j - T_i)$ is the actual headway between the lead and following aircraft $(T_{ij} + B_{ij})$.
- This actual headway includes the buffer times since air traffic control will apply those buffers to each successive arrival pair.
- Our analysis focuses in finding suitable gaps between successive aircraft arrivals.

Gap Analysis

Assume that we would like to find instances such that the gap is zero. This is the limiting case to schedule one departure between successive arrivals.

$$0 = (T_j - T_i) - \frac{\delta}{V_j} - ROT_i \tag{11}$$

knowing

$$0 = (T_{ij} + B_{ij}) - \frac{\delta}{V_j} - ROT_i \tag{12}$$

Mixed Runway Operations (Gap Analysis)

$$(T_{ij} + B_{ij}) = \frac{\delta}{V_j} + ROT_i \quad (13)$$

For n departures in gap k the expected value of $T_{ij} + B_{ij}$ has to be longer than:

$$(T_{ij} + B_{ij}) = \frac{\delta}{V_j} + ROT_i + (n-1)TD_k \quad (14)$$

where TD_k is the runway occupancy time of departure k.

Finding Departure Occupancy Time TD_k

- In VFR conditions:
- Air traffic controllers can dispatch aircraft as soon as the previous departure clears the runway while still enforcing wake turbulence criteria
- Under IMC conditions, the runway occupancy time for a departing aircraft TD_k is smaller than the minimum headway allowed between departures. This happens because under IMC conditions aircraft are expected to follow a prescribed climb procedure and usually navigate to a departure fix before changing heading.
- Let ε_{ij} be the minimum departure-departure headway applied by air traffic control. Equation (14) can then be modified to estimate the availability of a gap to release n departures.

Gap Analysis

$$(T_{ij} + B_{ij}) = \frac{\delta}{V_j} + ROT_i + (n-1)\varepsilon_{ij} \qquad (15)$$

- One final term usually added to this equation is a pilot reaction time term to account for a possible delay time (departing aircraft) to initiate the takeoff roll. This time is justified because jet engines used in transport aircraft take a few seconds to "spool up" and generate full thrust. Let τ be the time delay (in seconds) for the departing aircraft.

Gap Analysis (Adding Pilot/ATC Time Delays)

Adding the pilot/ATC controller time delay term Equation (14) becomes,

$$(T_{ij} + B_{ij}) = \frac{\delta}{V_j} + ROT_i + (n-1)\varepsilon_{ij} + \tau \qquad (16)$$

Since $(T_{ij} + B_{ij})$ is calculated as an expected value in the analysis for arrivals only,

$$E(T_{ij} + B_{ij}) \geq E\left(\frac{\delta}{V_j}\right) + E(ROT_i) + \qquad (17)$$

$$(n-1)E(\varepsilon_{ij}) + E(\tau)$$

Consolidated Wake Turbulence Recategorization Classification (CWT)

- FAA Introduced a **consolidated wake re-categorization in 2019**
- FAA Order JO 7110.126B

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

Air Traffic Organization Policy

ORDER
JO 7110.126B

Effective Date:
November 9, 2021

SUBJ: Consolidated Wake Turbulence (CWT)

1. **Purpose of This Order**. This order provides procedural guidance to FAA Order JO 7110.65, Air Traffic Control, related to the use of Consolidated Wake Turbulence procedures and separation minima.

Consolidated Wake Turbulence Recategorization Classification (CWT)

Defines nine wake classes including pairwise classes

Appendix A
Aircraft Wake Categories

Category A – A388 and A225.

Category B – Pairwise Upper Heavy aircraft.

Category C – Pairwise Lower Heavy aircraft

Category D – Non-Pairwise Heavy aircraft.

Category E – B757 aircraft.

Category F – Upper Large aircraft excluding B757 aircraft.

Category G – Lower Large aircraft.

Category H – Upper Small aircraft with a maximum takeoff weight of more than 15,400 pounds up to 41,000 pounds.

Category I – Lower Small aircraft with a maximum takeoff weight of 15,400 pounds or less.

Source: FAA Order JO 7110.126B

Consolidated Wake Turbulence Recategorization Classification (CWT)

Defines nine wake classes including pairwise classes

Category	Description
A	A388
B	Pairwise Upper Heavy aircraft
C	Pairwise Lower Heavy aircraft
D	Non-Pairwise Heavy aircraft
E	B757 aircraft
F	Upper Large aircraft excluding B757 aircraft
G	Lower Large aircraft
H	Upper Small aircraft with a maximum takeoff weight of more than 15,400 pounds up to 41,000 pounds
I	Lower Small aircraft with a maximum takeoff weight of 15,400 pounds or less

Source: FAA Order JO 7110.126B

Consolidated Wake Turbulence Recategorization Classification (CWT)

Aircraft Types Categorized

A Super	B Upper Heavy	C Lower Heavy	D Non-Pairwise Heavy		E B757	F Upper Large		G Lower Large		H Upper Small	I Lower Small
A388	A332	A306	A124	DC85	B752	A318	C130	AT43	E170	ASTR	BE10
A225	A333	A30B	A339	DC86	B753	A319	C30J	AT72	E45X	B190	BE20
	A343	A310	A342	DC87		A320	CVLT	CL60	E75L	BE40	BE58
	A345	B762	A3ST	E3CF		A321	DC93	CRJ1	E75S	B350	BE99
	A346	B763	A400	E3TF		B712	DC95	CRJ2	F16	C560	C208
	A359	B764	A50	E6		B721	DH8D	CRJ7	F18H	C56X	C210
	B742	C17	AN22	E767		B722	E190	CRJ9	F18S	C680	C25A
	B744	DC10	B1	IL62		B732	GL5T	CRJX	F900	C750	C25B
	B748	K35R	B2	IL76		B733	GLEX	DC91	FA7X	CL30	C402
	B772	MD11	B52	IL86		B734	GLF5	DH8A	GLF2	E120	C441
	B773		B703	IL96		B735	GLF6	DH8B	GLF3	F2TH	C525
	B77L		B741	K35E		B736	MD82	DH8C	GLF4	FA50	C550
	B77W		B743	KE3		B737	MD83	E135	SB20	GALX	P180
	B788		B74D	L101		B738	MD87	E145	SF34	H25B	PAY2
	B789		B74R	MYA4		B739	MD88			LJ31	PA31
	C5		B74S	R135			MD90			LJ35	PC12
	C5M		B78X	T144						LJ45	SR22

Source: FAA Order JO 7110.126B

Consolidated Wake Turbulence Classification

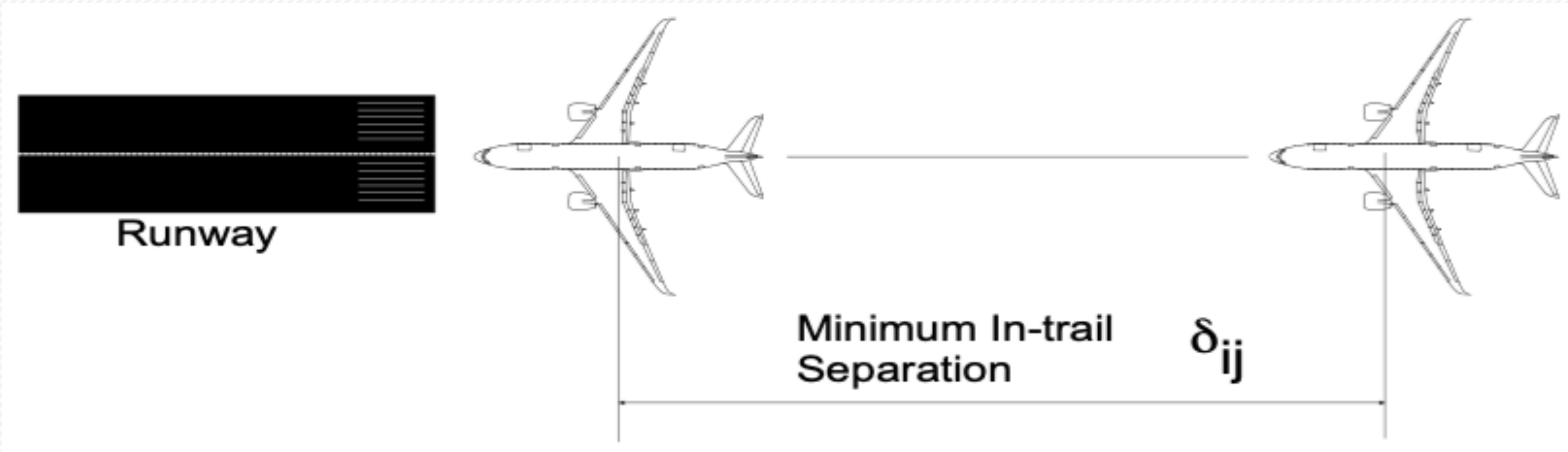
Class	Representative Aircraft	Picture of Representative Aircraft
A	Airbus A380-800	
B	Boeing 747-400, Boeing 777-300ER, Airbus A330-300, Airbus A350-900, Airbus A300-600, Boeing 787-8/9	
C	McDonnell Douglas DC-10, Boeing MD-10, Boeing Douglas MD-11, Boeing 767-300	
E	Boeing 757-200 and -300	
F	,Boeing 737-800, Airbus A320, Airbus A321, McDonnell Douglas MD-80, Embraer 190, Bombardier CS-300, Gulfstream 550 and 650	

Consolidated Wake Turbulence Classification

Class	Representative Aircraft	Picture of Representative Aircraft
G	Regional Jets and Large Corporate Jets Bombardier CRJ-900, Embraer 170/175, Bombardier CRJ-700, Embraer 145, Bombardier CRJ-200, Dassault Falcon 7X	
H	Large turboprops and Mid-Size Corporate Jets Beechcraft King Air B350, Bombardier Challenger 300, Falcon 50, Cessna Citation 750, cessna Latitude (C680A)	
I	Small aircraft (Single and Multi-engine Piston) and Small Corporate Jets Cessna CitationJet 3, Cessna 182, Cessna 172, Pilatus PC12, cessna 421, Cessnq 310	

In-Trail Arrival-Arrival Separation Rules under CWT Standards

IMC Conditions **Airport Surveillance Radar and ADS-B Available**



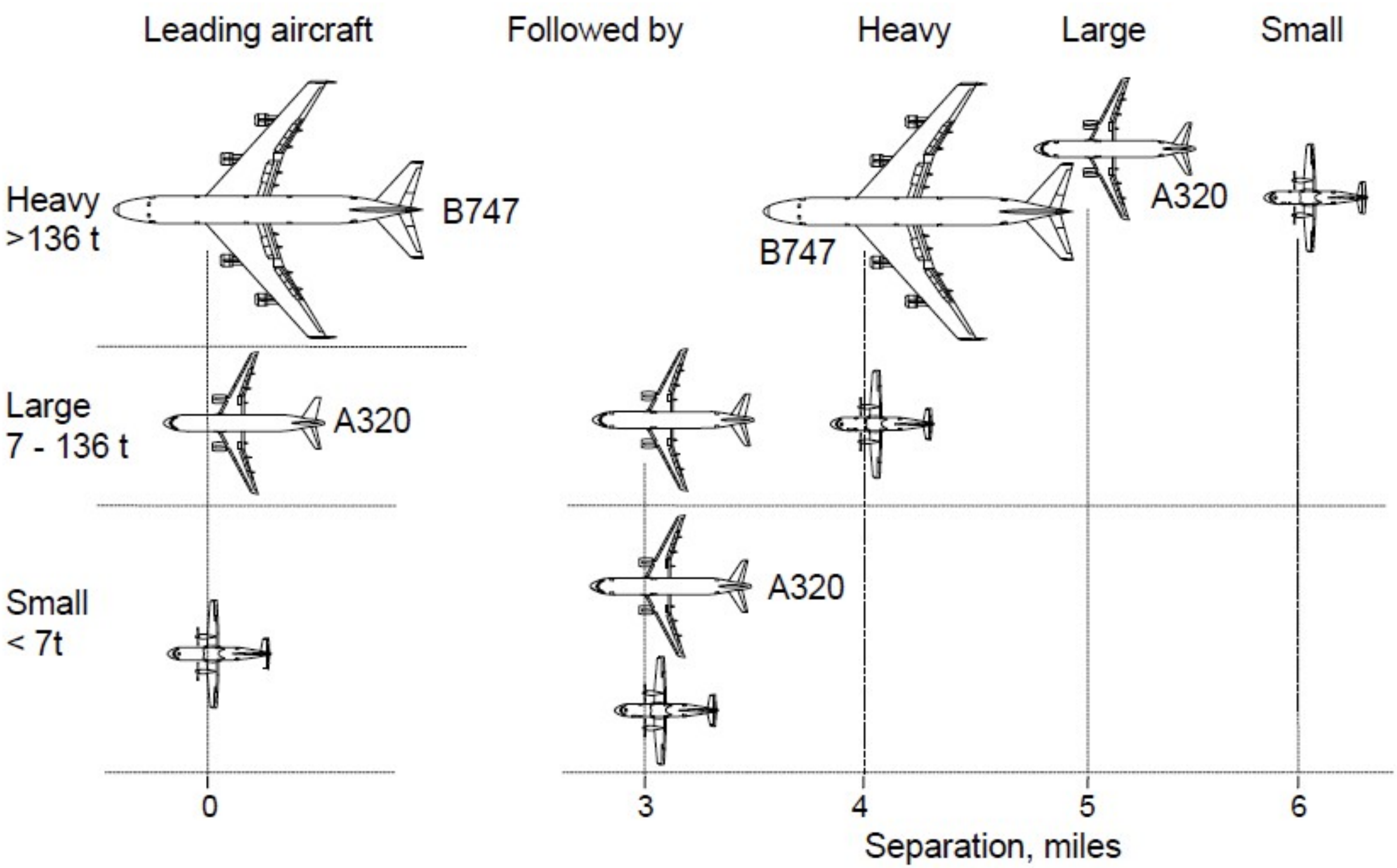
		FOLLOWER								
		A	B	C	D	E	F	G	H	I
LEADER	A		5 NM	6 NM	6 NM	7 NM	7 NM	7 NM	8 NM	8 NM
	B		3 NM	4 NM	4 NM	5 NM	5 NM	5 NM	5 NM	5 NM
	C					3.5 NM	3.5 NM	3.5 NM	5 NM	5 NM
	D		3 NM	4 NM	4 NM	5 NM	5 NM	5 NM	5 NM	5 NM
	E									4 NM
	F									
	G									
	H									
	I									

Empty cells values are Minimum Radar Separations (MRS) - 3nautical miles

Runways that meet an average Runway Occupancy Time < 50 seconds can reduce MRS to 2.5 nm

Source: FAA Order JO 7110.126B

Typical In-Trail Wake Airspace Separations IMC Conditions (ICAO)



Lang, Eriksen and Tittsworth, WakeNet 3 Europe, 2010

Legacy Aircraft Wake Groups

Aircraft Group	Maximum Takeoff Weight (lb)	Sample Aircraft
Superheavy	>1,000,000	Airbus A380-800
Heavy	255,000 to 1e6	Boeing 747-8, Airbus A340-600, Airbus A330-300, Boeing 767-300
B757	255,000	Boeing 757-300 and Boeing 757-200
Large	> 41,000 and < 255,000	Boeing 737-700, Airbus A320-200, Embraer E175, Bombardier CRJ-900, etc.
Small	<41,000	All single and multi-engine piston aircraft, single engine turboprops and small light business jets

Visual Meteorological Condition Separations

- Under visual meteorological conditions, pilots are expected to be responsible for separations
- Data collected at airfields in the United States indicates that VMC separations are 10-15% below those observed under IMC conditions
- Therefore:
  - Runways have more capacity under VMC conditions for the same fleet mix
  - Higher runway utilization is possible under VMC conditions
  - Runway occupancy times and VMC airspace separations are closer in magnitude

Typical Air Traffic Control Departure-Departure Separations

Same runway departure separations (see JO 7110.126B) - Section 3-9-6

Lead Aircraft	Trailing Aircraft								
	A	B	C	D	E	F	G	H	I
A	120	180	180	180	180	180	180	180	180
B	120	120	120	120	120	120	120	120	120
C	120	120	120	120	120	120	120	120	120
D	120	120	120	120	120	120	120	120	120
E	60	60	60	60	60	60	60	60	120
F	60	60	60	60	60	60	60	60	60
G	60	60	60	60	60	60	60	60	60
H	60	60	60	60	60	60	60	60	60
I	60	60	60	60	60	60	60	60	60

Minimum Separations are in seconds

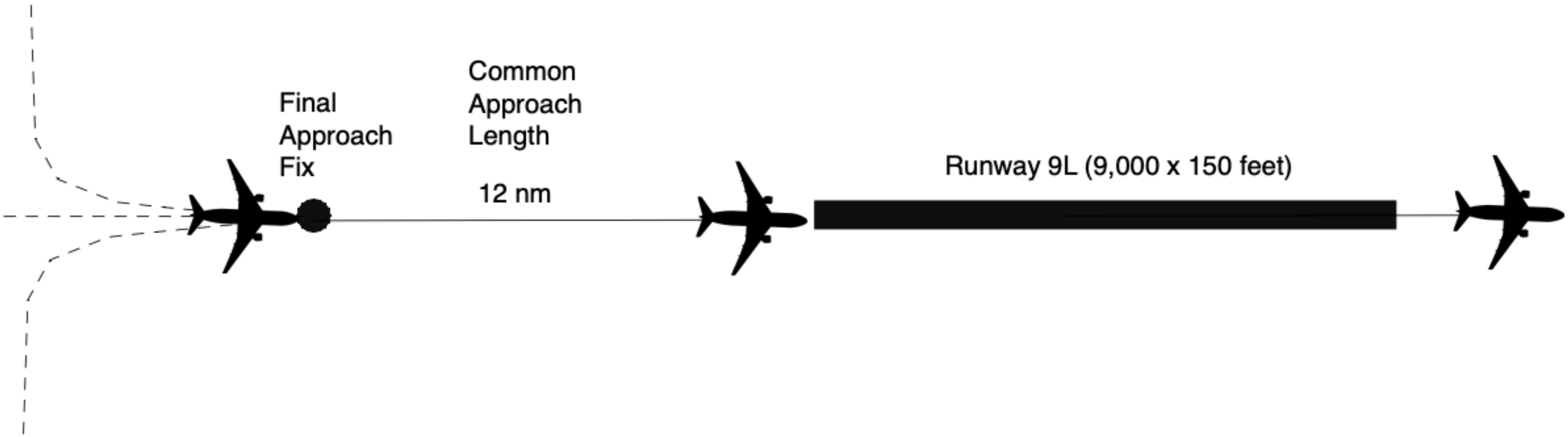
Legacy Departure-Departure In-Trail Separations

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

Lead Aircraft	Trailing Aircraft				
	Superheavy	Heavy	B757	Large	Small
Superheavy	120	180	180	180	180
Heavy	120	120	120	120	120
B757	120	120	120	120	120
Large	60	60	60	60	60
Small	60	60	60	60	60

Departure-departure separations are in seconds

Example Problem
Single Runway Airport



Objectives:

1) Find arrivals-only runway capacity
2) Find departures-only runway capacity
3) Find mixed operations runway capacity (departures with 100% arrival priority)
4) Construct an arrival-departure diagram (Pareto diagram)

Problem Definition and Technical Parameters

Determine the saturation capacity of an airport serving three groups of aircraft provided in the table below.

- Assume radar surveillance is available with 20 seconds for the standard deviation of in-trail delivery accuracy error and a probability of violation of 5%.
- Assume the common approach length γ to be 12 miles.
- Use the latest CWT arrival-arrival separation criteria
- Use the CWT departure-departure separation criteria

Aircraft CWT Group	Percent Mix (%)	Runway Occupancy Time (s)	Typical Approach Speed (knots) from FAF
F	82	51	132
E	10	54	137
B	8	65	151
Totals	100		

FAF - Final Approach Fix

Select the CWT Arrival-Arrival Separations

LEADER \ FOLLOWER	A	B	C	D	E	F	G	H	I
A		5 NM	6 NM	6 NM	7 NM	7 NM	7 NM	8 NM	8 NM
B		3 NM	4 NM	4 NM	5 NM	5 NM	5 NM	5 NM	5 NM
C					3.5 NM	3.5 NM	3.5 NM	5 NM	5 NM
D		3 NM	4 NM	4 NM	5 NM	5 NM	5 NM	5 NM	5 NM
E									4 NM
F									
G									
H									
I									

δ_{ij}

Minimum arrival-arrival separation matrix

Lead Aircraft	Trailing Aircraft		
	B	E	F
B	3	5	5
E	3	3	3
F	3	3	3

ROT values are greater than 50 seconds
Use 3 nautical mile minimum in-trail separation

Minimum Separations are in nautical miles

Select the CWT Departure-Departure Separations

Lead Aircraft	Trailing Aircraft								
	A	B	C	D	E	F	G	H	I
A	120	180	180	180	180	180	180	180	180
B	120	120	120	120	120	120	120	120	120
C	120	120	120	120	120	120	120	120	120
D	120	120	120	120	120	120	120	120	120
E	60	60	60	60	60	60	60	60	120
F	60	60	60	60	60	60	60	60	60
G	60	60	60	60	60	60	60	60	60
H	60	60	60	60	60	60	60	60	60
I	60	60	60	60	60	60	60	60	60

CWT minimum Separations are in seconds
No buffers included

ϵ_{ij}

Minimum departure-departure separation matrix

Lead Aircraft	Trailing Aircraft		
	B	E	F
B	120	120	120
E	60	60	60
F	60	60	60

Minimum departure separations are in seconds
No buffers included

Determine Aircraft Mix and Probabilities

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

Table 1. Probability Matrix (P_{ij}). Aircraft (i) follows aircraft (j).

	Trailing Aircraft (Header Columns)		
Lead (column 1)	F	E	B
F	0.672	0.082	0.066
E	0.082	0.010	0.008
B	0.066	0.008	0.006

Example:
Group F (lead) and Group F (follower)
0.82 x 0.82 = 0.672

Example:
Group F (lead) and Group B (follower)
0.82 x 0.08 = 0.066

Note: verify that $\sum P_{ij} = 1.0$

Compute Headways Between Successive Arrivals

V_F = 132 knots

V_B = 151 knots

Closing case:

Lead = F , Following = B

$$T_{F-B} = \frac{\delta_{F-B}}{V_B} = \frac{3}{151} = 0.0199 \text{ hours}$$

Usually is convenient to express headway in seconds.

$$T_{F-B} = \frac{\delta_{F-B}}{V_B} = \frac{3}{151} 3600 = 71.5 \text{ seconds}$$

Closing Case (apply this case when speeds are the same)

Closing case:

Lead = F , Following = F

V_F = 132 knots

$$T_{F-F} = \frac{\delta_{F-F}}{V_F} = \frac{3}{132} = 0.0227 \text{ hours}$$

Usually is convenient to express headway in seconds.

$$T_{F-F} = \frac{\delta_{F-F}}{V_F} = \frac{3}{132} 3600 = 81.8 \text{ seconds}$$

Opening Case (Lead is Faster)

Lead = B , Following = F

V_F = 132 knots

V_B = 151 knots

$$T_{B-F} = \frac{\delta_{B-F}}{V_F} + \gamma\left(\frac{1}{V_F} - \frac{1}{V_B}\right) \text{ seconds}$$

$$T_{B-F} = \frac{5}{132} + 12\left[\frac{1}{132} - \frac{1}{151}\right]$$

$$T_{B-F} = 177.5 \text{ seconds}$$

Arrival-Arrival Headway Table (No Buffers)

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

Table 2. Error-Free headways (in seconds) when aircraft (i) follows aircraft (j).

	Trailing Aircraft (Header Columns)		
Lead (column 1)	F	E	B
F	82	79	72
E	94	79	72
B	178	161	72

Values in seconds

Compute the Expected Value of Headway

The expected value of the headway is:

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

	Trailing Aircraft (Header Columns)		
Lead (column 1)	F	E	B
F	82	79	72
E	94	79	72
B	178	161	72

	Trailing Aircraft (Header Columns)		
Lead (column 1)	F	E	B
F	0.672	0.082	0.066
E	0.082	0.010	0.008
B	0.066	0.008	0.006

$$E(T_{ij}) = 82(0.672)+79(0.082)+72(0.066) + 94(0.082) + 79(0.01)$$

$$+72(0.008) + 178(0.066) + 161(0.008) + 72(0.006)$$

$$E(T_{ij}) = 88.61 \text{ seconds}$$

No ATC in-trail separation buffers included

Buffer Time Calculations

V_F = 132 knots

V_B = 151 knots

- **Opening case calculation example**

$$Bij = max(0,\sigma_0 q_v - \delta_{B-F}(\frac{1}{V_F} - \frac{1}{V_B}))$$

$$B_{B-F} = max(0,20(1.65) - 5(\frac{1}{132} - \frac{1}{151})3600)$$

$$B_{B-F} = max(0,15.84) = 15.84$$

Buffer Time Calculations

$$Bij = \sigma_0 q_v$$

Closing case

$$Bij = max(0, \sigma_0 q_v - \delta_{B-F}(\frac{1}{V_F} - \frac{1}{V_B}))$$

Opening case

Table 3. Buffer matrix (in seconds) when aircraft (i) follows aircraft (j).

	Trailing Aircraft (Header Columns)		
Lead (column 1)	F	E	B
F	33.00	33.00	33.00
E	30.01	33.00	33.00
B	15.84	20.82	33.00

Values in seconds

Arrivals-Only Runway Capacity Analysis

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

Actual headways (in seconds) when aircraft (i) follows aircraft (j).

Table 4. $T_{ij} + B_{ij}$ matrix (in seconds) when aircraft (i) follows aircraft (j).

		Trailing Aircraft (Header Columns)	
Lead (column 1)	F	E	B
F	114.8	111.8	104.5
E	123.8	111.8	104.5
B	193.4	181.4	104.5

Values in seconds

Expected Value of Headways (Including Buffer Times)

The expected value of the actual headways $E(T_{ij} + B_{ij})$ is **120.14 seconds**. The arrivals only capacity is,

$$C_{arrivals} = \frac{1}{E(T_{ij} + B_{ij})} \text{ vehicles per second}$$

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

$$C_{arrivals} = \frac{3600}{\mathrm{E}(\mathrm{T}_{ij} + \mathrm{B}_{ij})} = 29.96 \text{ arrivals per hour}$$

Arrivals-Only Runway Capacity

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

$$C_{arrivals} = \frac{3600}{120.14} = 29.96 \text{ aircraft arrivals per hour}$$

Note: this value is typical for US airports when runways are operated in Instrument Meteorological Conditions (IMC)

When operating in Visual Meteorological Conditions (VMC), the separations are typically reduced by 10-12% resulting in higher runway capacity.

Analysis of Runway Gaps

- Gaps can be studied for all nine possible arrival instances
- For example, if a CWT class B aircraft is followed by a CWT class F, there is a headway of 193 seconds between two successive arrivals.
- This leaves a large gap that be exploited by air traffic controllers to handle a few departures on the same runway.

$$E(T_{ij} + B_{ij}) \geq E\left(\frac{\delta}{V_j}\right) + E(ROT_i) + (n-1)E(\varepsilon_{ij}) + E(\tau)$$

Left hand side
Has been calculated
As **120.14 seconds**

		Trailing Aircraft (Header Columns)	
Lead (column 1)	F	E	B
F	114.8	111.8	104.5
E	123.8	111.8	104.5
B	193.4	181.4	104.5

Intermediate Calculations

Calculation of expected value: $E(\frac{\delta}{V_j})$

$$E(\frac{\delta}{V_j}) = \sum_{j=1}^{3} P_j(\frac{\delta}{V_j})$$

$$E(\frac{\delta}{V_j}) = P_B(\frac{\delta}{V_B}) + P_E(\frac{\delta}{V_E}) + P_F(\frac{\delta}{V_F})$$

$$E(\frac{\delta}{V_j}) = 53.8$$

Intermediate Calculations

- Calculation of $E(ROT_j)$

Expected value of Runway Occupancy Time (ROT)

$$E(ROT_j) = \sum_{j=1}^{3} P_j (ROT_j)$$

	F	E	B
ROT (s)	51	54	65
Percent Mix (%)	82	10	8

$$E(ROT_j) = 52.42 \text{ seconds}$$

Intermediate Calculations

This calculates the expected value between successive departures

- Calculation of $E\left(\varepsilon_{ij}\right)$

Departure-Departure Separation Matrix with Buffers (seconds)			
		Trailing Aircraft (Header Columns)	
Lead (column 1)	F	E	B
F	70	70	70
E	70	70	70
B	130	130	130

	Trailing Aircraft (Header Columns)		
Lead (column 1)	F	E	B
F	0.672	0.082	0.066
E	0.082	0.010	0.008
B	0.066	0.008	0.006

$$E\left(\varepsilon_{ij}\right) = 79.84 \text{ seconds}$$

Computation of Minimum Gaps

$$E(T_{ij} + B_{ij}) \geq 53.8 + 52.4 + (n - 1)79.8 + 10 \text{ seconds}$$

$$E(T_{ij} + B_{ij}) \geq 53.8 + 52.4 + 10 + 79.8n - 79.8 \text{ seconds}$$

$$E(T_{ij} + B_{ij}) \geq 36.4 + 78n \text{ seconds}$$

For $n = 1$ (one departure between arrivals) we need,

$$E(T_{ij} + B_{ij})_{n=1} \geq 116.2 \text{ seconds}$$

For $n = 2$ (two departures between arrivals) we need,

$$E(T_{ij} + B_{ij})_{n=2} \geq 181.02 \text{ seconds}$$

Computation of Minimum Gaps

For $n = 3$ (three departures between arrivals) we need,

$$E(T_{ij} + B_{ij})_{n=3} \geq 245.8 \text{ seconds}$$

For $n = 4$ (four departures between arrivals) we need,

$$E(T_{ij} + B_{ij})_{n=4} \geq 310.62 \text{ seconds and so.}$$

We need to compare the values stated in with values $(T_{ij} + B_{ij})$ against the gaps needed to schedule n departures per arrival gap instance.

Assess Gaps that Allow Departures

Required Gaps

n=1 departure

$$E(T_{ij}+B_{ij}) >= 116\ seconds$$

n=2 departures

$$E(T_{ij}+B_{ij}) >= 181\ seconds$$

n=3 departures

$$E(T_{ij}+B_{ij}) >= 246\ seconds$$

Table 4. $T_{ij} + B_{ij}$ matrix (in seconds) when aircraft (i) follows aircraft (j).

		Trailing Aircraft (Header Columns)	
Lead (column 1)	F	E	B
F	114.8	111.8	104.5
E	123.8	111.8	104.5
B	193.4	181.4	104.5

Values in seconds

Arrival-arrival gap between F class aircraft followed by F class is too small

	Trailing Aircraft (Header Columns)		
Lead (column 1)	F	E	B
F	0	0	0
E	1	0	0
B	2	2	0

Arrival-arrival gap between B class aircraft followed by F class allows two departures

Gap Analysis

The following table summarizes the number of departures possible when an aircraft of type (i) follows aircraft of type (j). We assume random arrivals.

Table 5. Number of departures per arrival gap when aircraft (i) follows aircraft (j).

	Trailing Aircraft (Header Columns)		
Lead (column 1)	F	E	B
F	0	0	0
E	1	0	0
B	2	2	0

Cells with zeros, imply the arrival-arrival gaps are too short to permit a departure

Interpretation of Gap Analysis Results

- One departure (on average) can be scheduled between a class E aircraft followed by a class F aircraft.
- Note that a class E - class F arrival sequence provides a gap of 123.8 seconds
- Since 116.2 seconds are needed to schedule a departure (expected value for all types of operations)
- One departure per gap (class E followed by class F) is possible
- Other cells are computed in a similar fashion.

	Trailing Aircraft (Header Columns)		
Lead (column 1)	F	E	B
F	0	0	0
E	1	0	0
B	2	2	0

Analysis of Arrival Gaps

- Now we determine how many times each gap occurs during the period of interest? (say one hour)
- From our analysis of arrivals only, we determined that on the average hour 29.92 arrivals could be processed at the runway. Since two successive arrivals are needed to form a gap, we can infer that an average of 28.92 gaps are present in one hour.
- The probability of each one of the nine arrival sequences is known and has been calculated before.

Analysis of Arrival Gaps

- Consider the instance of a leading class B aircraft followed by a class F aircraft
- 6.6% of the time this instance occurs at the airport
- There are **28.92 departure gaps** (DG) per hour so we can estimate the expected number of hourly departures per arrival instance (ED_{B-F})

$$ED_{B-F} = TG(P_{B-F})(DG_{B-F})$$

	Trailing Aircraft (Header Columns)		
Lead (column 1)	F	E	B
F	0.672	0.082	0.066
E	0.082	0.010	0.008
B	0.066	0.008	0.006

where: TG is the total number of gaps per hour, P_{B-F} is the probability that a class B aircraft is followed by a class F aircraft, and DG_{B-F} is the number of departures per gap for each instance (numbers in Table 5).

Finding Expected Departures per Arrival Gap

Expected departures per hour for gaps when class B aircraft is followed by another class B aircraft

	Trailing Aircraft (Header Columns)		
Lead (column 1)	F	E	B
F	0.672	0.082	0.066
E	0.082	0.010	0.008
B	0.066	0.008	0.006

Probability matrix

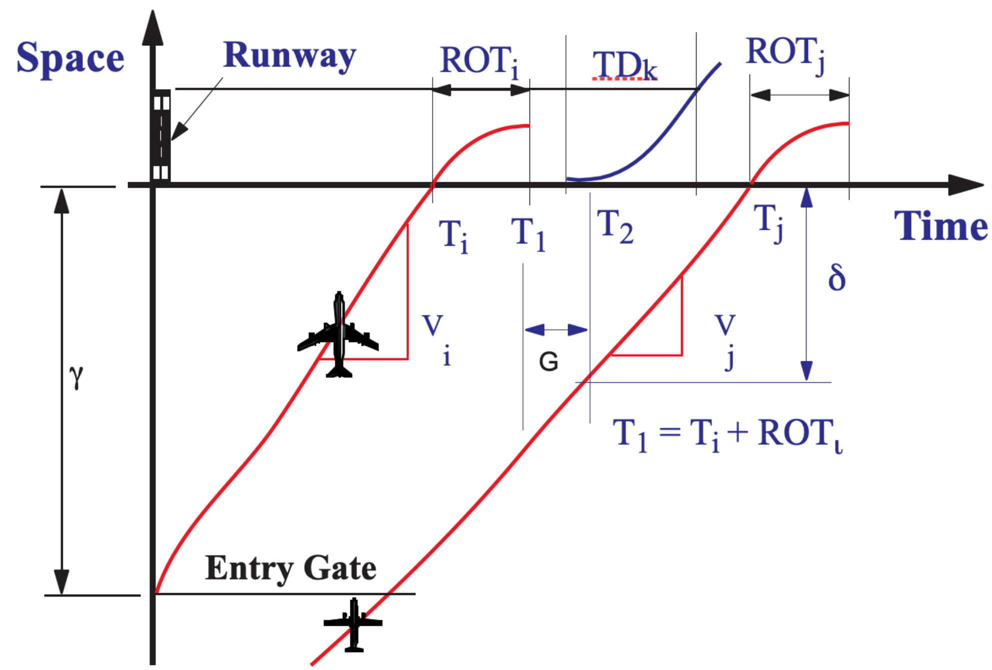
$$ED_{B-B} = TG(PB_{B-B})(DG_{B-B})$$

$$ED_{B-B} = 28.92(0.006)(0) = 0$$

Expected departures per hour for gaps when class E aircraft is followed by another class F aircraft

$$ED_{E-F} = TG(PB_{E-F})(DG_{E-F})$$

$$ED_{E-F} = 28.92(0.082)(1) = 2.38$$



Departures with Arrival Priority

Table 6 summarizes the number of departures per hour per instance.

Table 6. Expected departures per hour per arrival instance when aircraft (i) follows aircraft (j).

		Trailing Aircraft (Header Columns)	
Lead (column 1)	F	E	B
F	0.00	0.00	0.00
E	2.38	0.00	0.00
B	3.80	0.46	0.00

Total departures per hour = **6.64 departures per hour**

Estimating Hourly Mixed Operations

$$C_{arrivals} = \frac{3600}{120.14} = 29.92 \text{ arrivals per hour}$$

$$C_{departures} = 6.64 \text{ departures per hour with 100\% arrival priority}$$

- The results indicate that a single runway can process 29.92 arrivals per hour
- At the same time, during the same hour, the runway can process 6.64 departures per hour using the natural gaps left by the arrivals

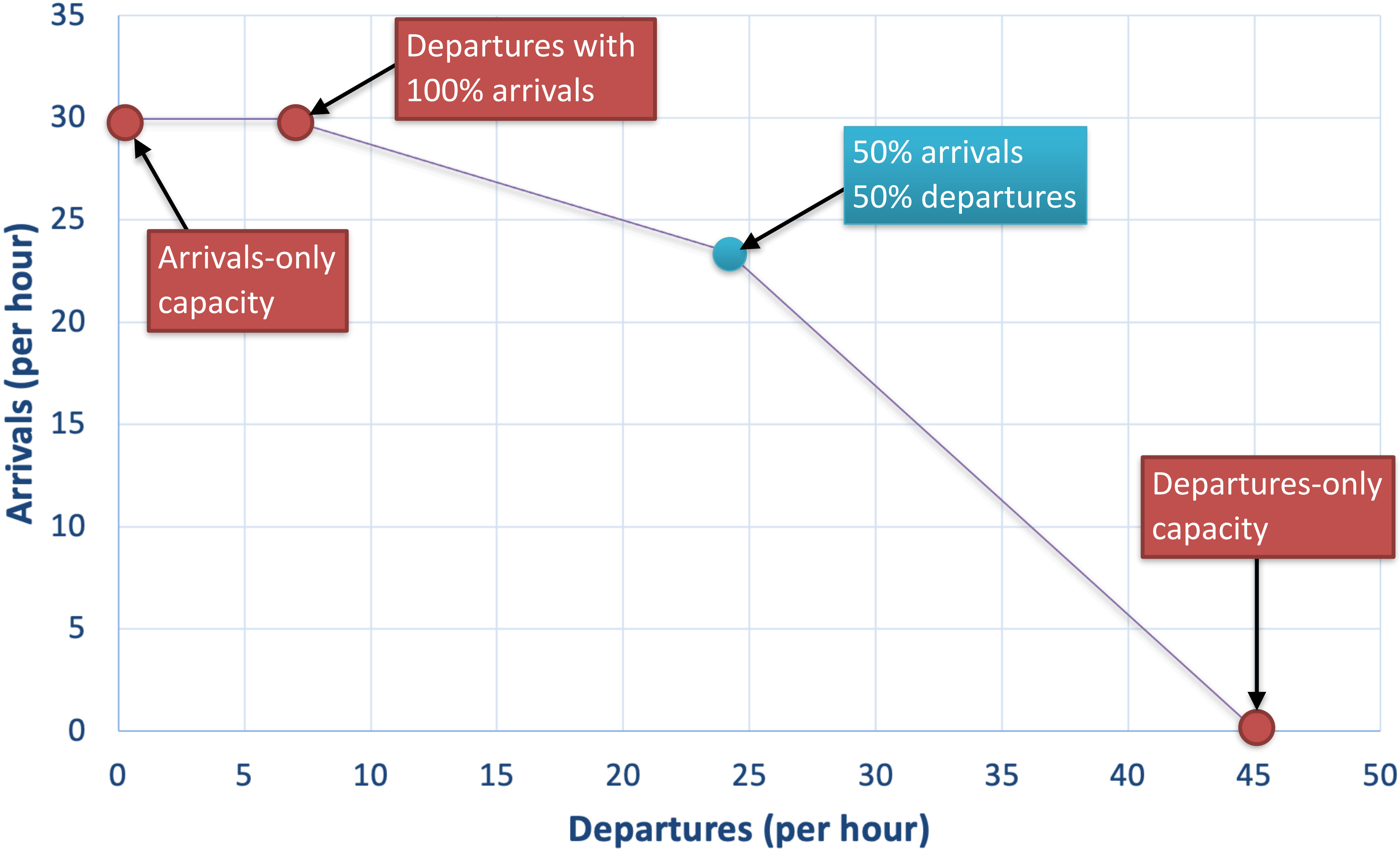
Departures-Only Runway Capacity

If **only departures are processed at this runway** (no arrivals), the departures only capacity is the reciprocal of the departure headway (79.8 seconds),

$$C_{dep-NA} = \frac{3600}{79.8} = \mathbf{45.1} \text{ **departures per hour with no arrivals**}$$

- We now define a capacity diagram to display all three hourly capacity results in a single diagram.
- These diagrams represent a Pareto frontier of arrivals and departures.
- The airport can be operated inside the Pareto boundary.

Arrival-Departure Capacity Diagram (Pareto Frontier)



Excel Spreadsheet to Estimate Single Runway Capacity

Runway Saturation Capacity Estimation
Using the Analytical Model for Runway Capacity

Programmer: A. Trani (Fall 2022)
Amendments: 2

Technical Parameters (inputs)				Parameter	Values		
Dep-Arrival Separation (nm)				δ	2		
Common Approach Length (nm)				γ	12		
Standard deviation of Position Delivery Error (s)				σ	20		
Probability of Violation				Pv	5		
Cumulative Normal at Pv				qv	1.65		
Buffer for departure-departure (seconds)					10		
	F	E	B				
ROT (s)	51	54	65	70	70	52.42	E(ROT)
Percent Mix (%)	82	10	8	0.00	0.00	100	Total %
Vapproach (knots)	132	137	151	150.0	150.0		

Minimum Separation Matrix (nm)		Arrivals-Arrivals		
	Trailing Aircraft (Header Columns)			
Lead (column 1)	F	E	B	
F	3	3	3	
E	3	3	3	
B	5	5	3	

Excel Spreadsheet to Estimate Single Runway Capacity

Error Free Separation Matrix (Tij)

	Trailing Aircraft (Header Columns)					
Lead (column 1)	F	E	B			Expected Value
F	82	79	72			E(Tij)
E	94	79	72			88.61
B	178	161	72			

Pij Matrix

	Trailing Aircraft (Header Columns)					
Lead (column 1)	F	E	B			Sum of Pij
F	0.672	0.082	0.066			0.820
E	0.082	0.010	0.008			0.100
B	0.066	0.008	0.006			0.080
						0.000
						0.000
						1.000

Buffer Matrix (Bij)

	Trailing Aircraft (Header Columns)					
Lead (column 1)	F	E	B			Expected Value
F	33.00	33.00	33.00			B(Tij)
E	30.01	33.00	33.00			31.53
B	15.84	20.82	33.00			

Excel Spreadsheet to Estimate Single Runway Capacity

Augmented Matrix (Tij + Bij)

	Trailing Aircraft (Header Columns)						
Lead (column 1)	F	E	B				Expected Value
F	114.82	111.83	104.52				E(Tij) + B(Tij)
E	123.78	111.83	104.52				120.14
B	193.39	181.44	104.52				

Arrivals Only Capacity (per hour) 29.96

Minimum Departure-Departure Separation Matrix (seconds)

	Trailing Aircraft (Header Columns)						
Lead (column 1)	F	E	B				Expected Value
F	60	60	60				E(Td)
E	60	60	60				
B	120	120	120				64.8

Departures Only Capacity (per hour) without buffers 55.56

Departure-Departure Separation Matrix with Departure Buffers (seconds)

	Trailing Aircraft (Header Columns)						
Lead (column 1)	F	E	B				Expected Value
F	70	70	70				E(Td)
E	70	70	70				
B	130	130	130				79.84

Departures Only Capacity (per hour) - includes depart 45.09

Excel Spreadsheet to Estimate Single Runway Capacity

Estimation of Critical Departure Gaps

Departures		Gap (EΔTij)			
				E(ROT)	52.42
				E(δ/Vj)	53.80
1		116.22		Clear to Roll Time	10.00
2		181.02			
3		245.82			
4		310.62			
5		375.42			

Departures per Gap

Trailing Aircraft (Header Columns)

Lead (column 1)	F	E	B		
F	0	0	0	0	0
E	1	0	0	0	0
B	2	2	0	0	0
	0	0	0	0	0
	0	0	0	0	0

Departures per hour with 100% Arrival Priority

Trailing Aircraft (Header Columns)

Lead (column 1)	F	E	B			Sum	
F	0.00	0.00	0.00	0.00	0.00	0.00	
E	2.38	0.00	0.00	0.00	0.00	2.38	
B	3.80	0.46	0.00	0.00	0.00	4.26	
	0.00	0.00	0.00	0.00	0.00	0.00	
	0.00	0.00	0.00	0.00	0.00	0.00	
						6.64	Total Departures with 100% arrival priority

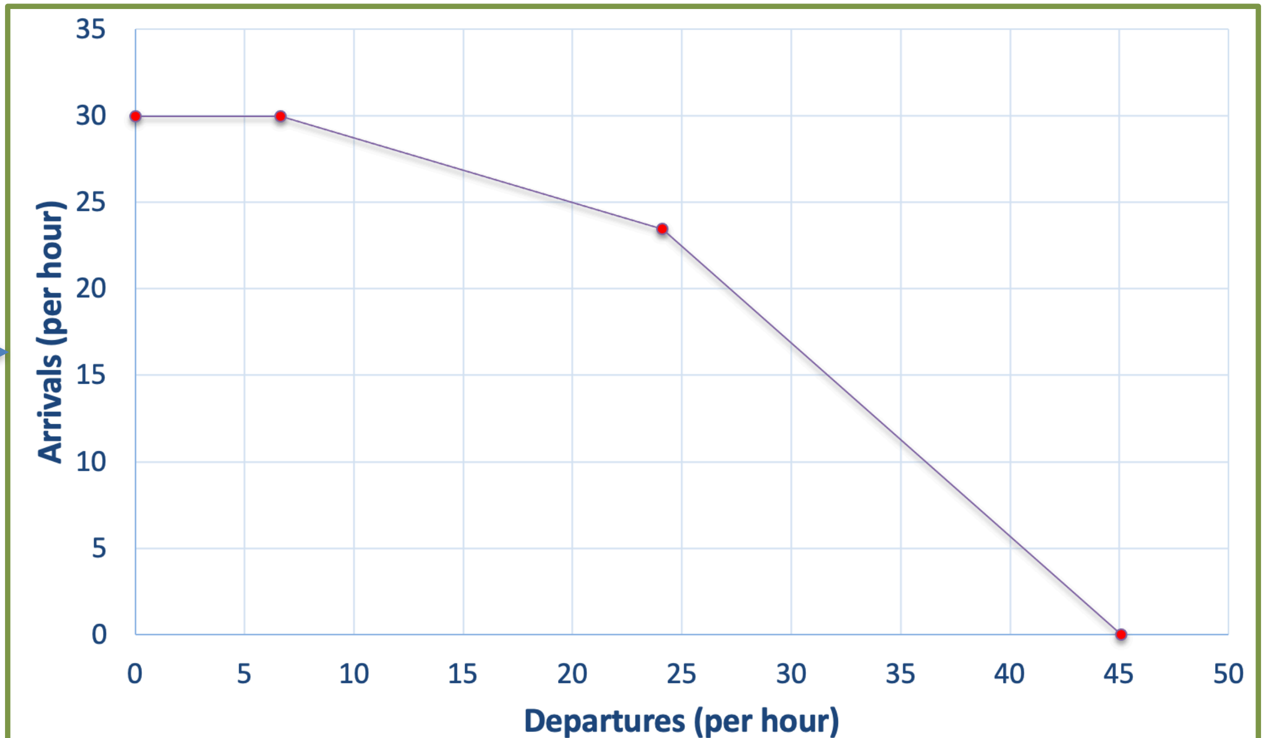
Summary for Arrival - Departure Diagram

Excel Spreadsheet to Estimate Single Runway Capacity

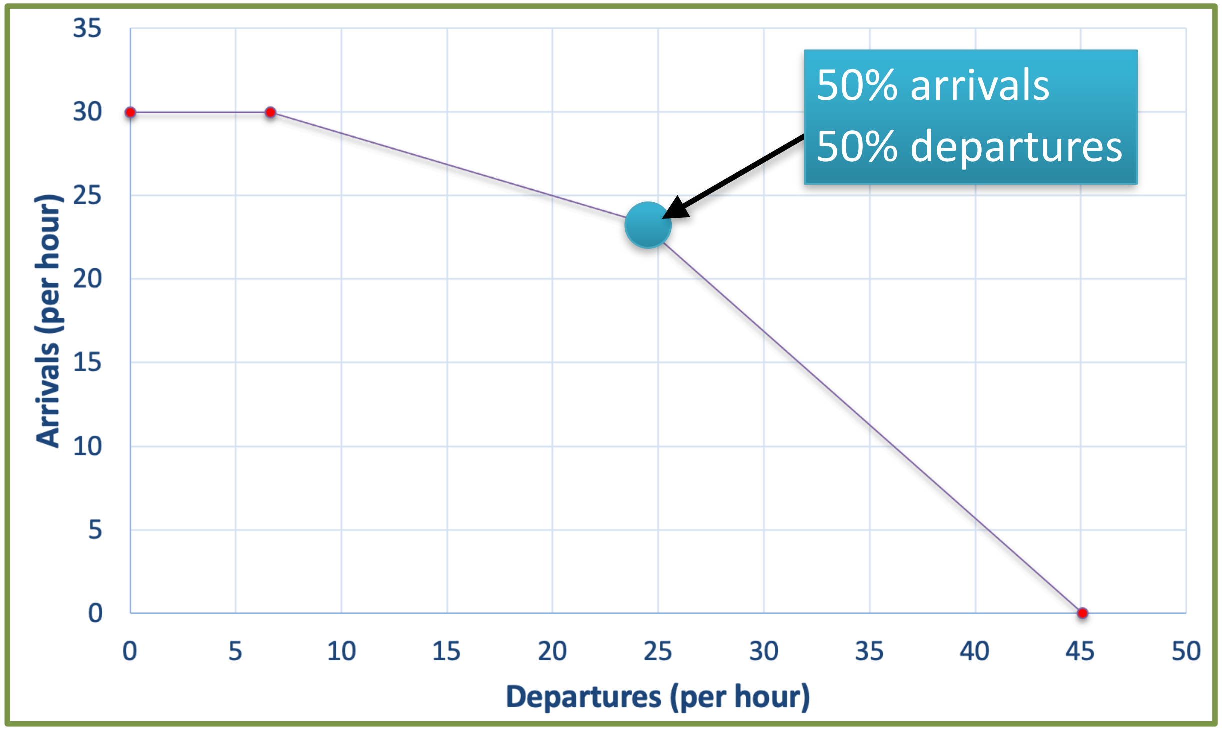
Summary for Arrival - Departure Diagram

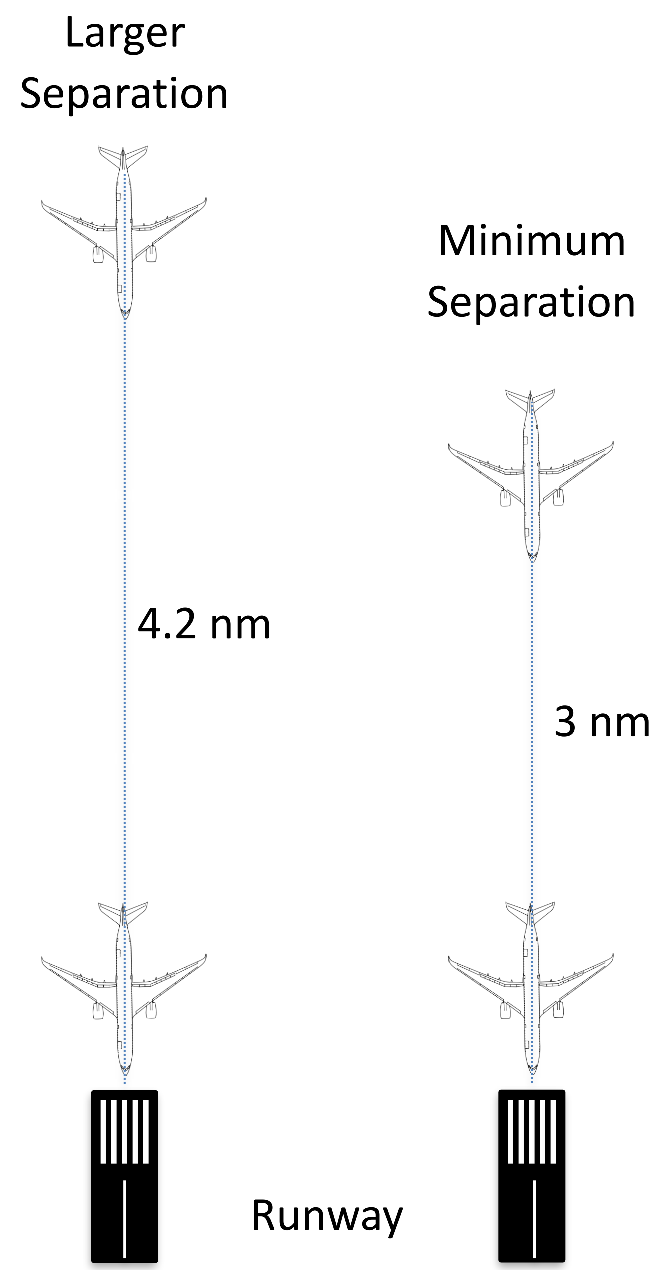
Arrivals	Departures		Operation Pattern		
29.96	0		Arrivals Only		Baseline
29.96	6.64		100% Arrivals + Departures		Baseline
23.46	24.12				Comp 2
0	45.09		Departures Only		Baseline

Computations Base | Program Description | Comp 2 | +



Finding Additional Points on the Pareto Diagram





Technical Parameters (inputs)				Parameter	Values			
Dep-Arrival Separation (nm)				δ	2			
Common Approach Length (nm)				γ	12			
Standard deviation of Position Delivery Error (s)				σ	20			
Probability of Violation				Pv	5		Clear to roll	
Cumulative Normal at Pv				qv	1.65		10	
Buffer for departure-departure (seconds)					10			
	F	E	B					
ROT (s)	51	54	65	70	70		52.42	E(ROT)
Percent Mix (%)	82	10	8	0.00	0.00		100	Total %
Vapproach (knots)	132	137	151	150.0	150.0			
Minimum Separation Matrix (nm)			Arrivals-Arrivals				Multiplier	
		Trailing Aircraft (Header Columns)					1.4	
Lead (column 1)	F	E	B					
F	4.2	4.2	4.2	0	0			
E	4.2	4.2	4.2	0	0			
B	7	7	4.2	0	0			
	0	0	0	0	0			
	0	0	0	0	0			

Finding Additional Points on Pareto Frontier

- Use the Multiplier cell in the **Comp 2 sheet** of the Excel spreadsheet provided
- The Multiplier factor multiplies the original separation matrix (δ_{ij}) to increase the arrival gaps between successive arrivals
- Large gaps produce more chances for departures
- Use iterations to produce multiple points along the arrival-capacity diagram (Pareto frontier)

Multiplier = 1.4 increases separation by 40% for each cell in sheet "Compuations Base"

	F	E	B		
ROT (s)	51	54	65	70	70
Percent Mix (%)	82	10	8	0.00	0.00
Vapproach (knots)	132	137	151	150.0	150.0
Minimum Separation Matrix (nm)		Arrivals-Arrivals			
	Trailing Aircraft (Header Columns)				
Lead (column 1)	F	E	B		
F	4.2	4.2	4.2	0	0
E	4.2	4.2	4.2	0	0
B	7	7	4.2	0	0
	0	0	0	0	0
	0	0	0	0	0

Multiplier
1.4

Computations Base | Program Description | Comp 2 | +

Finding Additional Points on Pareto Frontier

Minimum Separation Matrix (nm)			Arrivals-Arrivals
		Trailing Aircraft (Header Columns)	
Lead (column 1)	F	E	B
F	3	3	3
E	3	3	3
B	5	5	3

Original minimum separation matrix

24.12 departures per hour

Multiplier = 1.4
increases separation by 40% for each cell in sheet "Compuations Base"

Multiplier
1.4

Minimum Separation Matrix (nm)			Arrivals-Arrivals
		Trailing Aircraft (Header Columns)	
Lead (column 1)	F	E	B
F	4.2	4.2	4.2
E	4.2	4.2	4.2
B	7	7	4.2

Modified separation matrix
Multiplier = 1.4

24.12 departures per hour

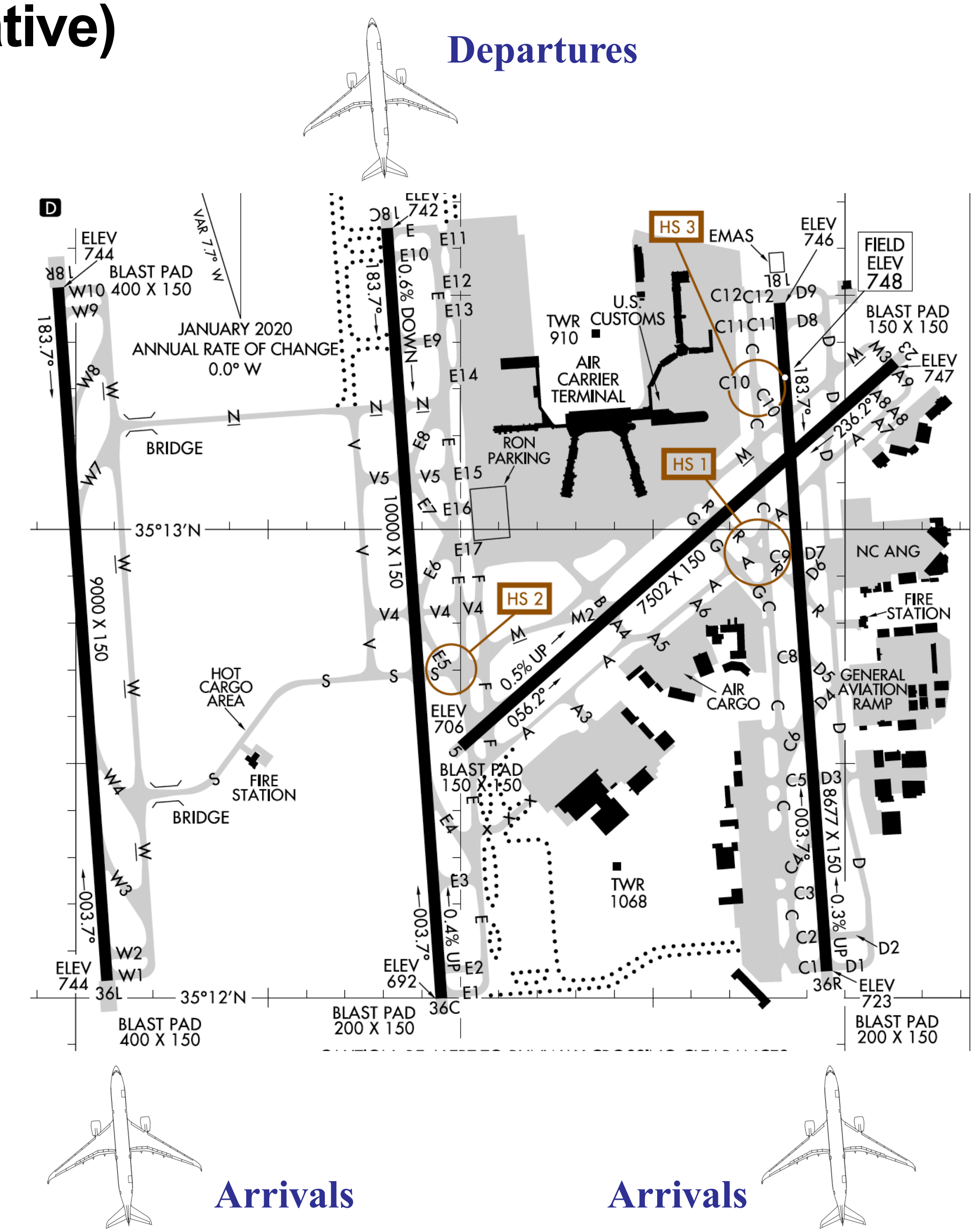
Estimating Runway Capacity for More than One Runway

- If runway operations are independent you can estimate arrival and departure saturation capacities for each runway independently
- If the operations on runways are dependent estimate the runway occupancy times (both for arrivals and departures) very carefully and establish a logical order of operations on the runways.

Example 2 - Charlotte-Douglas Intl. Airport (Three Runways Operative)

Operational Conditions

1) Runways 36L and 36R are used for departures
2) Runway 36C is used for departures
3) Parallel runway separation > 4,300 ft.
4) Airport surveillance radar and ADS-B
5) Aircraft mix
   a) Class C - 3%
   b) Class F- 47%
   c) Class G -45%
   d) Class H - 5%
6) Approach speeds
   a) Class C - 150 knots
   b) Class F- 140 knots
   c) Class G - 134 knots
   d) Class H -127 knots
7) Runway occupancy times
   a) Class C - 60 seconds
   b) Class F- 50 seconds
   c) Class G - 48 seconds
   d) Class H - 47 seconds
8) Common approach length - 10 nm
9) In-trail delivery error standard deviation -18 s.
10) Consolidated Wake Turbulence separations
11) 10-second clear to roll time
12) 2.5 nm minimum radar separation

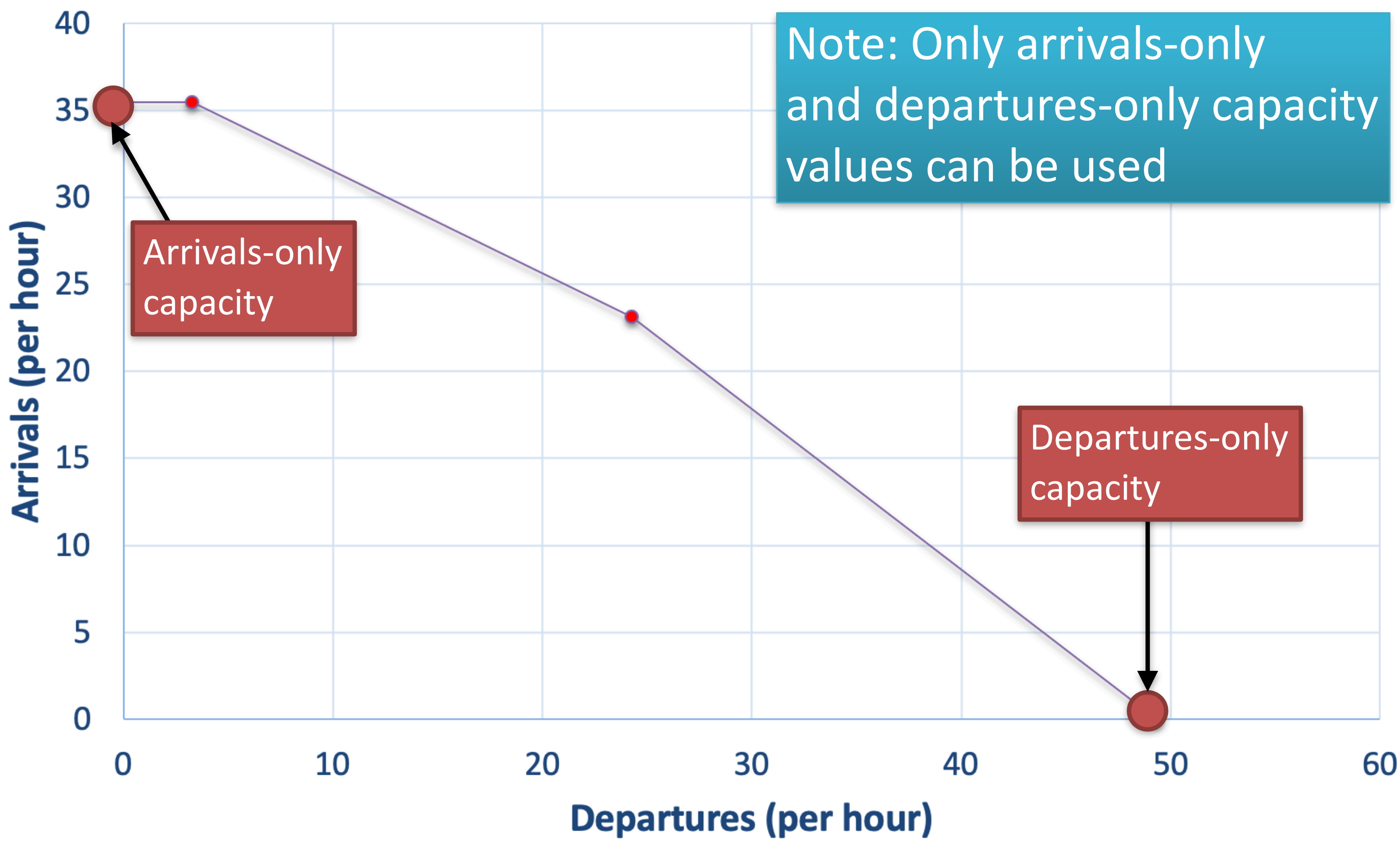


CWT Arrival-Arrival Separations

		FOLLOWER								
		A	B	C	D	E	F	G	H	I
LEADER	A		5 NM	6 NM	6 NM	7 NM	7 NM	7 NM	8 NM	8 NM
	B		3 NM	4 NM	4 NM	5 NM	5 NM	5 NM	5 NM	5 NM
	C					3.5 NM	3.5 NM	3.5 NM	5 NM	5 NM
	D		3 NM	4 NM	4 NM	5 NM	5 NM	5 NM	5 NM	5 NM
	E									4 NM
	F									
	G									
	H									
	I									

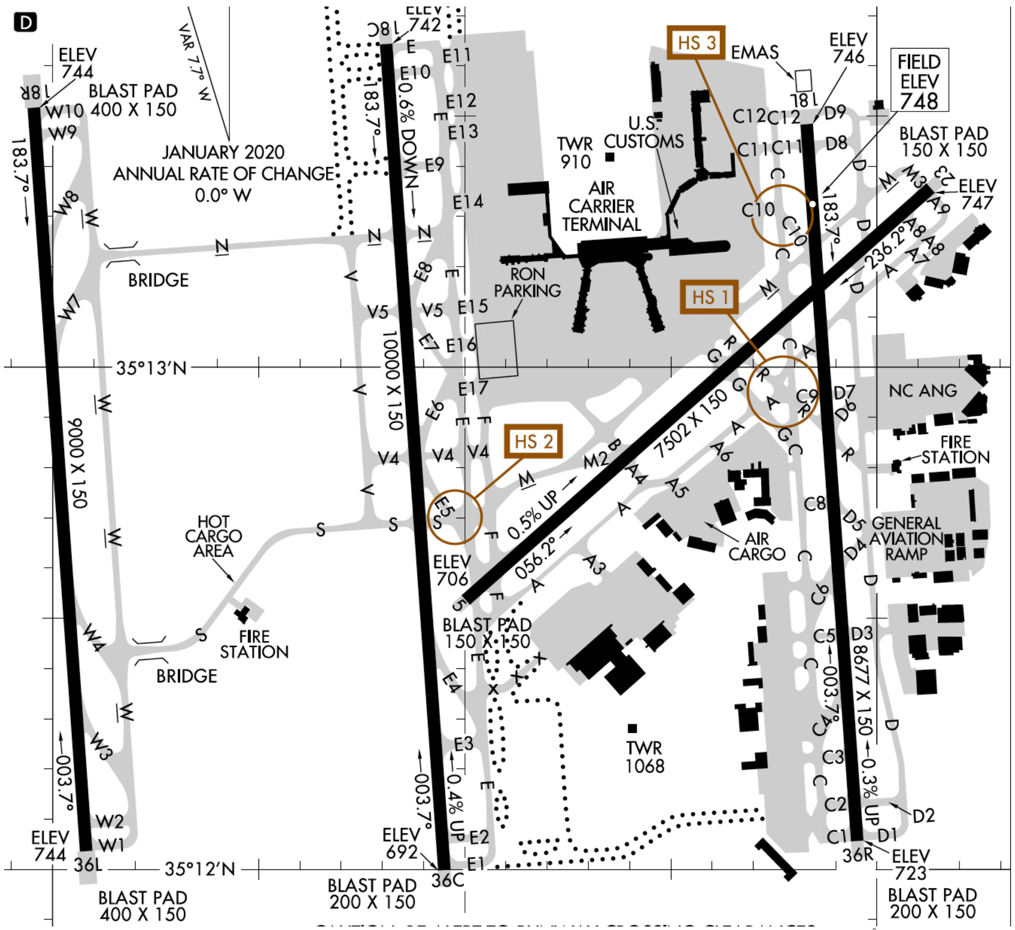
Minimum Separations are in nautical miles

Results Using Single Runway Excel File



Results Using Single Runway Excel File

49.3 departures per hour



35.5 Arrivals per hour

35.5 Arrivals per hour

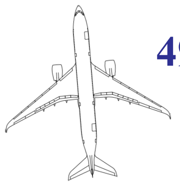
Runway 36C - 49.3 departures/hr

Runway 36L - 35.5 arrivals/hr
Runway 36R - 35.5 arrivals/hr

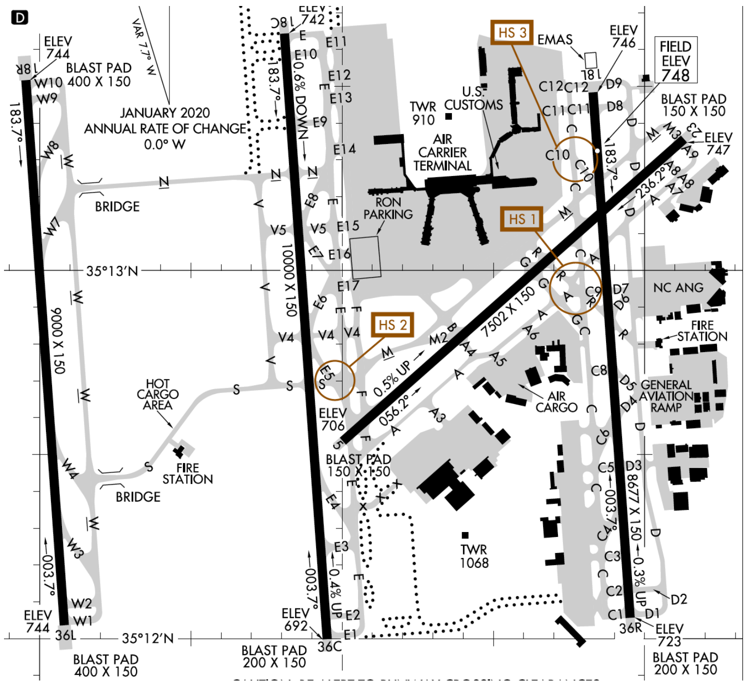
Arrivals = 71/hr
Departures = 49.3/hr

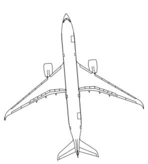
Total operations = 120.3/hr

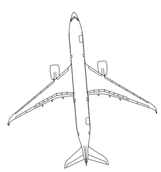
CLT Runway Capacity (Segregated Operations)



49.3 departures per hour

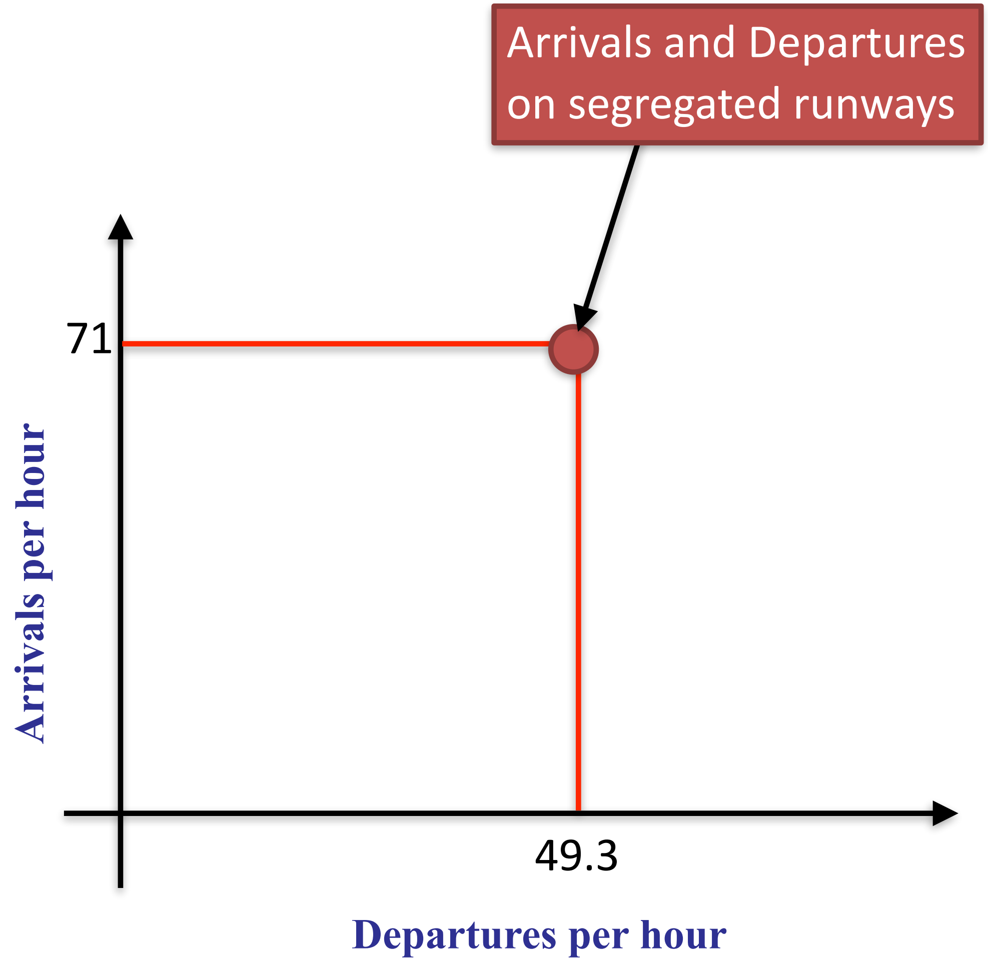






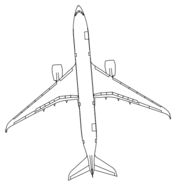
35.5 Arrivals per hour

35.5 Arrivals per hour

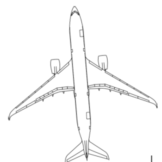


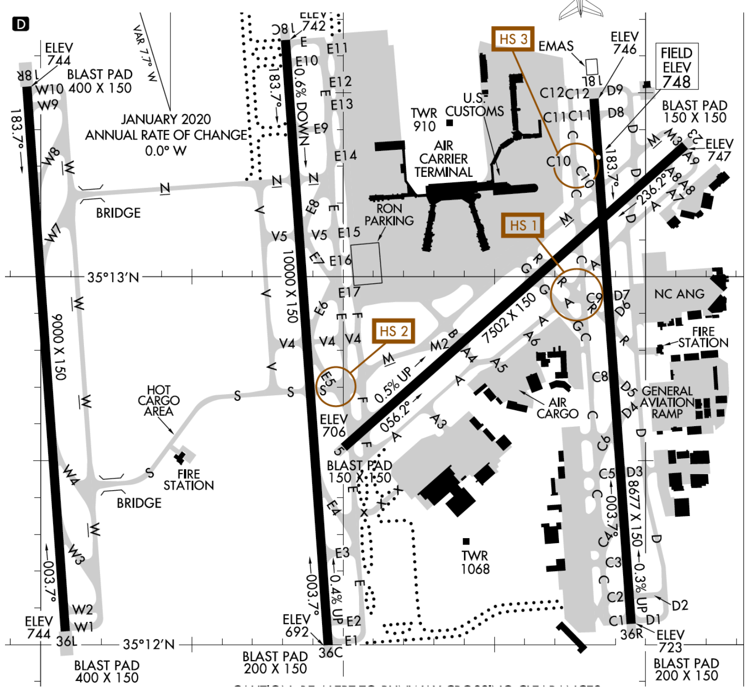
CLT Runway Capacity : Two Departure Runways, One Arrival Runway

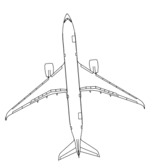
49.3 departures per hour



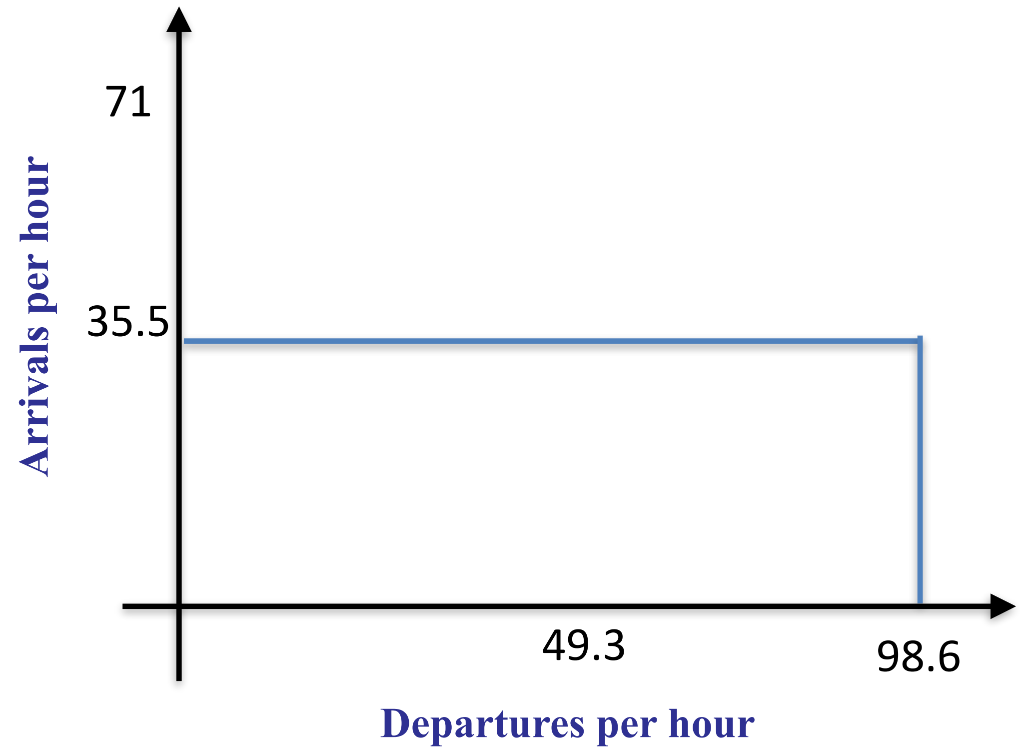
49.3 departures per hour





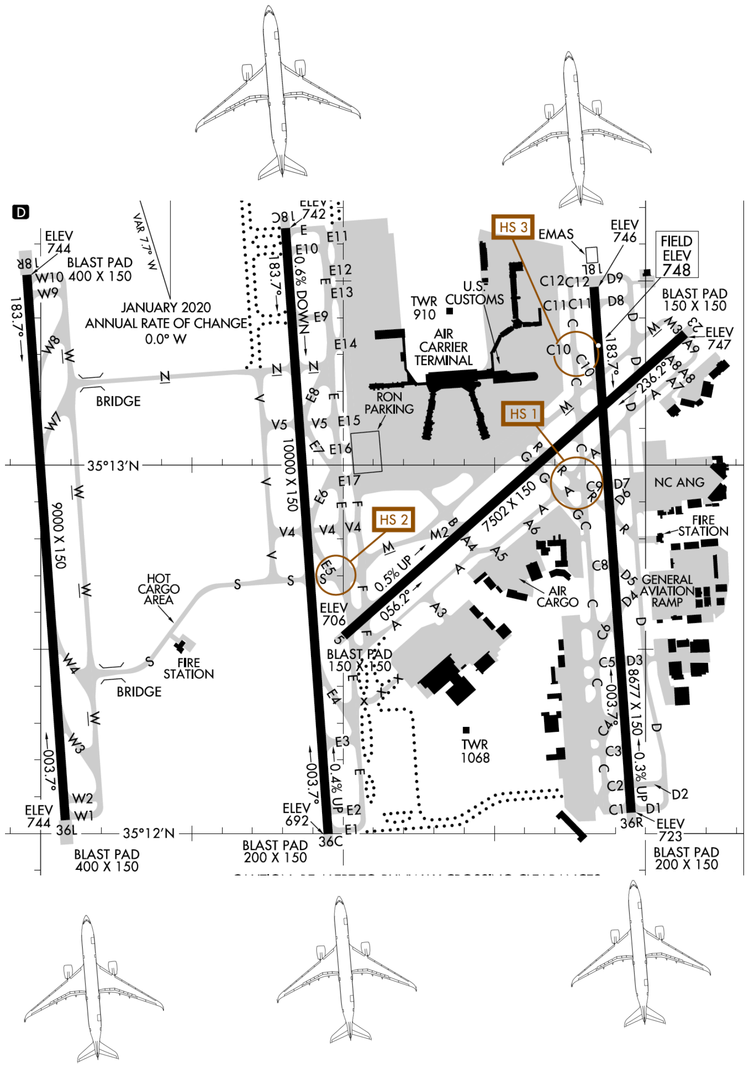


35.5 Arrivals per hour

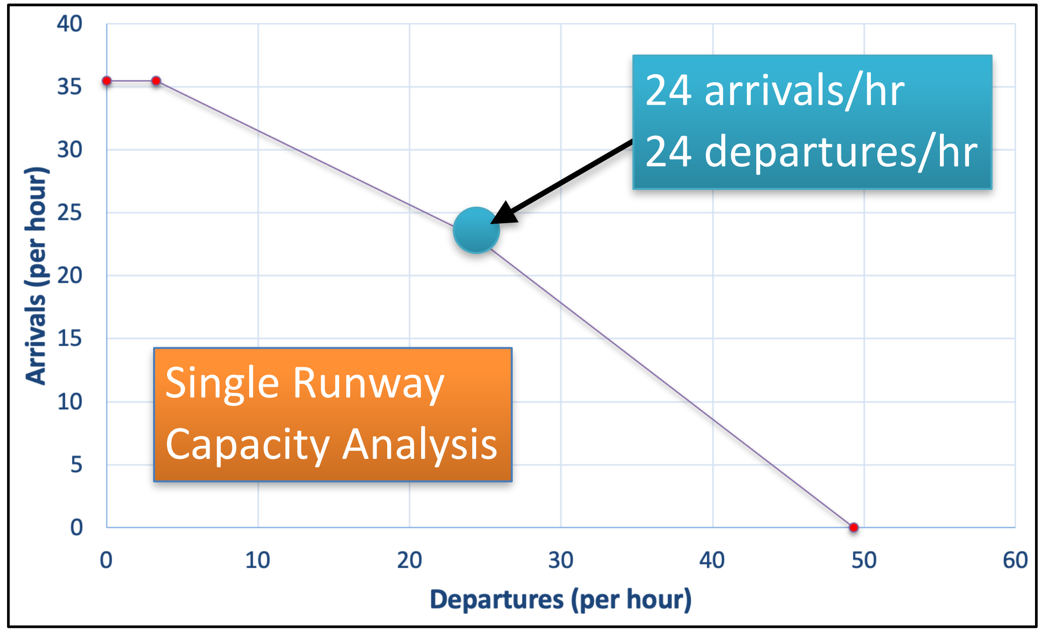


VirginiaTech
Invent the Future

CLT Runway Capacity : Mixed Operations on Runways 36R and 36C



35.5 arrivals per hour



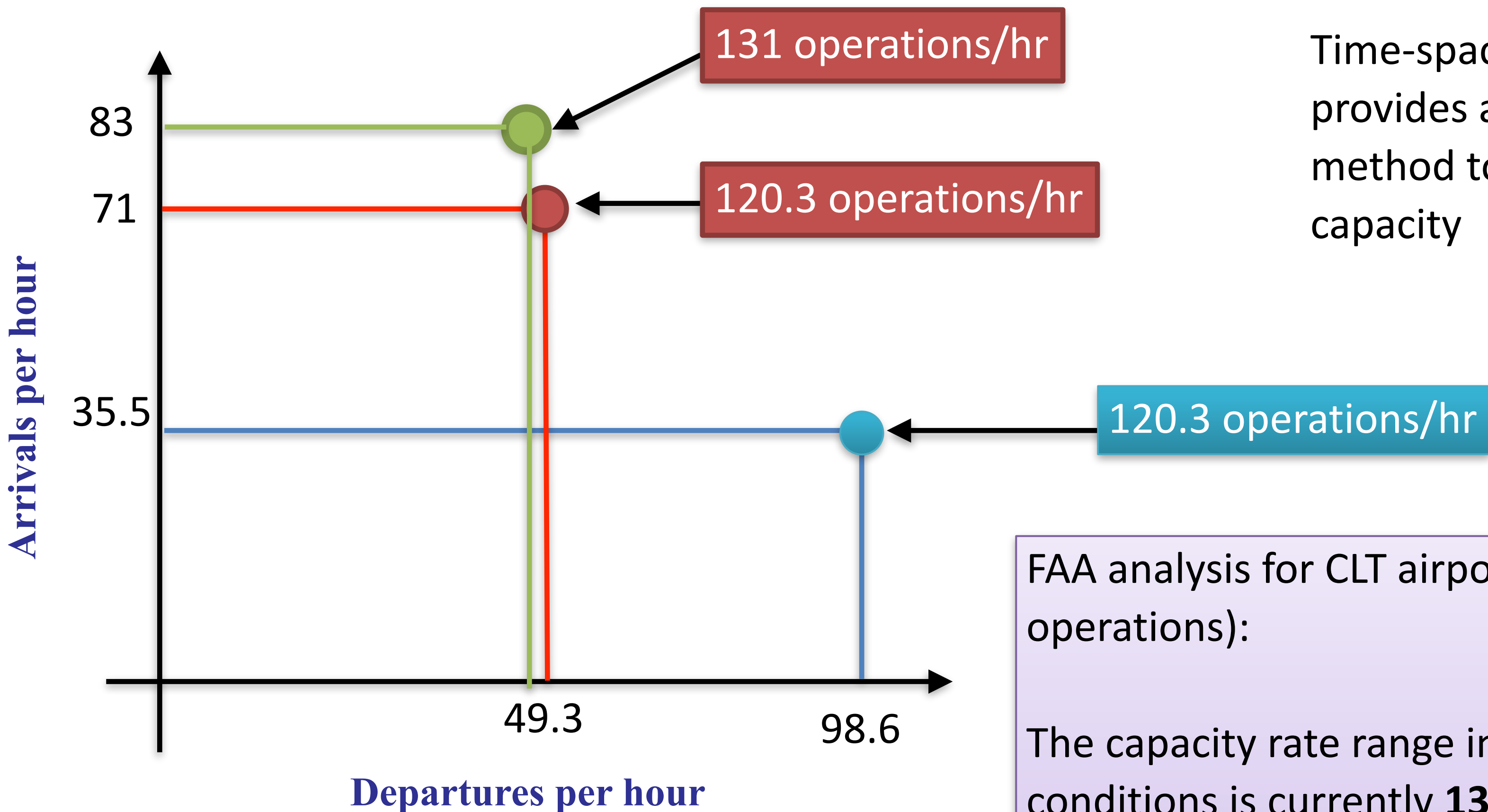
Runway 36C
24 departures/hr
24 arrivals/hr
Runway 36R
24 departures/hr
24 arrivals/hr
Runway 36CL
35.5 arrivals/hr

Total arrivals operations
83 arrivals/hr

Total departure operations
48 departures/hr

131 operations per hour

CLT Runway Capacity: Comparison of Two Segregated Operational Modes



Time-space analysis provides a quick and reliable method to estimate runway capacity

FAA analysis for CLT airport (North flow operations):

The capacity rate range in North flow Instrument conditions is currently **135-140 operations** per hour.

Reduced separation (2.5 NM) between arrivals is authorized for instrument approaches to Runways 36C, 36L, and 36R at CLT.

https://www.faa.gov/sites/faa.gov/files/airports/planning_capacity/profiles/CLT-Airport-Capacity-Profile-2015.pdf

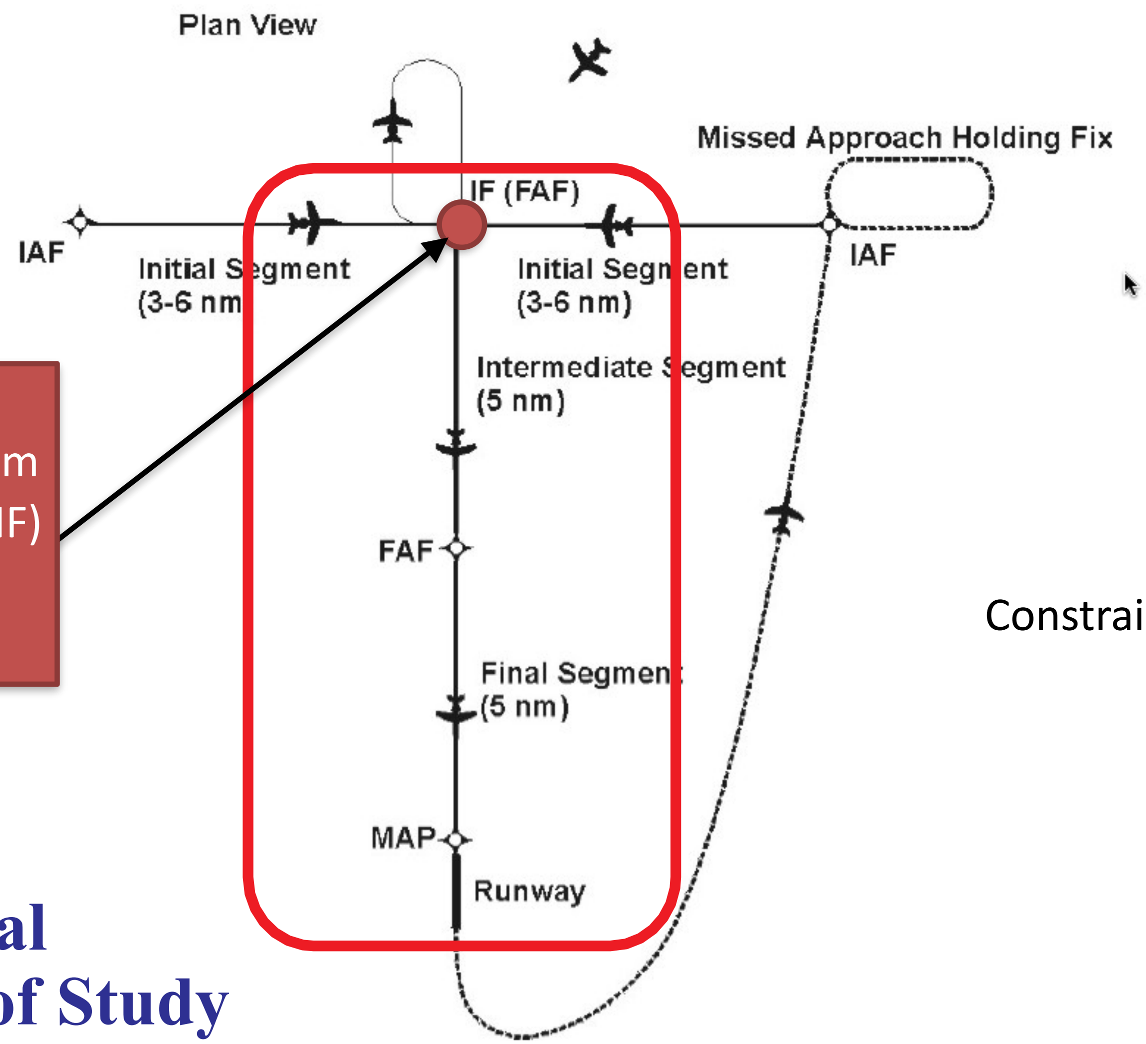
Airports without Air Traffic Control Tower

- Existing airports without a control tower have small runway saturation capacities in Instrument Meteorological Conditions (IMC) conditions (**5-6 arrivals per hour**)

- These airports require large headways (10-12 minutes) between aircraft because ATC cannot "see" the aircraft in radar (ATC applies **procedural separations**)

- New technologies such as Automated Depedance Surveyance mode B (ADS-B) help ATC to reduce in-trail separations at non-towered airports

Uncontrolled Airport Scenario

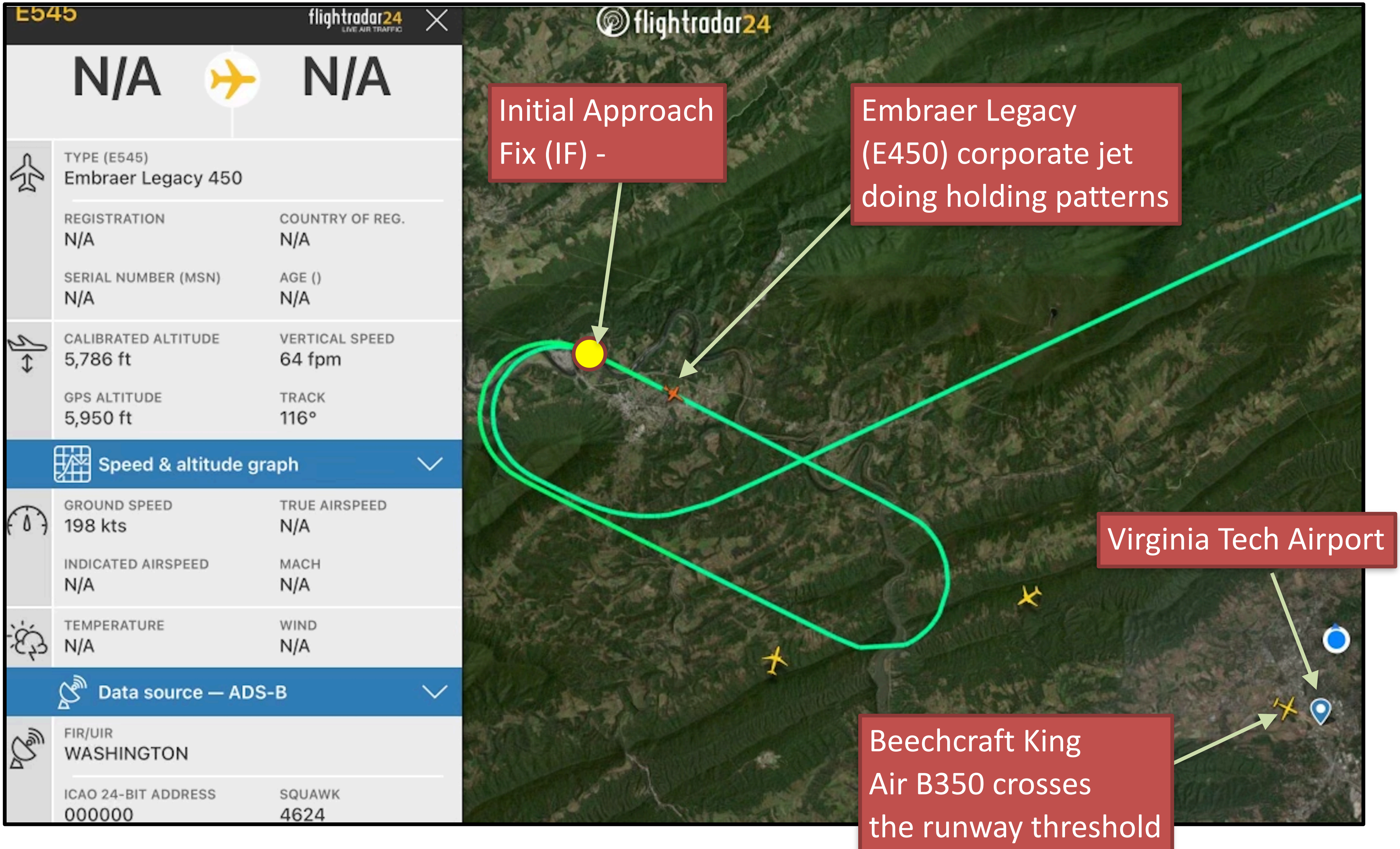


Aircraft cannot be released inbound from Initial Approach Fix (IF) until previous arrival is on the runway

Constraints

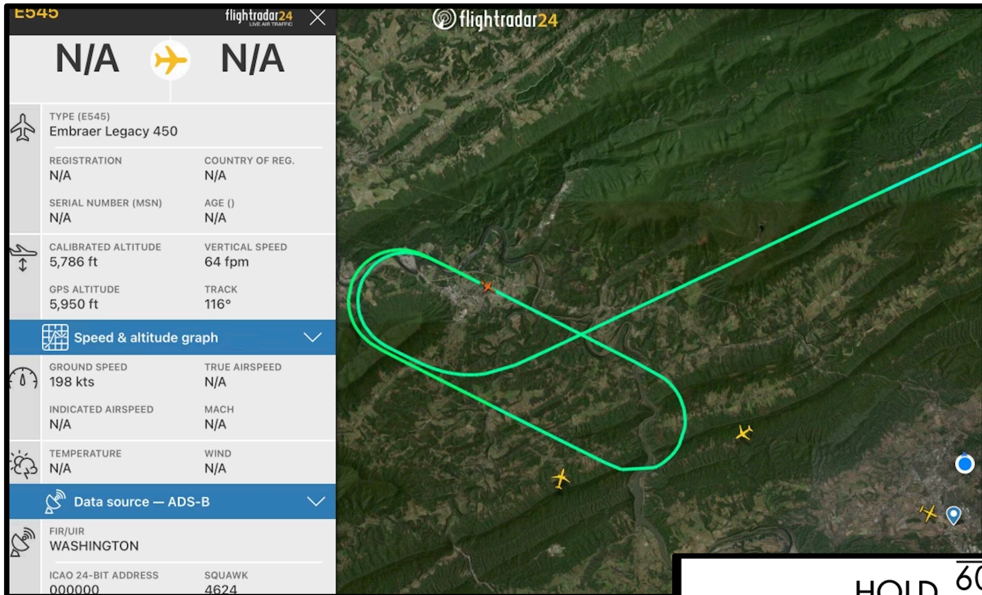
Critical Area of Study

Uncontrolled Airport Scenario (Virginia Tech Airport)



Source: flightradar24.com

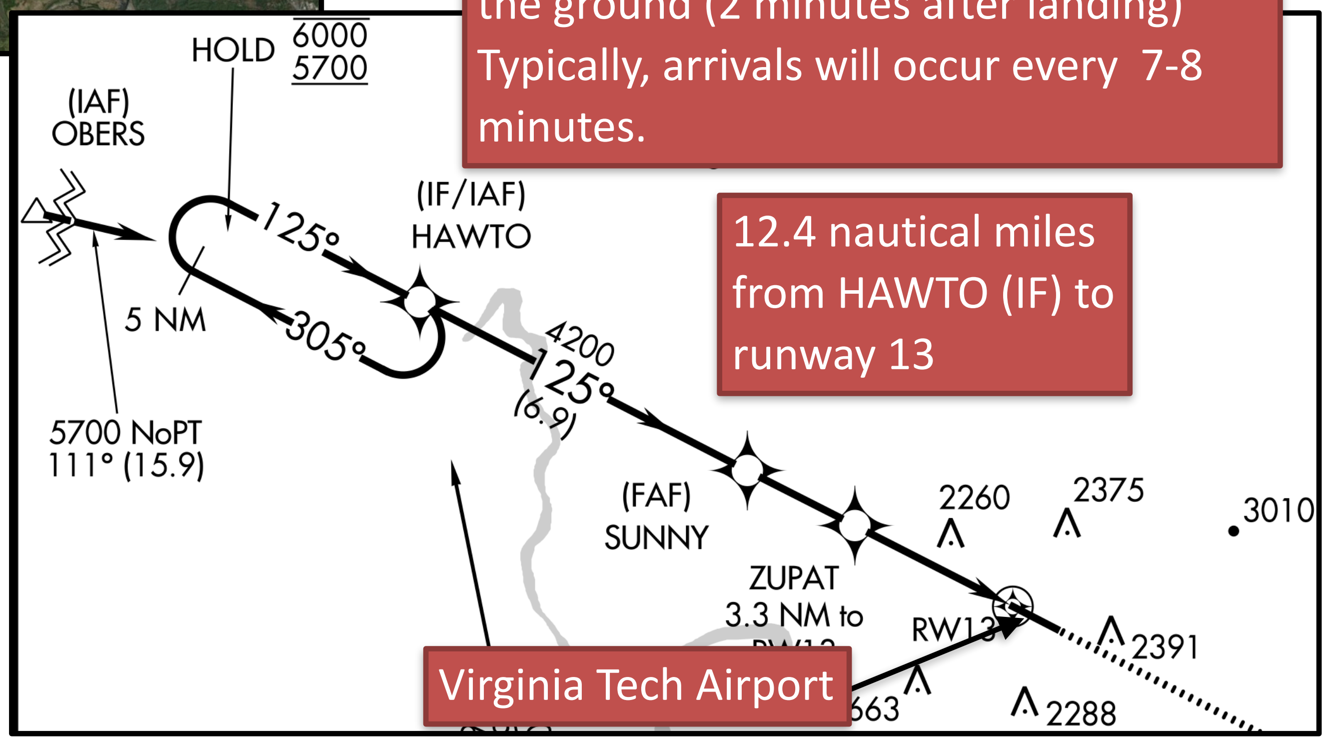
Uncontrolled Airport Scenario (Virginia Tech Airport)



Source: flightradar24.com

A corporate jet travels at an average ground speed of 150 knots from HAWTO to the runway.
It takes 5 minutes to travel 12.4 nm
In addition, the lead arrival needs to communicate with the Roanoke TRACON controller that the aircraft is on the ground (2 minutes after landing)
Typically, arrivals will occur every 7-8 minutes.

Arrival capacity to Virginia Tech airport in bad weather (IMC conditions) is ~7.5 per hour



12.4 nautical miles from HAWTO (IF) to runway 13

Virginia Tech Airport

Summary

- The saturation capacity of an airport depends on the runway configuration
- The **saturation capacity during VMC conditions is higher (typically 5-10% higher**) compared to IMC conditions (due to shorter separation minima)
- The variation in technical parameters such as γ and δ affects the results of saturation capacity
- The estimation of departures with 100% arrival priority in our analysis is conservative
- The time-space analysis does not provide with delay results (use deterministic queueing theory or FAA AC 150/5060 to estimate delay)