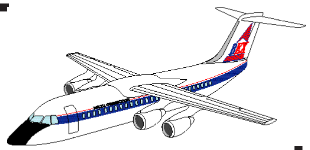
Runway and Airport Capacity

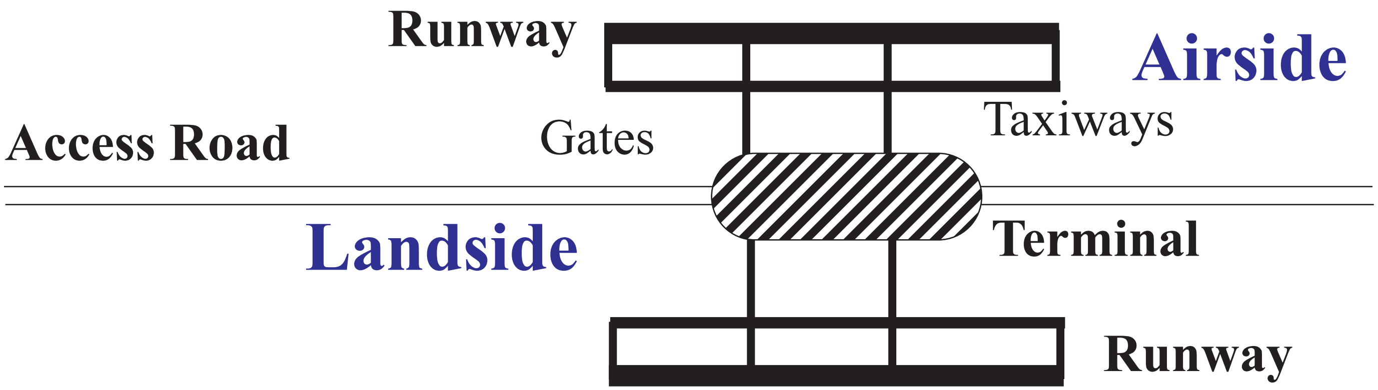
Dr. Antonio A. Trani
Professor
Virginia Tech

Spring 2023

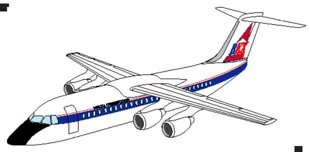
Methodologies to Assess Airport Capacity



The capacity of an airport is a complex issue. Several elements of the airport facility have to be examined. Namely: a) Airside and b) Landside components.



Airport and Airspace Components



The following components of NAS need to be examined:

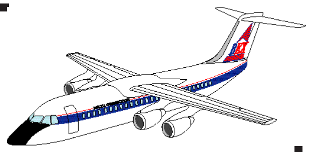
a) Airside

- Airspace
- Runways
- Taxiways

b) Landside

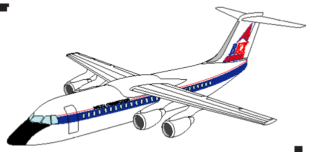
- Gates
- Terminal
- Access road

Methodologies to Study Airport Capacity/ Delay



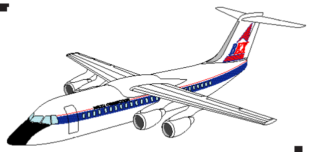
- Analytic models
  - Easier and faster to execute
  - Good for preliminary airport/airspace planning (when demand function is uncertain)
  - Results are generally less accurate but appropriate
- Simulation-based models
  - Require more work to execute
  - Good for detailed assessment of existing facilities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

Methodologies in Use to Study Capacity/ Delay



- Analytic models
  - - Time-space analysis
  - - Queueing models (deterministic and stochastic)
- Simulation-based models
  - - Monte Carlo Simulation
  - - Continuous simulation models
  - - Discrete-event simulation models

Time-Space Analysis



- A solid and 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

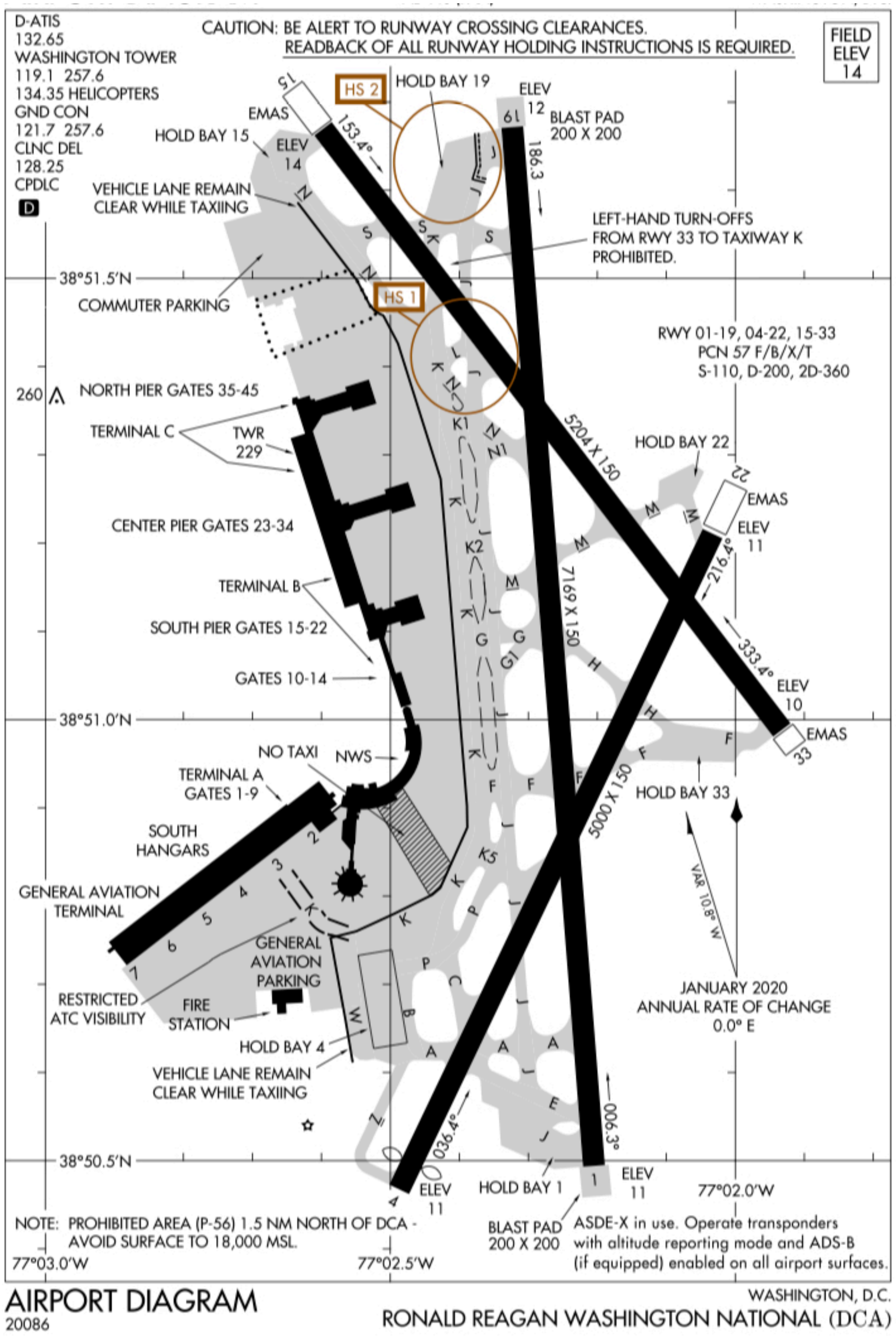
$$Capacity = \frac{1}{E(h)} \qquad (1)$$

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

Example of Busy Airport Operations

- Illustrate the sequence of operations at a busy airport (Ronald Reagan Airport)
- Provides some insight on the technical parameters of the analytic model to estimate runway capacity

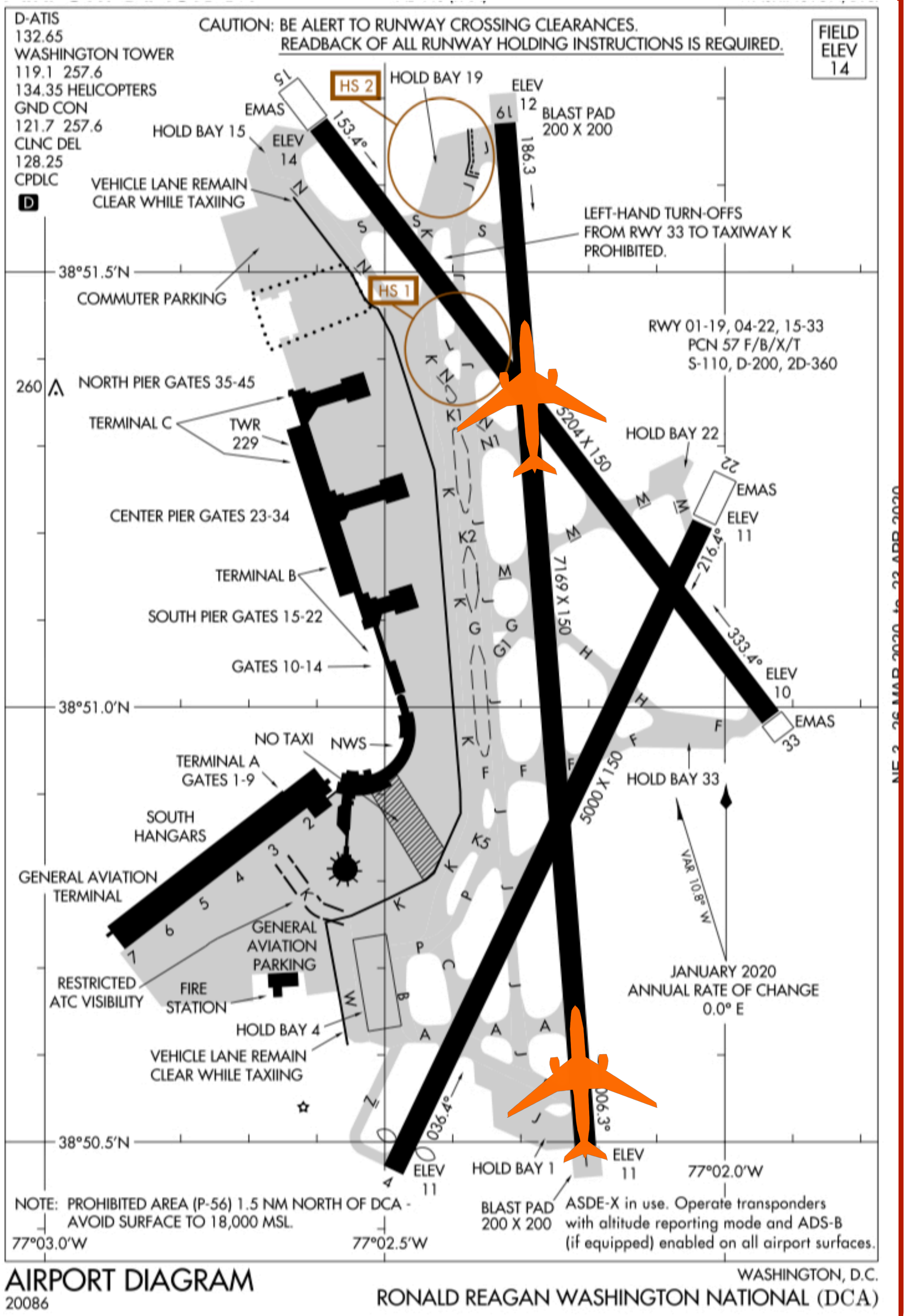
The Airport Configuration at DCA



Observations at a Busy Period of Time

Time= 0 seconds
Airbus A320 departure on runway 19

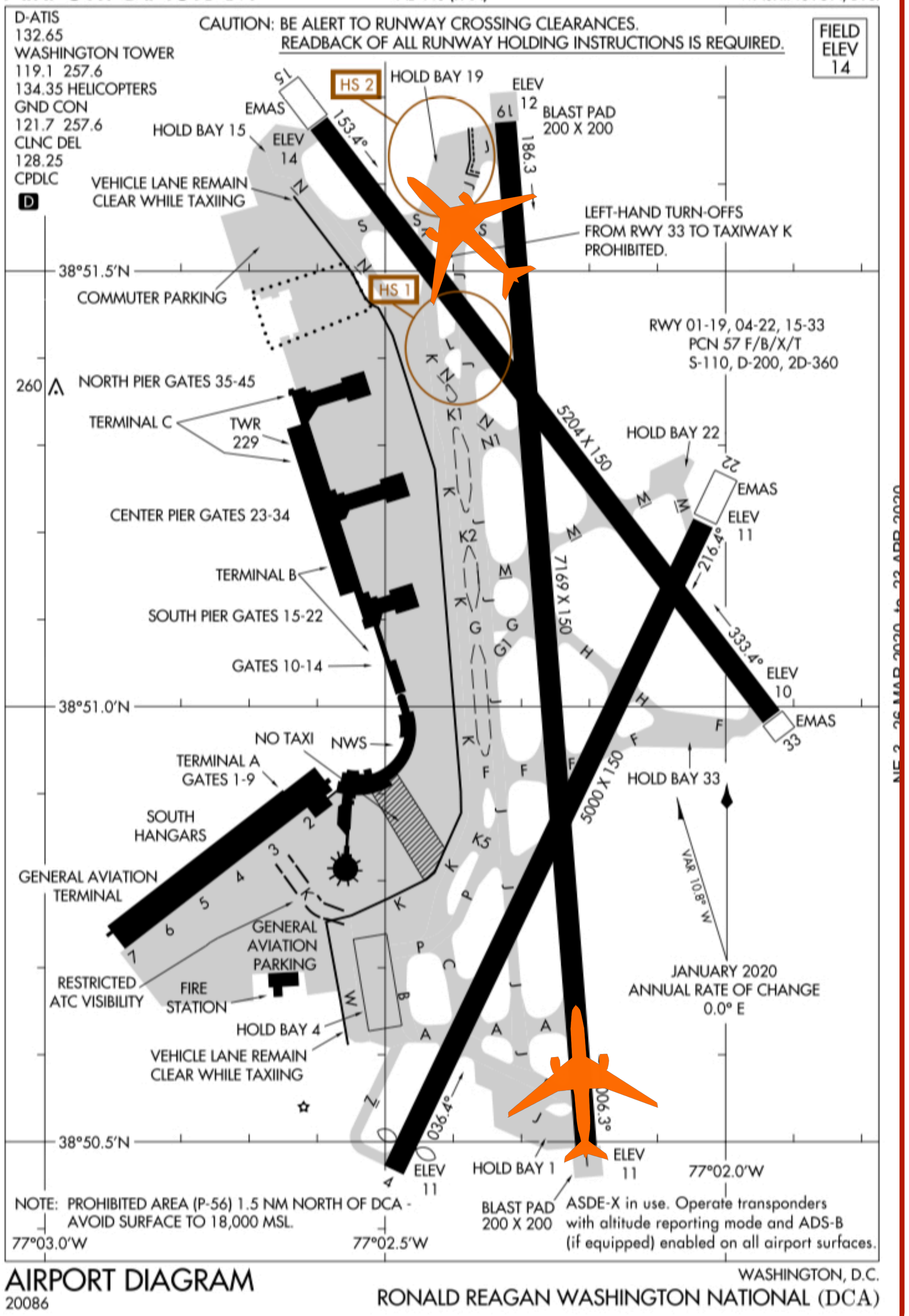
Time= 30 seconds
Airbus A320 on takeoff roll on runway 19



Observations at a Busy Period of Time

Time= 57 seconds
JetBlue Airbus A320 departure crosses the threshold of runway 19

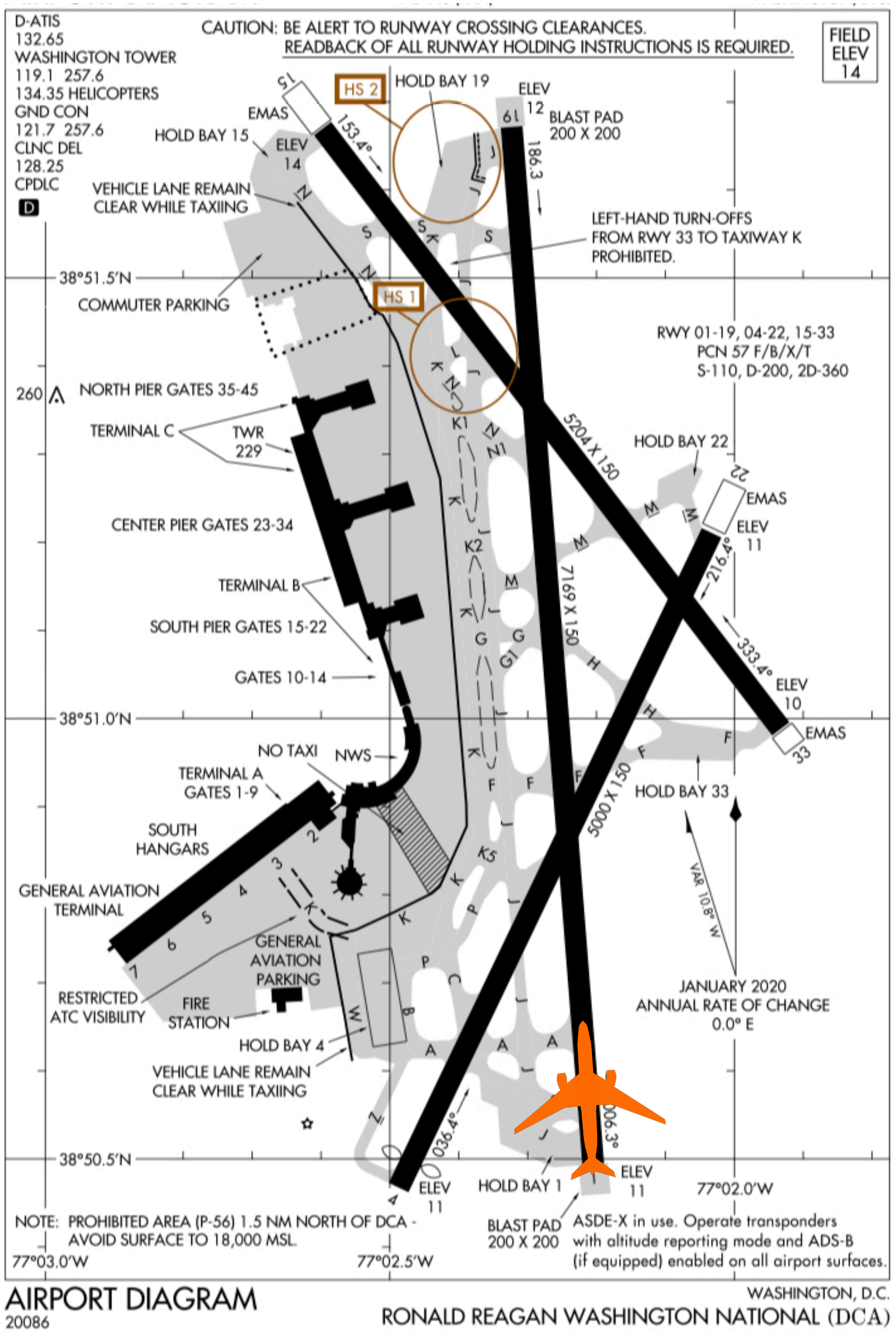
Time= 105 seconds
JetBlue Airbus A320 vacates runway 19



Observations at a Busy Period of Time

Time= 105 seconds
JetBlue Airbus A320 vacates runway 19

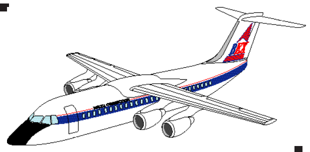
Time= 147 seconds
Boeing 737-800 crosses the threshold of runway 19



Observations

- 57 seconds between a departure starting its takeoff roll and the arrival crossing the threshold
- At 145 knots (typical approach speed for an Airbus A320), 57 seconds is equivalent to **2.3 nautical miles (distance** between an arrival and a departure)
- Runway occupancy time is observed to be **~48 seconds**
- Time between successive arrivals is **~90 seconds** (147-57 seconds) for RECAT D aircraft (i.e., large aircraft in the legacy wake classification)
- At 145 knots (Boeing 737-800), 90 seconds is equivalent to **3.6 nautical miles** (time between two arrivals)

Time-Space Analysis Nomenclature



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

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

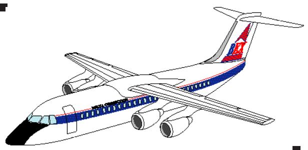
δ is the minimum arrival-departure separation (nm)

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)

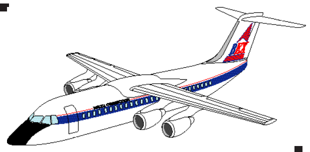
γ is the common approach length (nm)

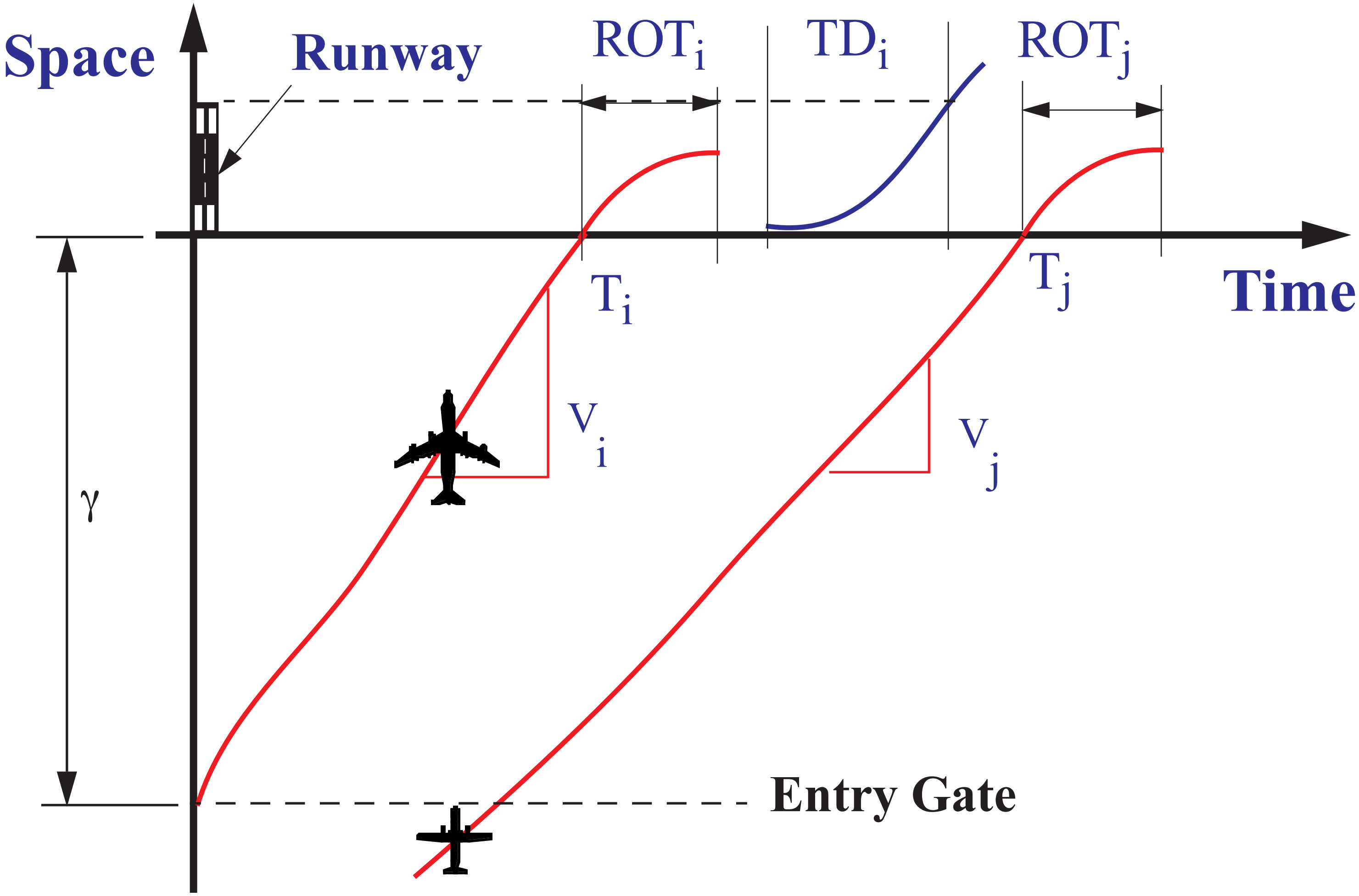
B_{ij} is the buffer times matrix between successive aircraft (s)

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

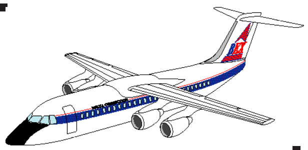
p_v is the probability of violation of the minimum separation criteria between two aircraft

Final Approach and Landing Processes





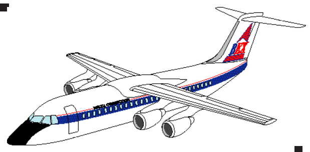
Possible Outcomes of a Single Runway Time-Space Diagram

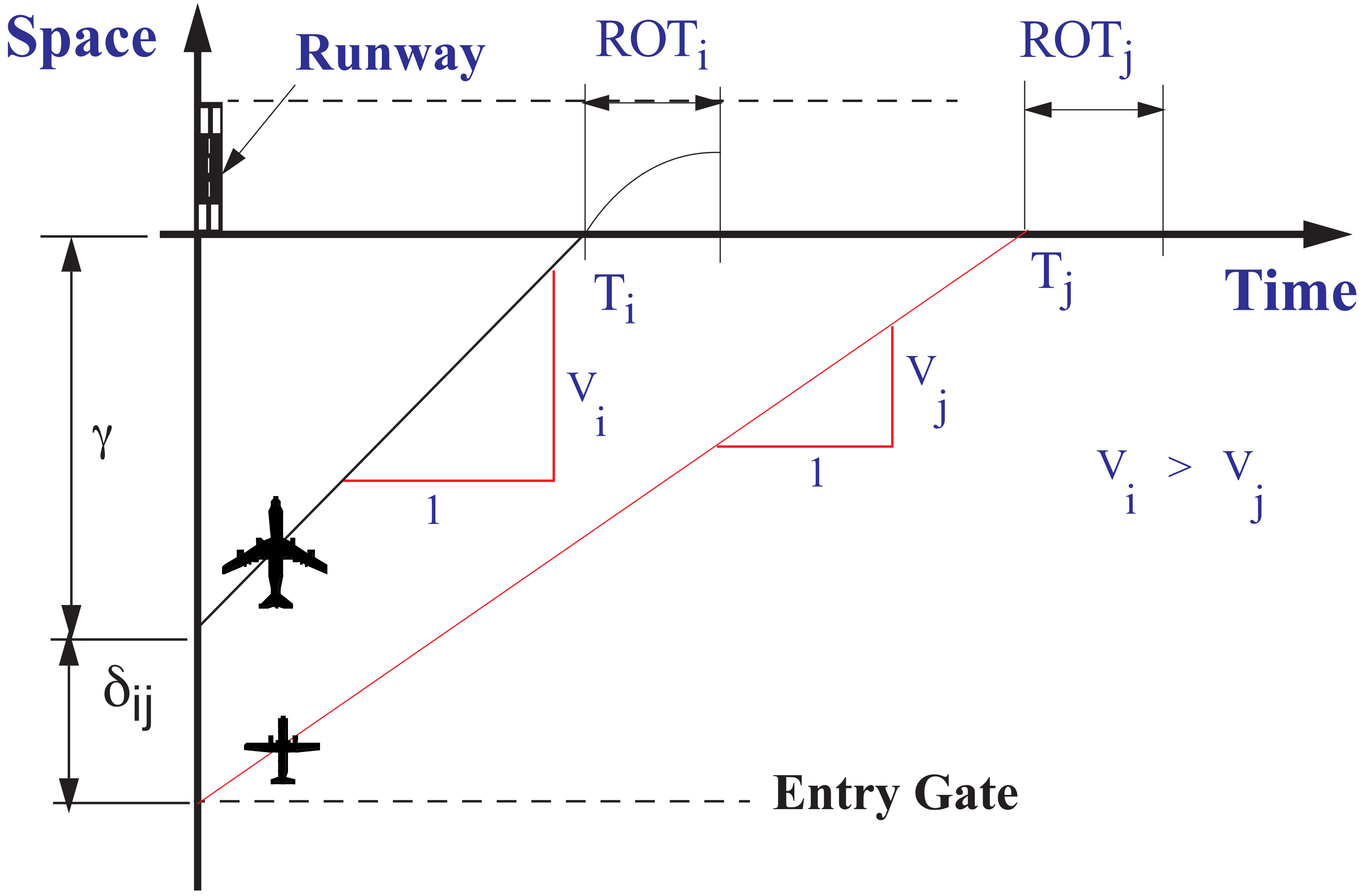


Since aircraft approaching a runway arrive in a random pattern we distinguish between two possible scenarios:

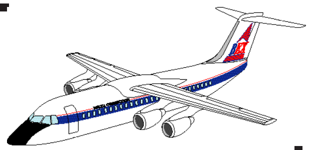
- Opening Case - Instance when the approach speed of lead aircraft is higher than trailing aircraft ($V_i > V_j$)
- Closing case - Instance when the approach of the lead aircraft is less than that of the trailing aircraft ($V_i \leq V_j$)

Opening Case Diagram (Arrivals Only)





Opening Case (Equations)



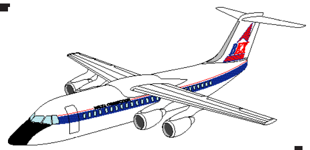
Error free headway, $T_{ij} = T_j - T_i$, (no pilot and ATC controller error) assuming control is exercised as the lead aircraft passes the entry gate,

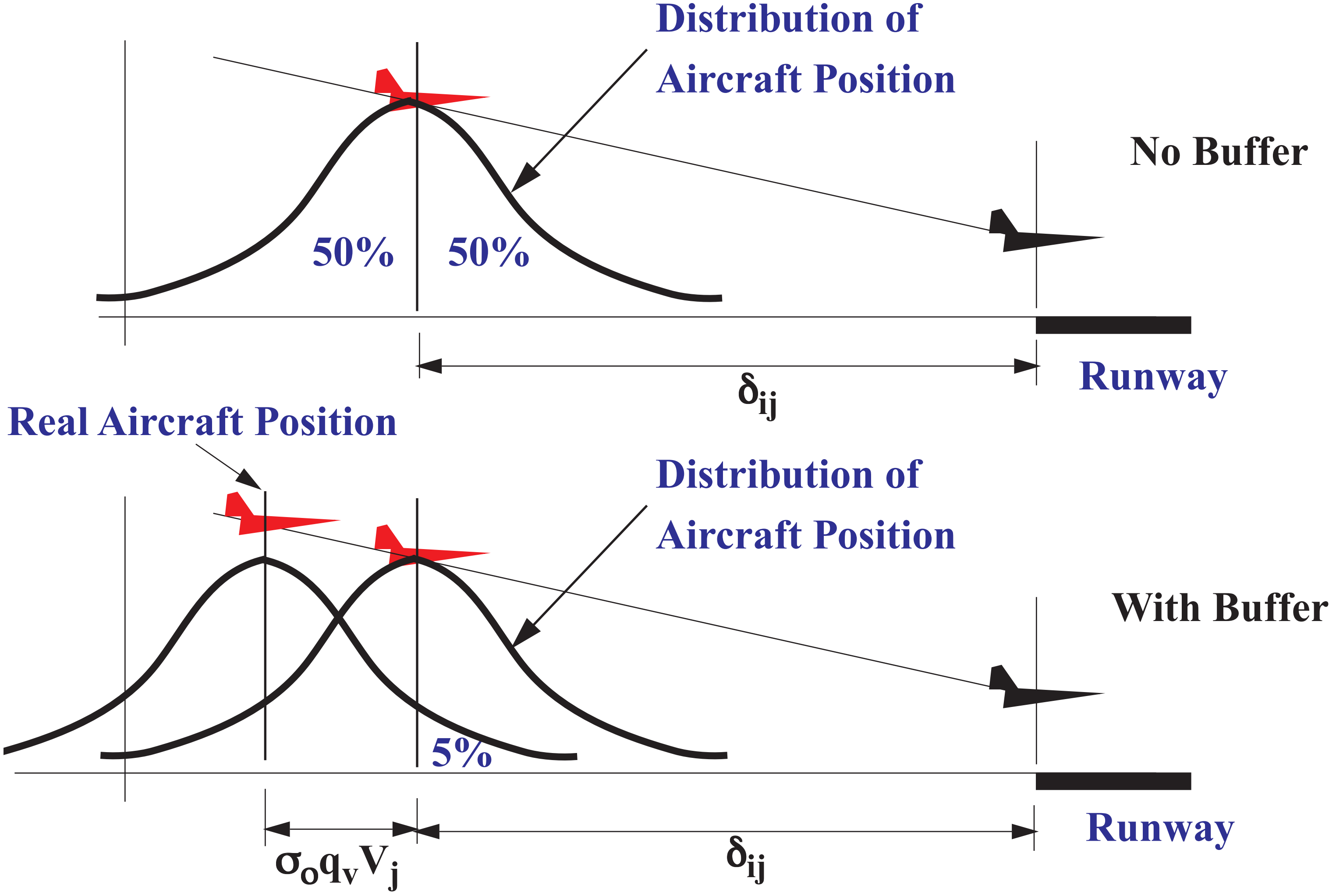
$$T_{ij} = \frac{\delta_{ij}}{V_j} + \gamma\left(\frac{1}{V_j} - \frac{1}{V_i}\right) \qquad (2)$$

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

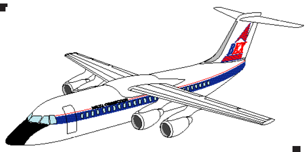
$$B_{ij} = \sigma_o q_v - \delta_{ij}\left(\frac{1}{V_j} - \frac{1}{V_i}\right) \text{ or zero if } B_{ij} < 0. \qquad (3)$$

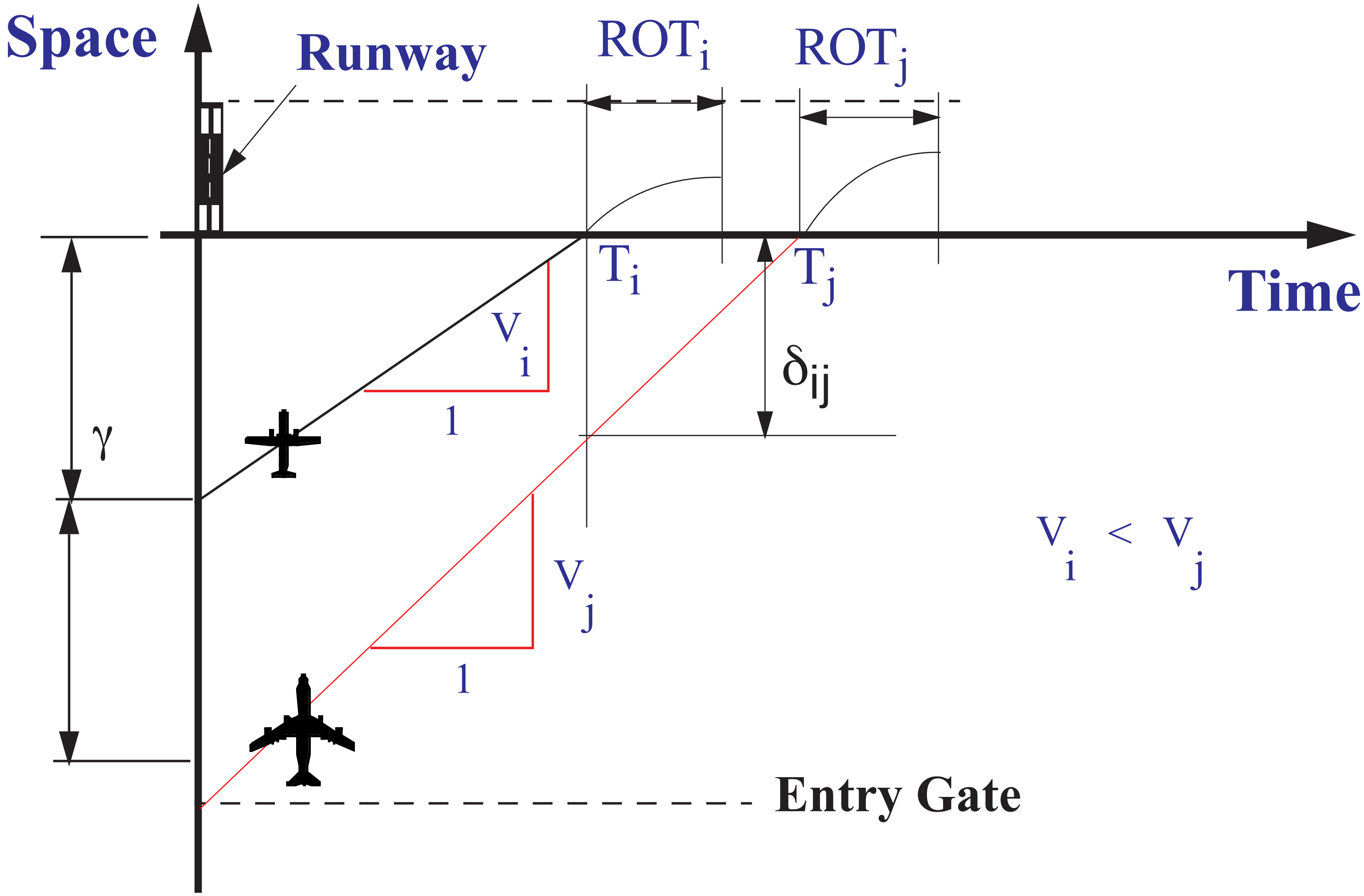
Understanding Position Errors



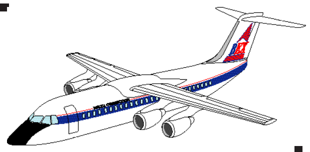


Closing Case Diagram (Arrivals Only)





Closing Case (Equations)

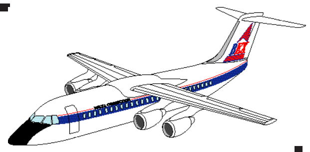


Error free headway, $T_{ij} = T_j - T_i$ (no pilot and ATC controller error) with the minimum separation enforced when the lead aircraft passes the runway threshold,

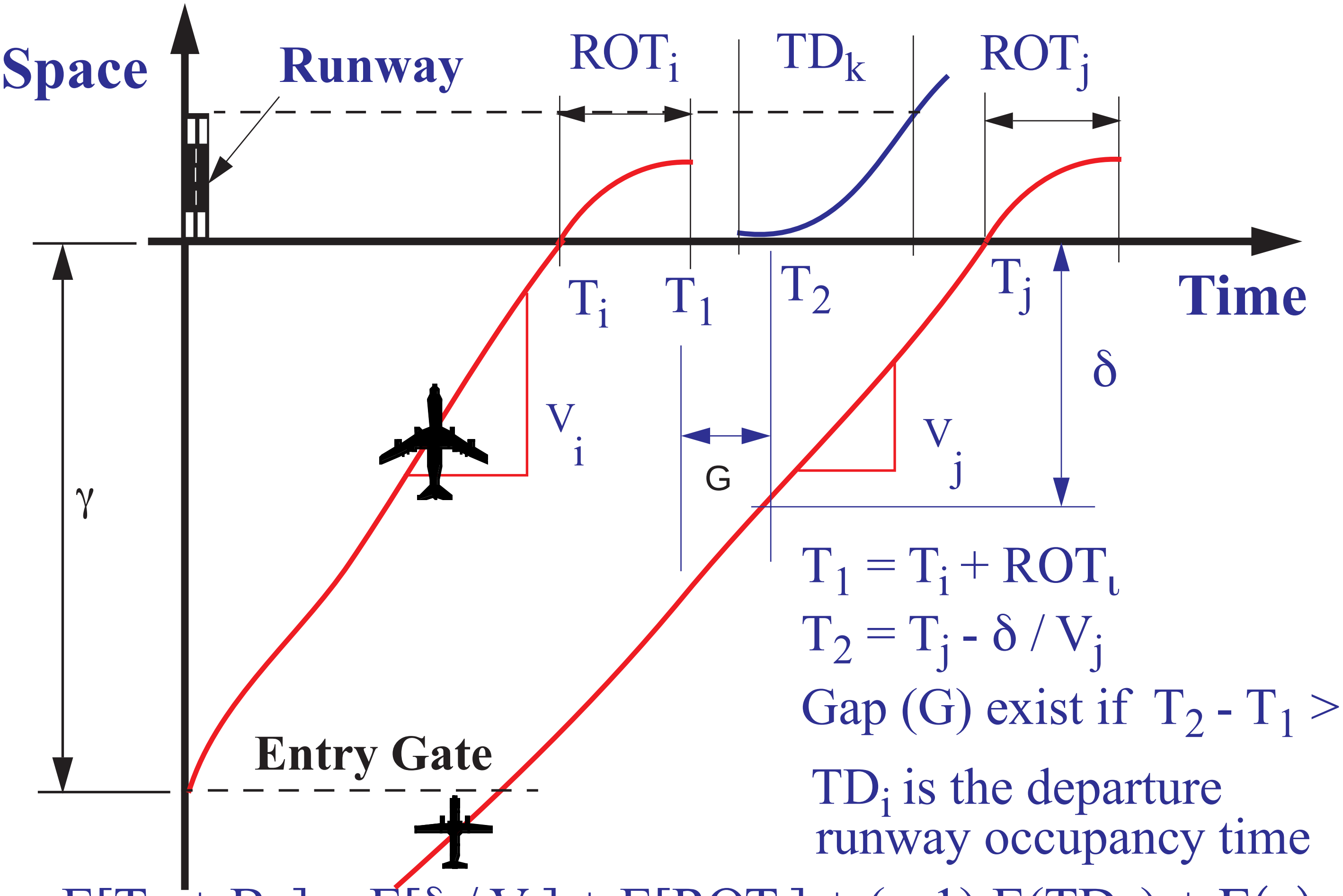
$$T_{ij} = \frac{\delta_{ij}}{V_j} \qquad (4)$$

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

$$B_{ij} = \sigma_o q_v \qquad (5)$$



Mixed Operations Diagram



$T_1 = T_i + ROT_\iota$

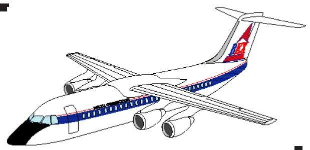
$T_2 = T_j - \delta / V_j$

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

TD_i is the departure runway occupancy time

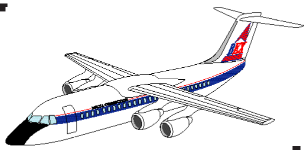
$$E[T_{ij} + B_{ij}] = E[\delta / V_j] + E[ROT_i] + (n-1)\,E(TD_k) + E(\tau)$$

Mixed Operations Notes



- The arriving aircraft leave natural gaps in the time space diagram
- When gaps (*G*) are sufficiently 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)

Mixed Operations Notes



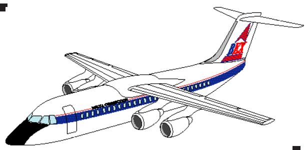
- In the U.S. the current minimum separation between arrivals and departures (δ) is 2 nautical miles

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.

$$G = T_2 - T_1 \tag{6}$$

Mixed Operations (Gap Analysis)



Mathematically,

$$T_1 = T_i + ROT_i \qquad (7)$$

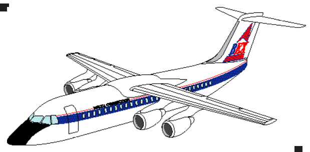
and

$$T_2 = T_j - \frac{\delta}{V_j} \qquad (8)$$

then

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

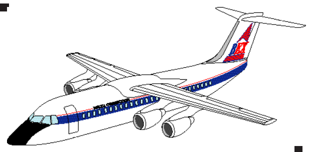
Mixed Operations (Gap Analysis)



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

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 now concentrates in finding suitable gaps between successive aircraft arrivals leaving.

Gap Analysis



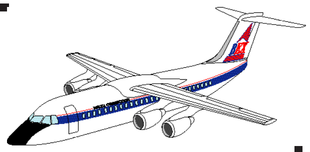
Assume that we would like to find instances such that the gap is zero. This is the limiting case to schedule one departure between successive arrivals.

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

knowing

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

Gap Analysis

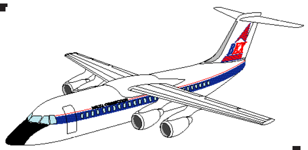


$$(T_{ij} + B_{ij}) = \frac{\delta}{V_j} + ROT_i \tag{13}$$

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

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

where TD_k is the runway occupancy time of departure k. This expression typically applies under VFR conditions because controllers can dispatch aircraft as

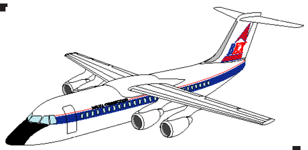


soon as the previous departure clears the runway end (provided that the lead aircraft turns quickly away from runway heading).

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.

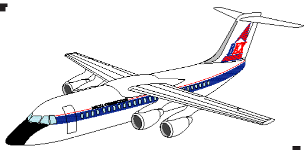
Gap Analysis



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

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 the time delay term Equation (14) becomes,

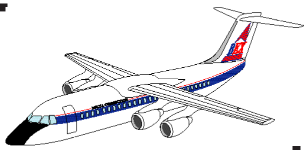
$$(T_{ij} + B_{ij}) = \frac{\delta}{V_j} + ROT_i + (n-1)\varepsilon_{ij} + \tau \qquad (16)$$

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

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

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

Gap Analysis

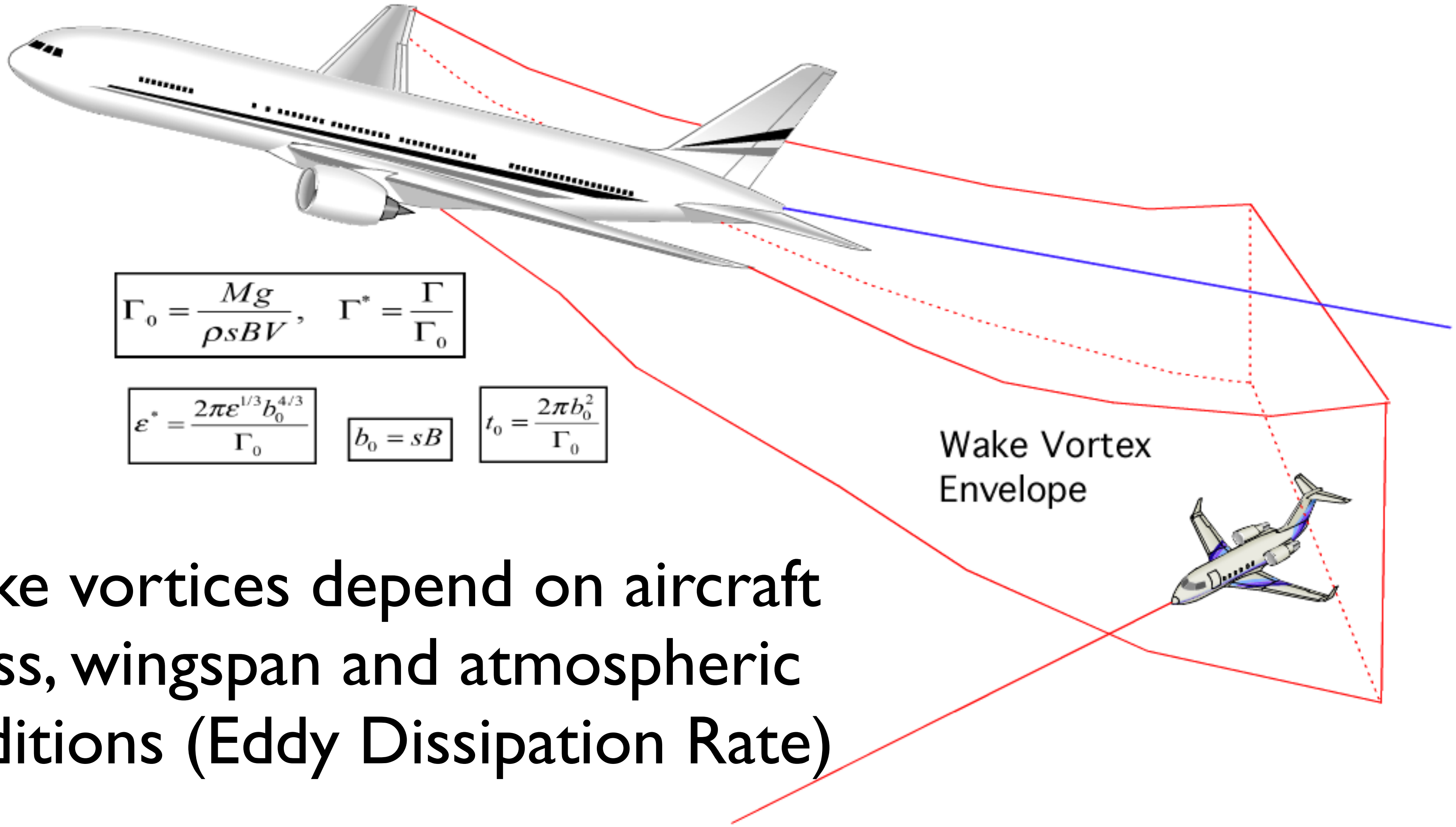


The use of Equation (17) allows us to estimate whether the natural gaps left by successive arrivals (expressed as the expected value of $(T_{ij} + B_{ij})$) is large enough to schedule n departures.

The practical use of Equation (17) is to compare the actual headways between successive arrivals $(T_{ij} + B_{ij})$ against the sum of all four terms in the right hand side of Equation (17). We do this for various possible departure scenarios that include n departures (typically 1, 2, 3, ... 6 departures).

Aircraft Separations

- Every aircraft generates wakes behind the wing due to the strong circulation (Γ) required to generate lift

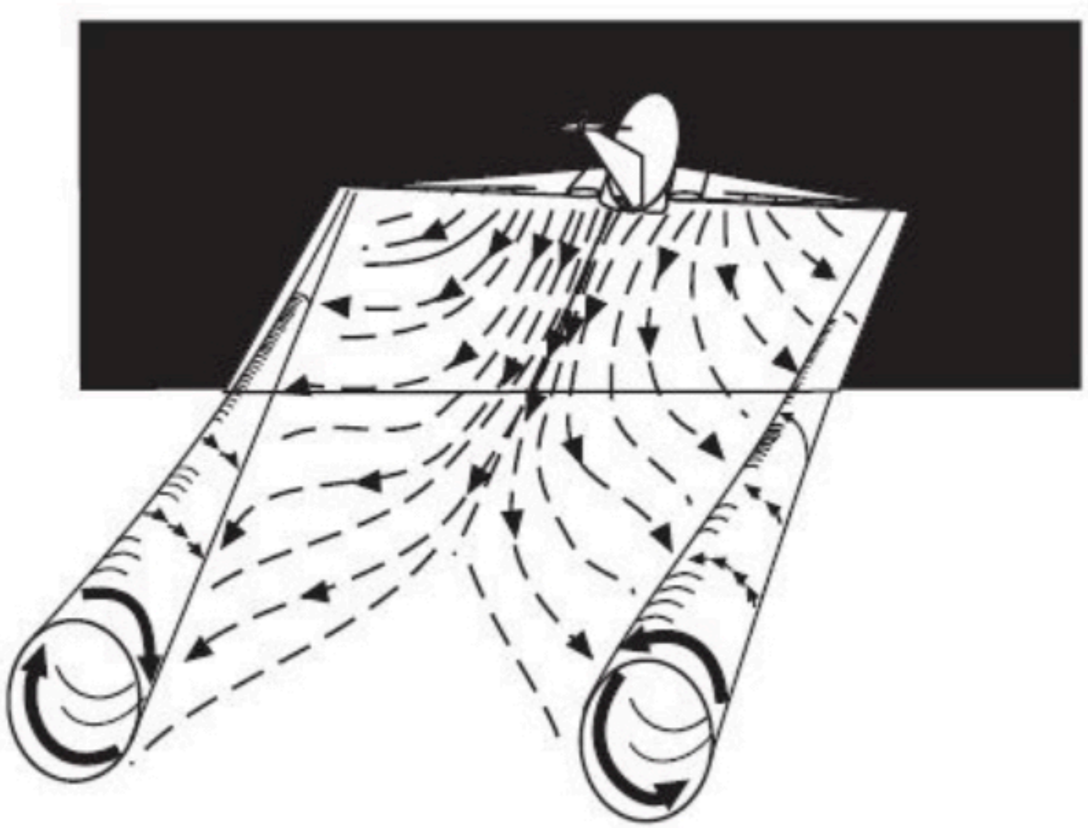


$$\boxed{\Gamma_0 = \frac{Mg}{\rho s B V}, \quad \Gamma^* = \frac{\Gamma}{\Gamma_0}}$$

$$\boxed{\varepsilon^* = \frac{2\pi\varepsilon^{1/3} b_0^{4/3}}{\Gamma_0}} \quad \boxed{b_0 = sB} \quad \boxed{t_0 = \frac{2\pi b_0^2}{\Gamma_0}}$$

Wake vortices depend on aircraft mass, wingspan and atmospheric conditions (Eddy Dissipation Rate)

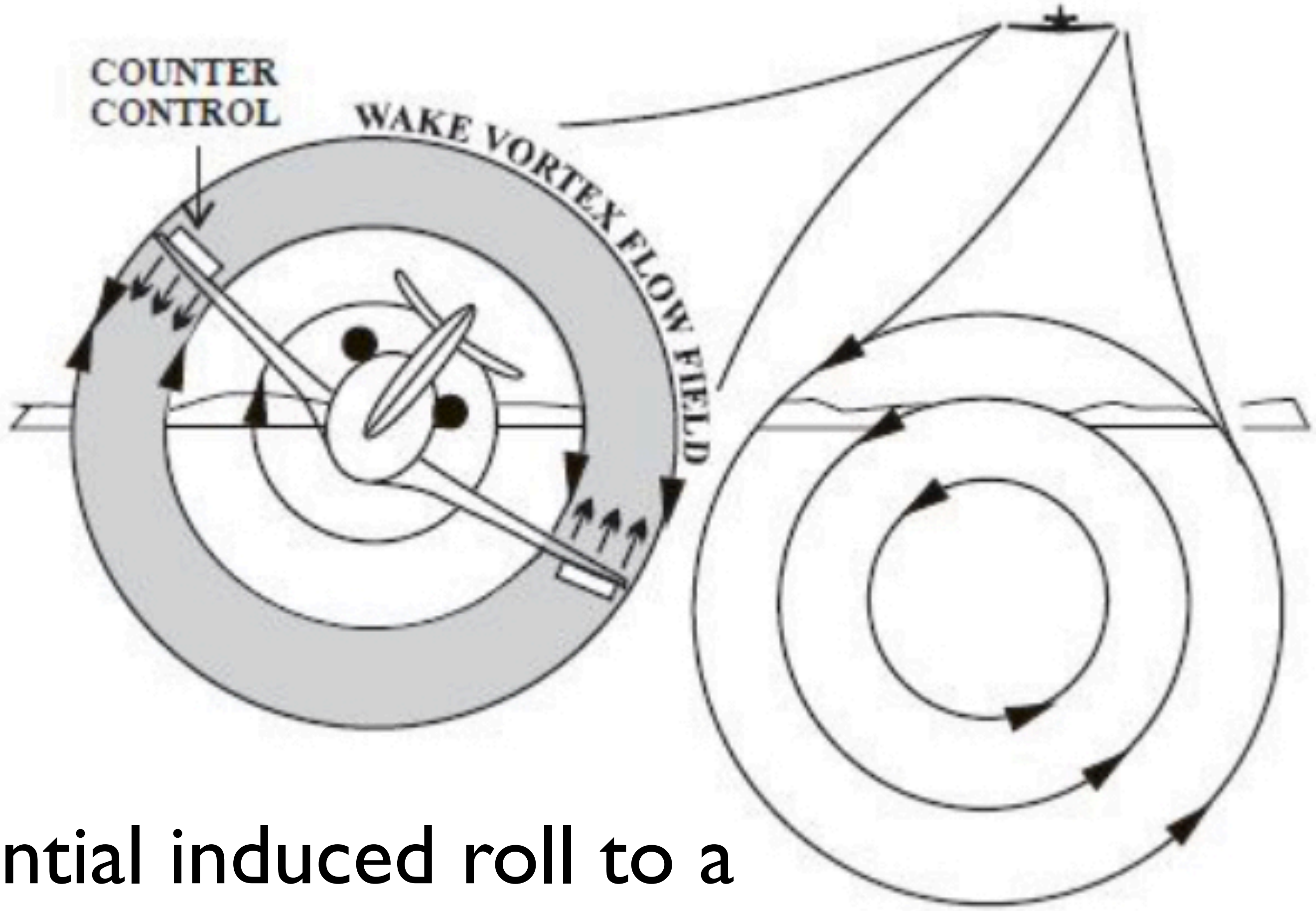
Wake Vortex Issues



Source: https://www.faa.gov/air_traffic/publications/atpubs/aim_html/chap7_section_4.html

Greatest danger is when aircraft are heavy, clean (no flap configuration and flying slow)

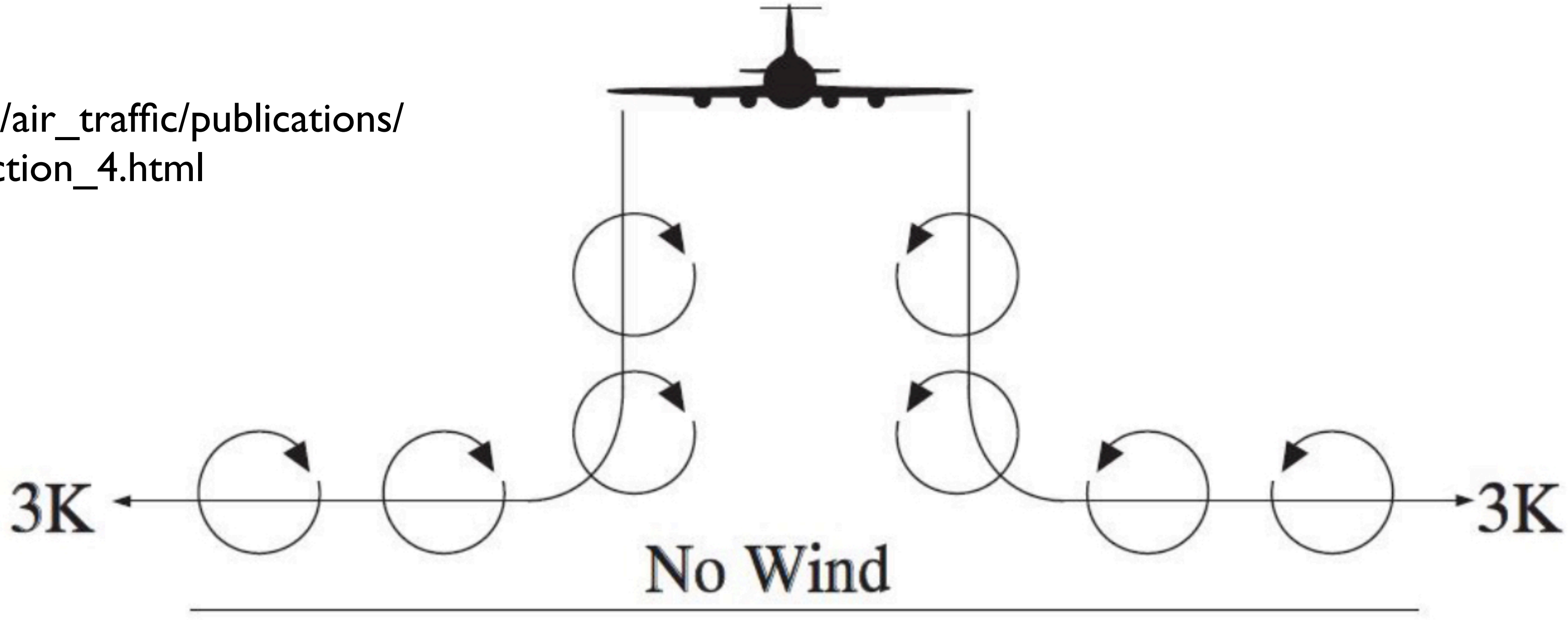
For heavy aircraft, wakes may last 150-200 seconds behind the generating aircraft



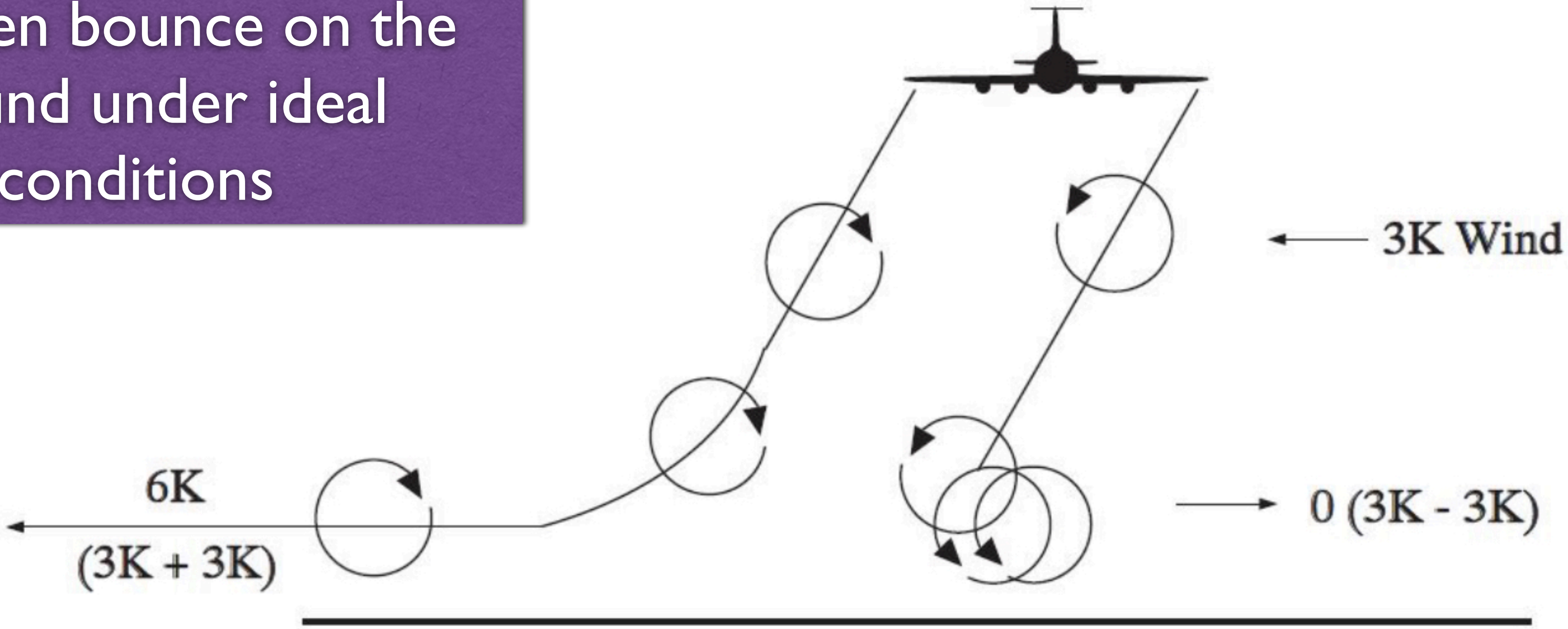
Potential induced roll to a following aircraft

Wake Vortex Issues (2)

Source: https://www.faa.gov/air_traffic/publications/atpubs/aim_html/chap7_section_4.html



Wakes can travel laterally and even bounce on the ground under ideal conditions



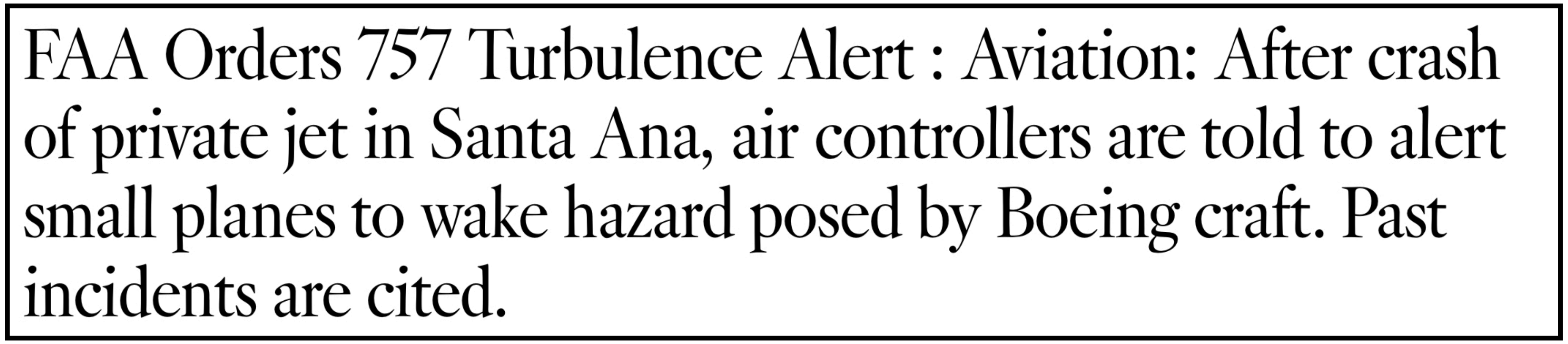
Wake Vortex Issues (3)

Wake vortex visualization behind a small regional jet (VFW 614)

https://commons.wikimedia.org/wiki/File:Visualisation_of_a_wake_vortex_ATTAS.jpg

Wake Vortex Classifications (History)

- 1970s - FAA develops a legacy wake vortex classification (small, large, heavy)
- 1993 - FAA adds Boeing 757-200 to the legacy classification as a group (at the time ATC handles the Boeing 757-200 like a heavy)

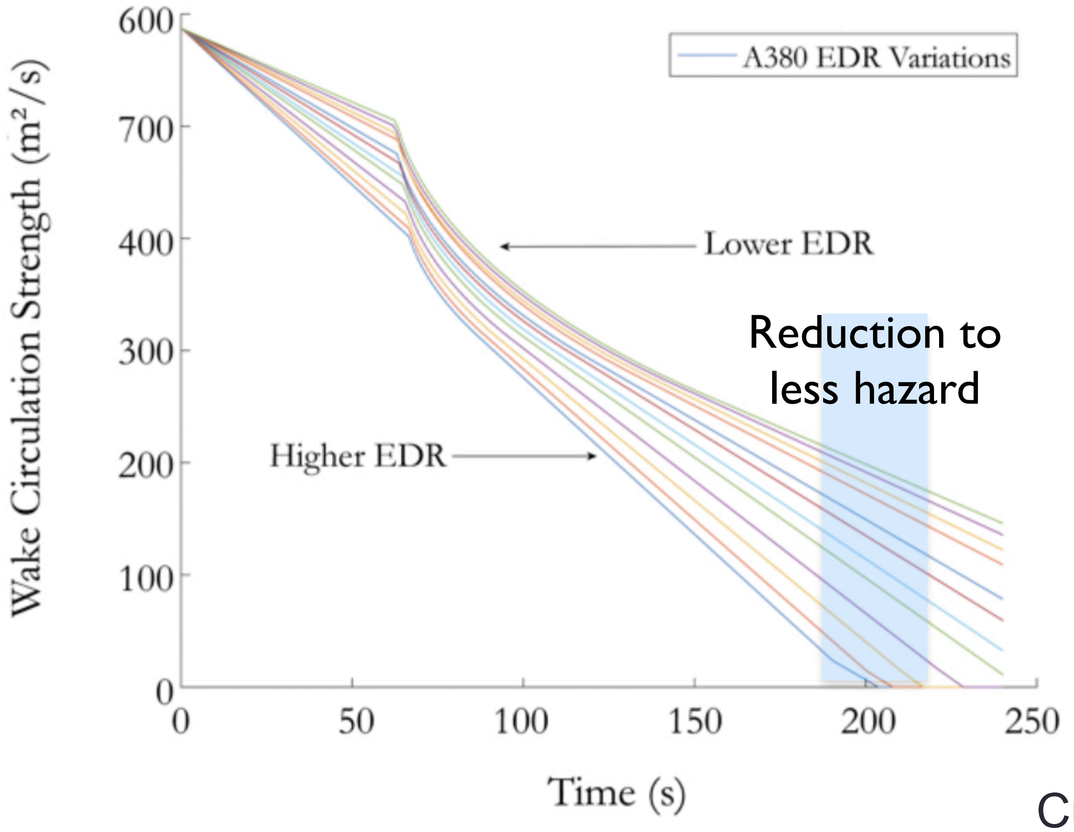


FAA Orders 757 Turbulence Alert : Aviation: After crash of private jet in Santa Ana, air controllers are told to alert small planes to wake hazard posed by Boeing craft. Past incidents are cited.

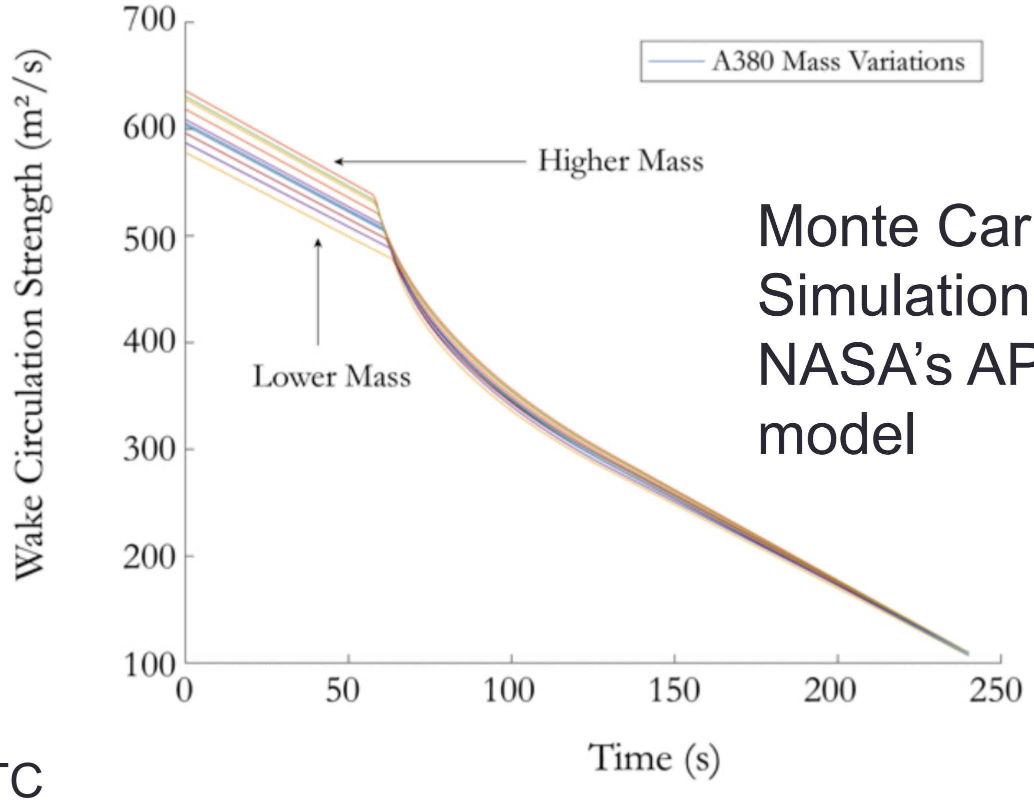
Source: Los Angeles Times (December/23/1993)

- 2012 - FAA implements RECAT (re-categorization Phase 1) with 6 or 7 groups
- 2019 - FAA develops a Consolidated Wake Turbulence Classification (CWT) with 9 groups

Wake Modeling using NASA's APA Model : Arrival Configuration (Source: J. Roa, Virginia Tech, 2019)



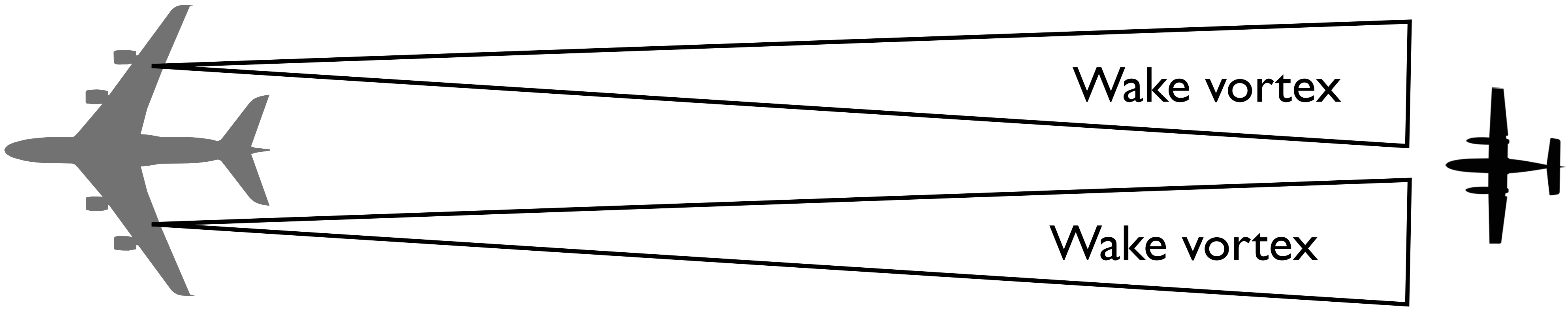
Reduction to less hazard



Monte Carlo Simulation using NASA's APA model

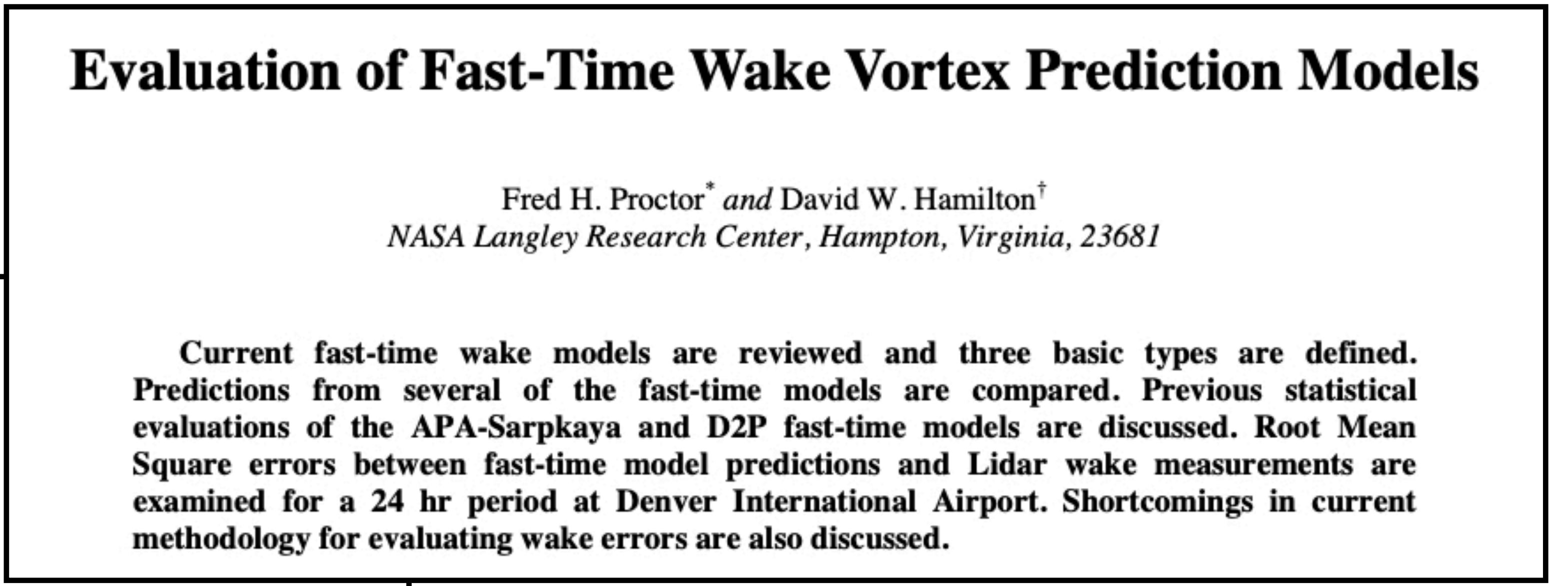
Current ATC separation behind class A is 240 seconds

Airbus A380
RECAT A



Cessna 441
RECAT F

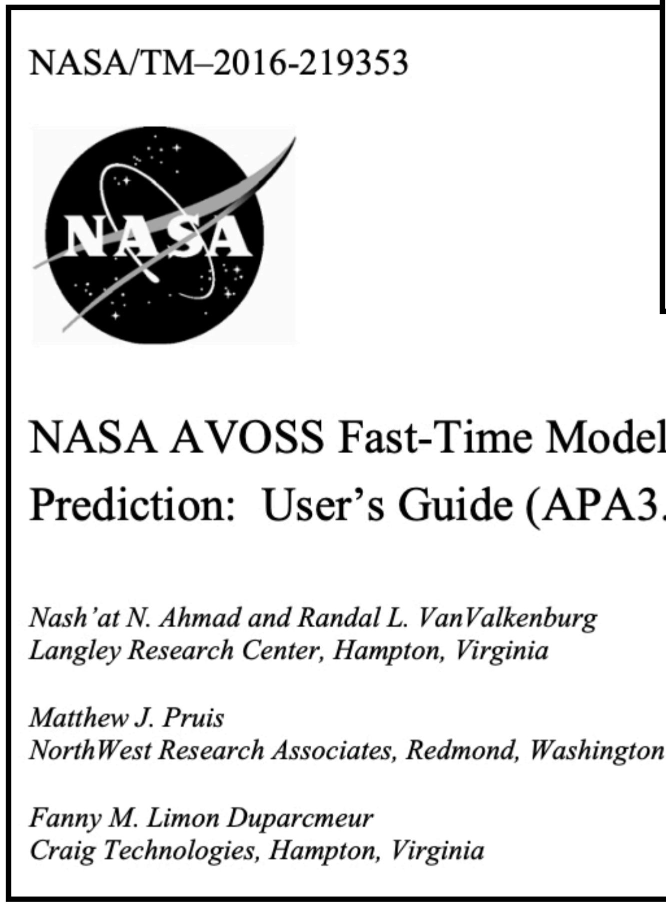
Learn More About Aircraft Wakes



Evaluation of Fast-Time Wake Vortex Prediction Models

Fred H. Proctor* *and* David W. Hamilton†
NASA Langley Research Center, Hampton, Virginia, 23681

Current fast-time wake models are reviewed and three basic types are defined. Predictions from several of the fast-time models are compared. Previous statistical evaluations of the APA-Sarpkaya and D2P fast-time models are discussed. Root Mean Square errors between fast-time model predictions and Lidar wake measurements are examined for a 24 hr period at Denver International Airport. Shortcomings in current methodology for evaluating wake errors are also discussed.



NASA/TM–2016-219353

NASA AVOSS Fast-Time Models for Aircraft Wake Prediction: User's Guide (APA3.8 and TDP2.1)

Nash'at N. Ahmad and Randal L. VanValkenburg
Langley Research Center, Hampton, Virginia

Matthew J. Pruis
NorthWest Research Associates, Redmond, Washington

Fanny M. Limon Duparcmeur
Craig Technologies, Hampton, Virginia

Simulation of Runway Operations with Application of Dynamic Wake Separations to Study Runway Limitations

Julio Roa, Antonio Trani, [...], and Navid Mirmohammadsadeghi +1 View all authors and affiliations

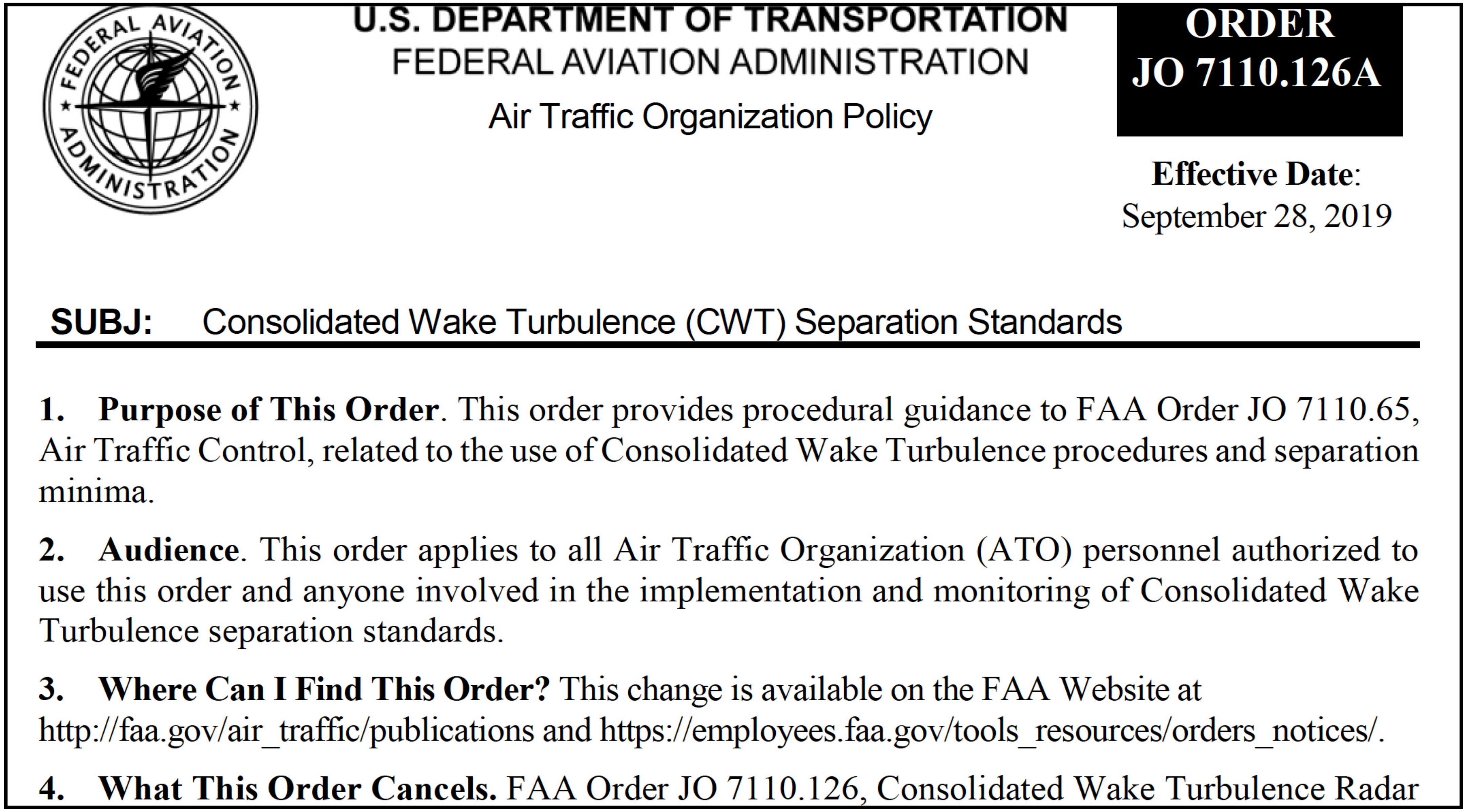
Volume 2674, Issue 12 | https://doi.org/10.1177/0361198120953152

Abstract

This paper presents an evaluation of runway operations at Chicago O'Hare International Airport to estimate the impact of proposed wake vortex separation including Recategorization Phase II and III dynamic separations. The evaluation uses a Monte Carlo simulation model that considers arrival and departure operations. The simulation accounts for static and dynamic wake vortex separations, aircraft fleet mix, runway occupancy times, aircraft approach speeds, aircraft wake circulation capacity, environmental conditions, and operational error buffers. Airport data considered for this analysis are based on Airport Surface Detection Equipment Model X records from Chicago O'Hare International Airport from January to November 2016. Dynamic wake separations are tailored to each unique set of conditions by using environmental and aircraft performance parameters as input and allowing aircraft to be exposed to the same wake vortex strength as in Recategorization Phase II (RECAT II). The analysis shows that further reductions beyond RECAT II for aircraft pairs separated by 2 nautical miles or less is not operationally feasible. These wake separations already result in little to no wake dependency. When this is the case, the challenges in wake separation are to meet runway occupancy times and to make sure aircraft separations allow for human operational variations without resulting in aircraft turnarounds or double-aircraft-

Consolidated Wake Turbulence Recategorization Classification (CWT)

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



U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Air Traffic Organization Policy

ORDER
JO 7110.126A

Effective Date:
September 28, 2019

SUBJ: Consolidated Wake Turbulence (CWT) Separation Standards

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.

2. **Audience**. This order applies to all Air Traffic Organization (ATO) personnel authorized to use this order and anyone involved in the implementation and monitoring of Consolidated Wake Turbulence separation standards.

3. **Where Can I Find This Order?** This change is available on the FAA Website at http://faa.gov/air_traffic/publications and https://employees.faa.gov/tools_resources/orders_notices/.

4. **What This Order Cancels.** FAA Order JO 7110.126, Consolidated Wake Turbulence Radar

Consolidated Wake Vortex Recategorization Classification

- *"FAA Order JO 7110.659 (RECAT 1.5) classified aircraft according to certificated takeoff weight, landing speed, wingspan, and the aircraft's ability to withstand a wake encounter."*
- *"FAA Order JO 7110.123 (RECAT Phase II), Appendix A and Appendix B, described a pairwise separation matrix developed for the most common ICAO type identifier aircraft. Each aircraft was addressed as both a leader and a follower in each pair."*
- *"The development of a* ***pairwise separation matrix*** *relied on wake-based data, rather than weight-based data."*
- *"Separation reductions were achieved with a better understanding of wake behavior and with pairwise separation of aircraft."*
- *"CWT is based on a nine category system that further refines the grouping of aircraft, provides throughput gains at many of today's constrained airports, and is manageable for all airports throughout the NAS."*

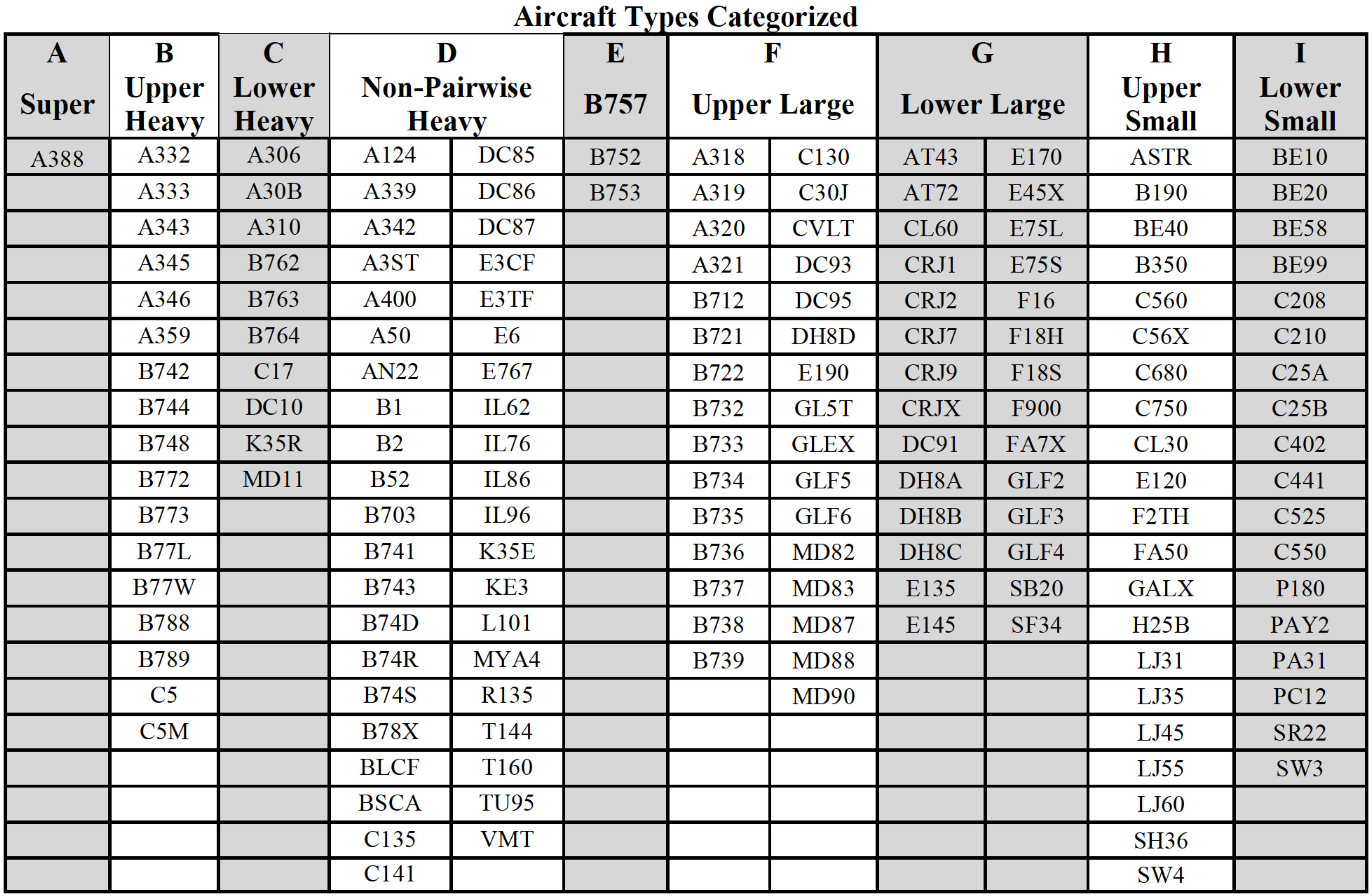
Source: FAA Order JO 7110.126A

Consolidated Wake Turbulence (CWT) Re-categorization Classification

Category	Description
A	A388
B	Pairwise Upper Heavy aircraft
C	Pairwise Lower Heavy aircraft
D	Non-Pairwise Heavy aircraft (infrequent operations)
E	Boeing 757 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 7110.126A

Consolidated Wake Vortex Recategorization Classification



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
	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
			BLCF	T160						LJ55	SW3
			BSCA	TU95						LJ60	
			C135	VMT						SH36	
			C141							SW4	

Source: FAA Order JO 7110.126A

Wake Vortex Classification (CWT Categories)

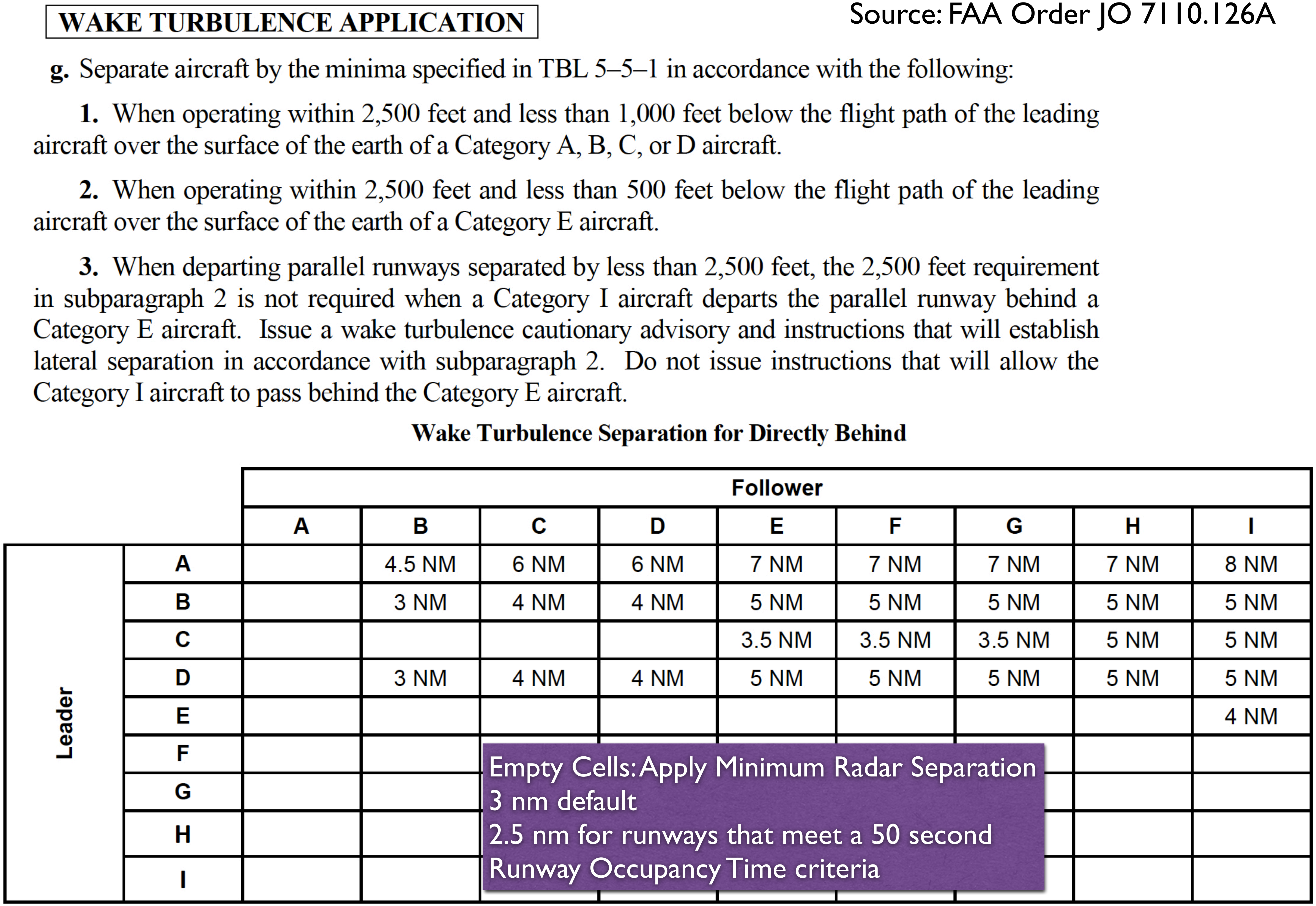
RECAT Class	*Representative Aircraft*	*Picture of Representative Aircraft*
A Super	***Airbus A380-800***	
B Upper Heavy	***Boeing 747-400, Boeing 777-300ER, Airbus A330-300, Airbus A350-900, Airbus A300-600, Boeing 787-8/9***	
C Lower Heavy	***McDonnell Douglas DC-10, Boeing MD-10, Boeing Douglas MD-11, Boeing 767-300***	
D Non-pairwise Heavy	***Airbus A340, KC-10, E3CF, A400***	
E B757	***Boeing 757-200 and 757-300***	

Wake Vortex Classification (CWT Categories)

RECAT Class	*Representative Aircraft*	*Picture of Representative Aircraft*
F *Upper Large*	***Boeing 737-800, Boeing 737-9Max, Airbus A320, Airbus A321, McDonnell Douglas MD-80, Embraer 190, Bombardier CS-300***	
G *Lower Large*	***Embraer 170/175, Bombardier CRJ-900, Bombardier CRJ-700, Embraer 145, Bombardier CRJ-200, Gulfstream 550, Falcon 7X, Saab 2000***	
H *Upper Small*	***Bombardier Challenger 350, Cessna Citation X, Dassault Falcon 50, Raytheon Hawker 800XP***	
I *Lower Small*	***Cessna CitationJet 2, Cessna 182, Cessna 172***	

Consolidated Wake Vortex Separations - **Directly Behind**

Source: FAA Order JO 7110.126A



WAKE TURBULENCE APPLICATION

g. Separate aircraft by the minima specified in TBL 5–5–1 in accordance with the following:

1. When operating within 2,500 feet and less than 1,000 feet below the flight path of the leading aircraft over the surface of the earth of a Category A, B, C, or D aircraft.

2. When operating within 2,500 feet and less than 500 feet below the flight path of the leading aircraft over the surface of the earth of a Category E aircraft.

3. When departing parallel runways separated by less than 2,500 feet, the 2,500 feet requirement in subparagraph 2 is not required when a Category I aircraft departs the parallel runway behind a Category E aircraft. Issue a wake turbulence cautionary advisory and instructions that will establish lateral separation in accordance with subparagraph 2. Do not issue instructions that will allow the Category I aircraft to pass behind the Category E aircraft.

Wake Turbulence Separation for Directly Behind

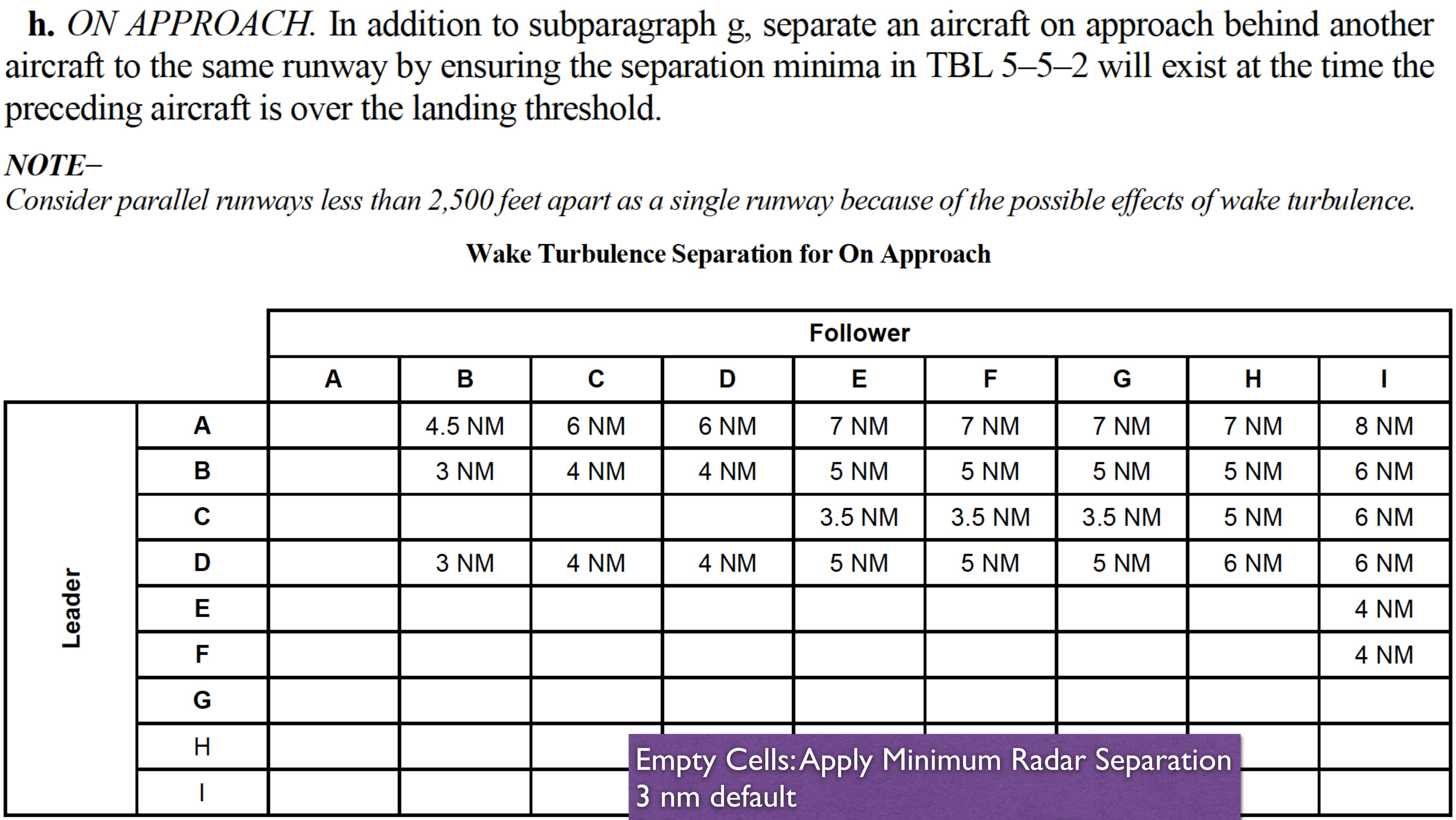
		Follower								
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Leader	**A**		4.5 NM	6 NM	6 NM	7 NM	7 NM	7 NM	7 NM	8 NM
	B		3 NM	4 NM	4 NM	5 NM	5 NM	5 NM	5 NM	5 NM
	C					3.5 NM	3.5 NM	3.5 NM	5 NM	5 NM
	D		3 NM	4 NM	4 NM	5 NM	5 NM	5 NM	5 NM	5 NM
	E									4 NM
	F									
	G									
	H									
	I									

Empty Cells: Apply Minimum Radar Separation
3 nm default
2.5 nm for runways that meet a 50 second Runway Occupancy Time criteria

Typical Wake Vortex Behavior

- Boeing 737-800 class (RECAT F in new consolidated wake turbulence class)
  - Wake descends up to 500 feet in 60-90 seconds
  - Time for wake vortex to dissipate ~ 60-90 seconds
- Boeing 777-300 class (RECAT B)
  - Wake descends up to 800 feet in 100-150 seconds
  - Time for wake vortex to dissipate ~ 120-150 seconds
- Airbus A380 class (RECAT A)
  - Wake descends up to 1000 feet in 150-240 seconds
  - Time for wake vortex to dissipate ~ 180-240 seconds

Consolidated Wake Vortex Separations - **On Approach**



h. *ON APPROACH.* In addition to subparagraph g, separate an aircraft on approach behind another aircraft to the same runway by ensuring the separation minima in TBL 5–5–2 will exist at the time the preceding aircraft is over the landing threshold.

NOTE–
Consider parallel runways less than 2,500 feet apart as a single runway because of the possible effects of wake turbulence.

Wake Turbulence Separation for On Approach

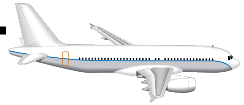
		Follower								
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Leader	**A**		4.5 NM	6 NM	6 NM	7 NM	7 NM	7 NM	7 NM	8 NM
	B		3 NM	4 NM	4 NM	5 NM	5 NM	5 NM	5 NM	6 NM
	C					3.5 NM	3.5 NM	3.5 NM	5 NM	6 NM
	D		3 NM	4 NM	4 NM	5 NM	5 NM	5 NM	6 NM	6 NM
	E									4 NM
	F									4 NM
	G									
	H									
	I									

Empty Cells: Apply Minimum Radar Separation
3 nm default
2.5 nm for runways that meet a 50 second Runway Occupancy Time criteria

Source: FAA Order JO 7110.126A

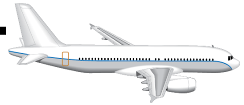
Implications of Aircraft Wake Classes

- In-trail separations are driven by wake class groups
- Runway capacity today is usually limited by in-trail separations
- For mixed operations, runway occupancy times are also be important



Aircraft Categories Used in Airport Runway Analysis

- Today, the FAA employs 5 aircraft groups to establish aircraft separations inside the terminal area:
  - Small, Large, B757, Heavy and Superheavy
  - The class Small + is seldom used for actual separations
- Today, ICAO (international body that regulates aviation activities outside the US) has 4 aircraft groups
  - Light, Medium, Heavy and Superheavy (A380)
- Many air navigation service providers may have deviations from these groups or classes (i.e., NAT UK recognizes 6 groups)



VMC 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% 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

Air Traffic Control (ATC) Departure-Departure In-Trail Separations

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

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

Separations are in seconds

Example 1: Single Runway Problem

- West Coast single runway airport (like San Diego)
- Three aircraft CWT groups operating at the airport

Aircraft CWT Group	F	E	B
ROT (s)	51	54	65
Percent Mix (%)	82	10	8
Vapproach (knots)	132	137	151

Problem Description

- West Coast single runway airport
- Three aircraft groups operate at the airport

Technical Parameters (inputs)	Values
Departure-Arrival Separation (nm)	2
Common Approach Length (nm)	12
Standard deviation of Position Delivery Error (s)	20
Probability of Violation - P_v	5
Cumulative Normal at (at 5% violation)	1.65
Buffer for departure-departure (seconds)	10

Data Sources to Obtain ROT and Approach Speeds Data

Landing Events Database (version 1.3.7)

You can download the landing events database at:

https://atsl.cee.vt.edu/products/runway-exit-design-interactive-model--redim-1.html

Landing Events Database

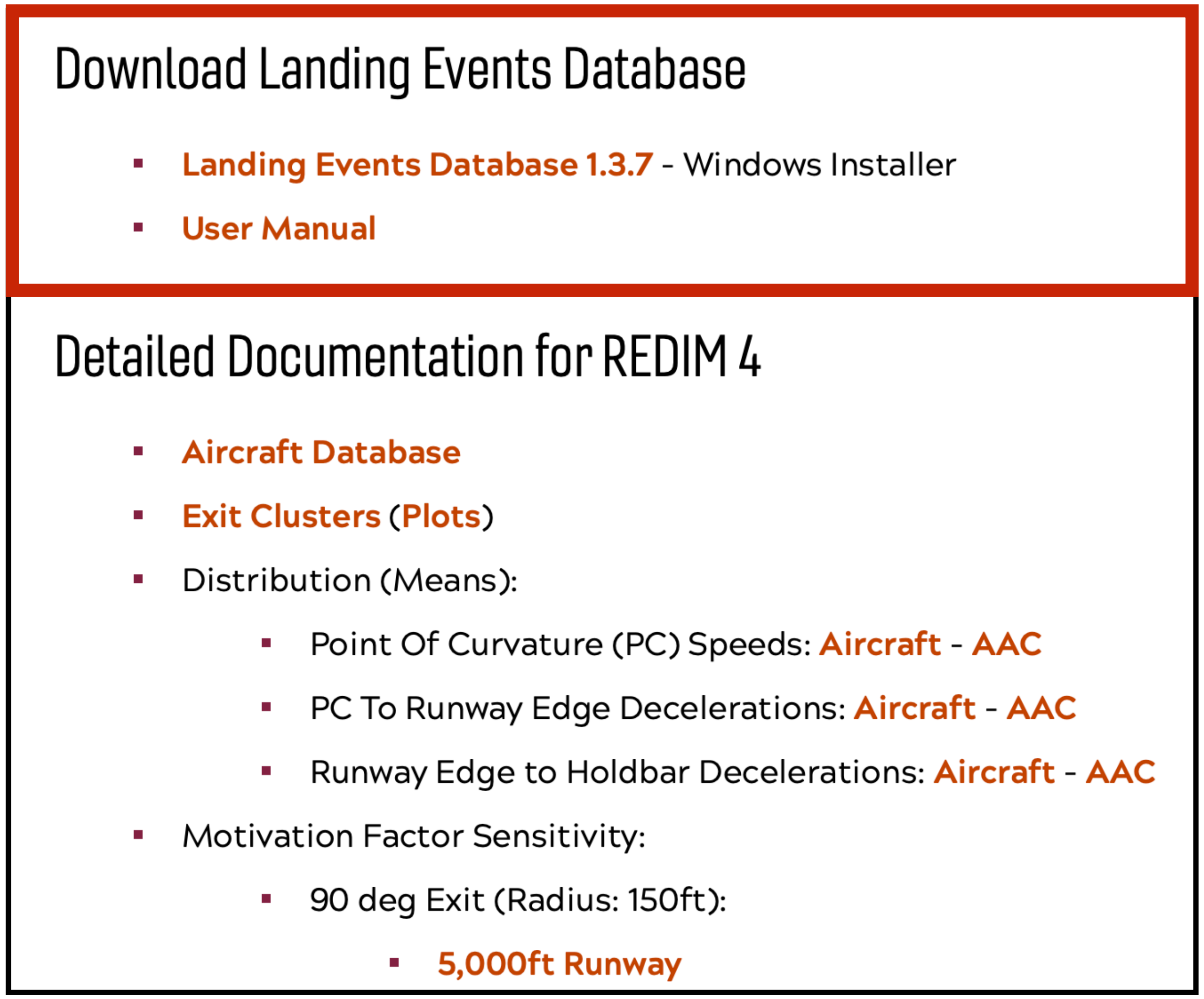
Version 1.3.7

Virginia Tech - Air Transportation Systems Lab

Dr. Antonio Trani (Team Leader)	Mani Bhargava Reddy Bollempalli
Nicolas Hinze (Team Co-Leader)	Mihir Rimjha
Navid Mirmohammadsadeghi	Arman Izadi

FAA - Project Sponsors

Kent Duffy	FAA Airports Planning and Environmental Division (APP-400)
Lauren Vitagliano	FAA William J. Hughes Technical Center



Download Landing Events Database

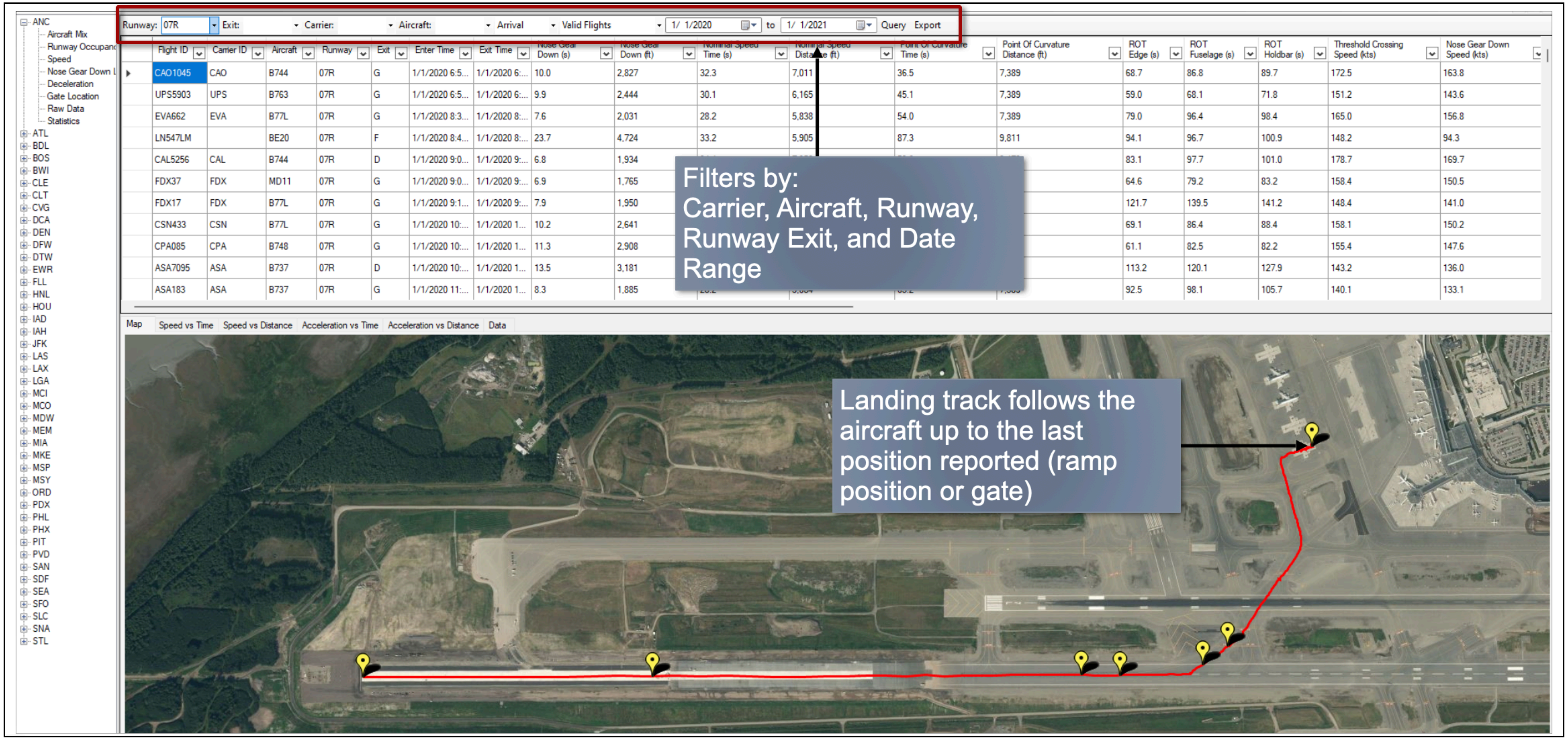
- **Landing Events Database 1.3.7** - Windows Installer
- **User Manual**

Detailed Documentation for REDIM 4

- **Aircraft Database**
- **Exit Clusters** (**Plots**)
- Distribution (Means):
  - Point Of Curvature (PC) Speeds: **Aircraft** - **AAC**
  - PC To Runway Edge Decelerations: **Aircraft** - **AAC**
  - Runway Edge to Holdbar Decelerations: **Aircraft** - **AAC**
- Motivation Factor Sensitivity:
  - 90 deg Exit (Radius: 150ft):
    - **5,000ft Runway**

Landing Events Database (version 1.3.7)

- ROT values can be obtained by airport, aircraft, and runway
- Raw data for Anchorage (ANC) International Airport



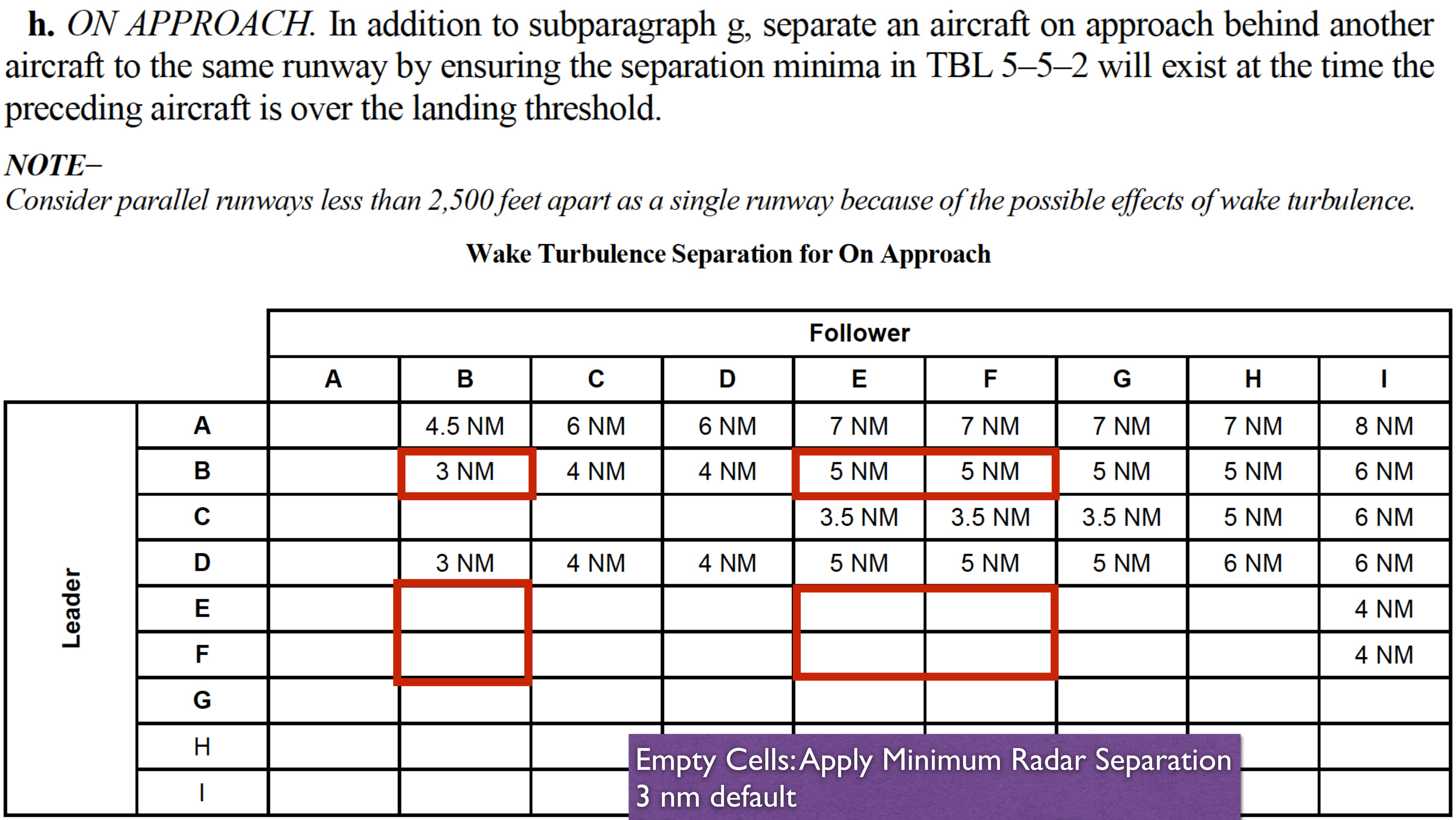
Runway: 07R
Exit:
Carrier:
Aircraft:
Arrival
Valid Flights
1/ 1/2020 to 1/ 1/2021

Flight ID	Carrier ID	Aircraft	Runway	Exit	Enter Time	Exit Time	Nose Gear Down (s)	Nose Gear Down (ft)	Nominal Speed Time (s)	Nominal Speed Distance (ft)	Point Of Curvature Time (s)	Point Of Curvature Distance (ft)	ROT Edge (s)	ROT Fuselage (s)	ROT Holdbar (s)	Threshold Crossing Speed (kts)	Nose Gear Down Speed (kts)
CAO1045	CAO	B744	07R	G	1/1/2020 6:5...	1/1/2020 6:...	10.0	2,827	32.3	7,011	36.5	7,389	68.7	86.8	89.7	172.5	163.8
UPS5903	UPS	B763	07R	G	1/1/2020 6:5...	1/1/2020 6:...	9.9	2,444	30.1	6,165	45.1	7,389	59.0	68.1	71.8	151.2	143.6
EVA662	EVA	B77L	07R	G	1/1/2020 8:3...	1/1/2020 8:...	7.6	2,031	28.2	5,838	54.0	7,389	79.0	96.4	98.4	165.0	156.8
LN547LM		BE20	07R	F	1/1/2020 8:4...	1/1/2020 8:...	23.7	4,724	33.2	5,905	87.3	9,811	94.1	96.7	100.9	148.2	94.3
CAL5256	CAL	B744	07R	D	1/1/2020 9:0...	1/1/2020 9:...	6.8	1,934	[illegible]	[illegible]	[illegible]	[illegible]	83.1	97.7	101.0	178.7	169.7
FDX37	FDX	MD11	07R	G	1/1/2020 9:0...	1/1/2020 9:...	6.9	1,765	[illegible]	[illegible]	[illegible]	[illegible]	64.6	79.2	83.2	158.4	150.5
FDX17	FDX	B77L	07R	G	1/1/2020 9:1...	1/1/2020 9:...	7.9	1,950	[illegible]	[illegible]	[illegible]	[illegible]	121.7	139.5	141.2	148.4	141.0
CSN433	CSN	B77L	07R	G	1/1/2020 10:...	1/1/2020 1...	10.2	2,641	[illegible]	[illegible]	[illegible]	[illegible]	69.1	86.4	88.4	158.1	150.2
CPA085	CPA	B748	07R	G	1/1/2020 10:...	1/1/2020 1...	11.3	2,908	[illegible]	[illegible]	[illegible]	[illegible]	61.1	82.5	82.2	155.4	147.6
ASA7095	ASA	B737	07R	D	1/1/2020 10:...	1/1/2020 1...	13.5	3,181	[illegible]	[illegible]	[illegible]	[illegible]	113.2	120.1	127.9	143.2	136.0
ASA183	ASA	B737	07R	G	1/1/2020 11:...	1/1/2020 1...	8.3	1,885	[illegible]	[illegible]	[illegible]	[illegible]	92.5	98.1	105.7	140.1	133.1

Filters by:
Carrier, Aircraft, Runway, Runway Exit, and Date Range

Landing track follows the aircraft up to the last position reported (ramp position or gate)

Consolidated Wake Vortex Separations - **On Approach**



h. *ON APPROACH.* In addition to subparagraph g, separate an aircraft on approach behind another aircraft to the same runway by ensuring the separation minima in TBL 5–5–2 will exist at the time the preceding aircraft is over the landing threshold.

NOTE–
Consider parallel runways less than 2,500 feet apart as a single runway because of the possible effects of wake turbulence.

Wake Turbulence Separation for On Approach

		Follower								
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Leader	**A**		4.5 NM	6 NM	6 NM	7 NM	7 NM	7 NM	7 NM	8 NM
	B		3 NM	4 NM	4 NM	5 NM	5 NM	5 NM	5 NM	6 NM
	C					3.5 NM	3.5 NM	3.5 NM	5 NM	6 NM
	D		3 NM	4 NM	4 NM	5 NM	5 NM	5 NM	6 NM	6 NM
	E									4 NM
	F									4 NM
	G									
	H									
	I									

Source: FAA Order JO 7110.126A

Empty Cells: Apply Minimum Radar Separation
3 nm default
2.5 nm for runways that meet a 50 second Runway Occupancy Time criteria

Minimum Arrival-Arrival Separation Matrix δ_{ij}

	Trailing Aircraft (Header Columns)		
Lead Aircraft (column 1)	F	E	B
F	3	3	3
E	3	3	3
B	5	5	3

- The minimum radar separation criteria is 3 nm because the runway has runway occupancy times above 50 seconds.

Aircraft CWT Group	F	E	B
ROT (s)	51	54	65

Probability of an Arrival Following Another Arrival Matrix (P_{ij})

	Trailing Aircraft (Header Columns)		
Lead Aircraft (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

The probability matrix implies random arrivals.

Note: Check that the summation of P_{ij} is always one.

Calculation of Error-Free Time Between Arrivals (T_{ij})

- Consider a class E aircraft followed by another class E
- Use the closing case equations

$$T_{ij} = \frac{\delta_{ij}}{V_j} \quad \text{and} \quad B_{ij} = \sigma_0 q_v$$

$$T_{EE} = \frac{\delta_{EE}}{V_E} = \frac{3}{137} = 0.0219 \text{ hours or 79 seconds}$$

$$B_{EE} = (20)1.65 = 33 \text{ seconds}$$

Note: Probability of violation is 5% and $q_v = 1.65$

Calculation of Error-Free Time Between Arrivals (T_{ij})

- Consider a class B (Upper Heavy) aircraft followed by a class F aircraft
- Use the opening case equations

$$T_{ij} = \frac{\delta_{ij}}{V_j} + \gamma\left(\frac{1}{V_j} - \frac{1}{V_i}\right) \quad \text{and} \quad B_{ij} = \sigma_0 q_v - \delta_{ij}\left(\frac{1}{V_j} - \frac{1}{V_i}\right)$$

$$T_{BF} = 178 \quad \text{seconds}$$

$$B_{BF} = 16 \quad \text{seconds}$$

Note: Probability of violation is 5% and $q_v = 1.65$

Error-Free (No Buffers) Time Between Arrivals Matrix (T_{ij})

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

- Use the opening and closing equations described in class.
- Cells in orange are opening cases. White cells are closing cases (including cases with equal approach speeds).

Buffer Matrix (B_{ij})

	Trailing Aircraft (Header Columns)		
Lead Aircraft (column 1)	F	E	B
F	33	33	33
E	30	33	33
B	16	21	33

Buffers are estimated using the opening and closing equations described in class.

Closing or equal speeds

$$B_{ij} = \sigma_0 q_v$$

Opening case

$$B_{ij} = \sigma_0 q_v - \delta_{ij}\left(\frac{1}{V_j} - \frac{1}{V_i}\right)$$

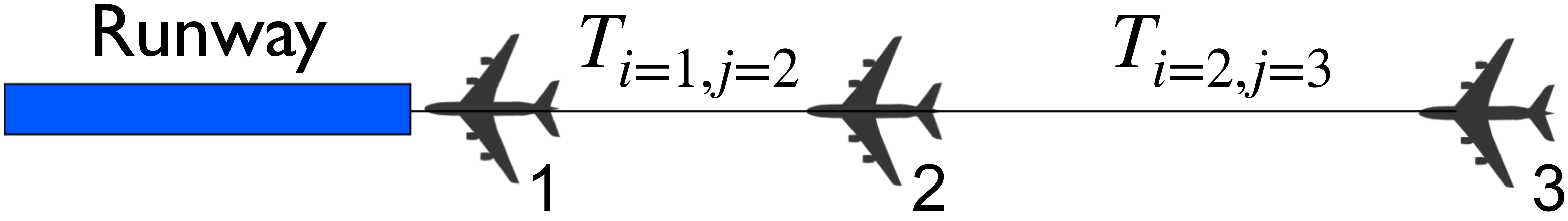
Error-Free Plus Buffer Matrix ($T_{ij} + B_{ij}$)

	Trailing Aircraft (Header Columns)		
Lead Aircraft (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

The $T_{ij} + B_{ij}$ matrix represents real-separations that are expected at the airport and include safety buffers.

$$E(T_{ij} + B_{ij}) = \sum (P_{ij} * (T_{ij} + B_{ij})) = 120.14 \quad \text{Seconds}$$

Arrivals Only Capacity is the Inverse of $(T_{ij} + B_{ij})$

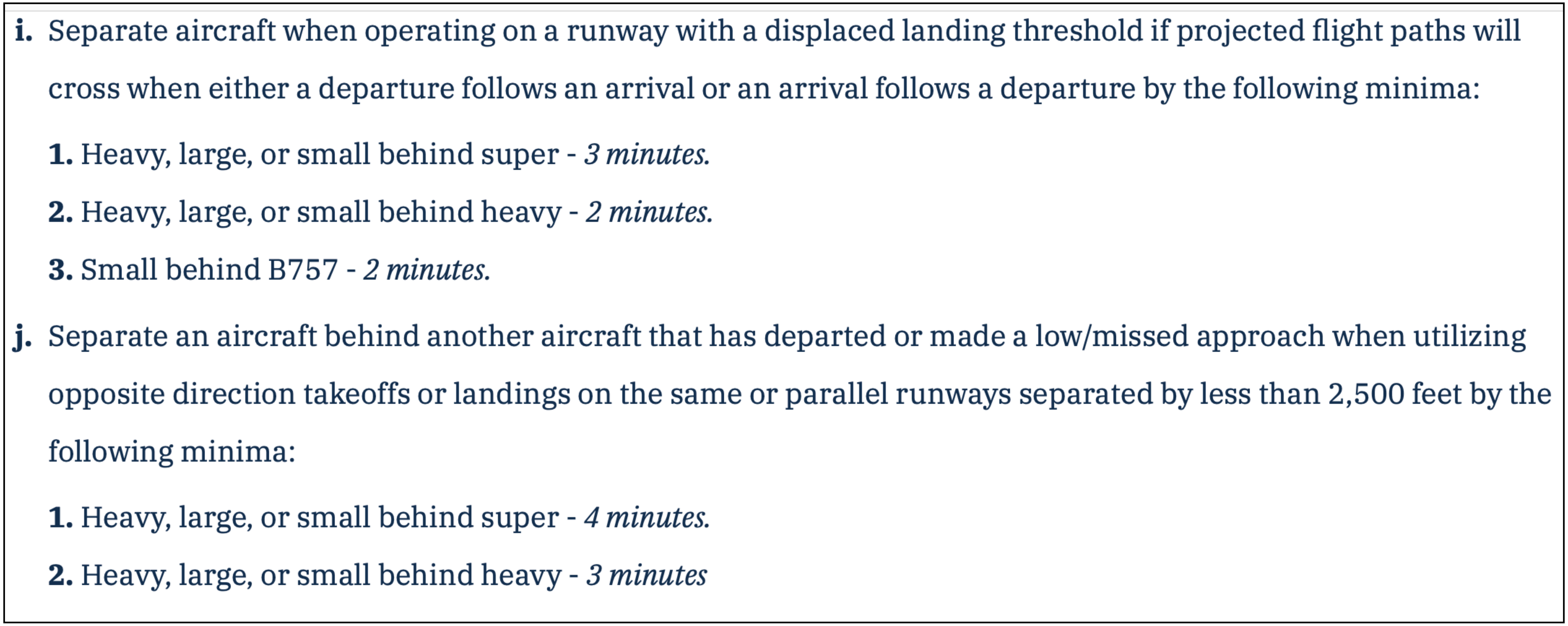


$$E(T_{ij} + B_{ij}) = \sum (P_{ij} * (T_{ij} + B_{ij})) = 120.14$$ Seconds

$$C_{arrivals} = \frac{1}{\sum P_{ij} * (T_{ij} + B_{ij})} = 29.96$$ Arrivals/hr

Departure-Departure Separation Information on FAA JO 7110.65Z (ATC Handbook)

Example language in FAA JO 7110.65Z



i. Separate aircraft when operating on a runway with a displaced landing threshold if projected flight paths will cross when either a departure follows an arrival or an arrival follows a departure by the following minima:

1. Heavy, large, or small behind super - *3 minutes.*

2. Heavy, large, or small behind heavy - *2 minutes.*

3. Small behind B757 - *2 minutes.*

j. Separate an aircraft behind another aircraft that has departed or made a low/missed approach when utilizing opposite direction takeoffs or landings on the same or parallel runways separated by less than 2,500 feet by the following minima:

1. Heavy, large, or small behind super - *4 minutes.*

2. Heavy, large, or small behind heavy - *3 minutes*

Language still references Super-Heavy, Heavy, Large, B757, and Small (see aircraft classifications handout)

Departure-Departure Separation Matrix Values in Seconds (no buffers)

	Trailing Aircraft (Header Columns)		
Lead Aircraft (column 1)	F	E	B
F	60	60	60
E	60	60	60
B	120	120	120

The FAA ATC Handbook (JO 7110.65Z) contains the air traffic control separations applied in the United States

https://www.faa.gov/air_traffic/publications/atpubs/atc_html/

Expected Inter-Departure Times

Let ϵ_{ij} be the departure-departure separation between successive departures (in seconds)

The expected value between successive departures is:

$$E(\epsilon_{ij}) = \sum P_{ij} * \epsilon_{ij} \qquad E(\epsilon_{ij}) = 64.8 \text{ Seconds}$$

$$E(\epsilon_{ij}) = P_{FF} * \epsilon_{FF} + P_{FE} * \epsilon_{FE} + P_{FB} * \epsilon_{FB} + P_{EF} * \epsilon_{EF} + P_{EE} * \epsilon_{EE} + \ldots$$

	Trailing Aircraft (Header Columns)		
Lead Aircraft (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

X

	Trailing Aircraft (Header Columns)		
Lead Aircraft (column 1)	F	E	B
F	60	60	60
E	60	60	60
B	120	120	120

Departure ATC-Pilot Buffers

- ATC-Pilot communications and engine thrust spool-up time add a buffer τ (in seconds) to ϵ_{ij}
- τ is the result of two contributing factors:
  - ATC-pilot communications time lags
  - Aircraft engine thrust spool-up time
- In this analysis we use a deterministic value for τ is 10 seconds

	Trailing Aircraft (Header Columns)		
Lead Aircraft (column 1)	F	E	B
F	70	70	70
E	70	70	70
B	130	130	130

Departures Analysis with Buffers

Let $E(\epsilon_{ij} + \tau)$ be the expected departure-departure separation between successive departures (in seconds)

$$E(\epsilon_{ij} + \tau) = \sum P_{ij} * (\epsilon_{ij} + \tau)$$

$$E(\epsilon_{ij} + \tau) = 79.84 \text{ Seconds}$$

$$C_{departures} = \frac{1}{E(\epsilon_{ij} + \tau)} = 45.1 \text{ Departures/hr}$$

	Trailing Aircraft (Header Columns)		
Lead Aircraft (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

X

Values of $(\epsilon_{ij} + \tau)$

	Trailing Aircraft (Header Columns)		
Lead Aircraft (column 1)	F	E	B
F	70	70	70
E	70	70	70
B	130	130	130

Gap Analysis

Goal: To find instances where Gaps exist allowing one departure between two successive arrivals

$$\boxed{E(T_{ij} + B_{ij})} > \boxed{E(\frac{\delta}{V}) + E(ROT_i) + (n-1)E(\epsilon_{ij}) + E(\tau))}$$

Time between aircraft i arrival And aircraft j

Gap for $(n-1)$ departures

We evaluate the right hand side of the equation parametrically with multiple values of n

Gap Analysis: $E(\frac{\delta}{V})$ Term

Example evaluation:

$$\boxed{E(\frac{\delta}{V})} + E(ROT_i) + (n-1)E(\epsilon_{ij}) + E(\tau))$$

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

$$E(\frac{\delta}{V}) = 0.82\frac{2}{132} + 0.10\frac{2}{137} + 0.08\frac{2}{151} \quad \text{Hours}$$

$$E(\frac{\delta}{V}) = 53.8 \quad \text{Seconds}$$

Gap Analysis: $E(ROT_i)$ Term

Example evaluation:

$$E(\frac{\delta}{V}) + \boxed{E(ROT_i)} + (n-1)E(\epsilon_{ij}) + E(\tau))$$

$$E(ROT_i) = P_F * ROT_E + P_E * ROT_F + P_B * ROT_B$$

$$E(ROT_i) = 0.82 * 51 + 0.10 * 54 + 0.08 * 65$$

$E(ROT_i) = 52.4$ Seconds

Gap Analysis: $E(\epsilon_{ij} + \tau)$ Term

Example evaluation:

$$E(\frac{\delta}{V}) + E(ROT_i) + \boxed{(n-1)E(\epsilon_{ij})} + E(\tau))$$

For one departure per gap:

$$(n-1)E(\epsilon_{ij} + \tau) = (0)E(\epsilon_{ij} + \tau) = 0$$

For two departures per gap:

$$(n-1)E(\epsilon_{ij} + \tau) = E(\epsilon_{ij} + \tau) = 79.8$$ Seconds

Gap Analysis: $E(\tau))$ Term

Example evaluation:

$$E(\frac{\delta}{V}) + E(ROT_i) + (n-1)E(\epsilon_{ij}) + \boxed{E(\tau))}$$

We assume the ATC-pilot and engine spool term is a constant at 10 seconds

Gap Analysis: Collecting Terms

The table below shows a summary of the minimum gap to release *n* departures between two successive arrivals

Example:
To release one departure between successive arrivals, the gap should be > 116.2 seconds

Departures (n)	Gap for n departures
1	116.2
2	181.0
3	245.8
4	310.6
5	375.4

Compare $(T_{ij} + B_{ij})$ with Minimum Departure Requirements

$$E(T_{ij} + B_{ij}) > E(\frac{\delta}{V}) + E(ROT_i) + (n-1)E(\epsilon_{ij}) + E(\tau))$$

- The analysis compares the right hand side and the left hand side to evaluate instances where arrival gaps is large enough to allow n departures

	Trailing Aircraft (Header Columns)		
Lead Aircraft (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

Departures (n)	Gap for n departures
1	116.2
2	181.0
3	245.8
4	310.6
5	375.4

Departures for Each Arrival Gap

$$E(T_{ij} + B_{ij}) > E(\frac{\delta}{V}) + E(ROT_i) + (n-1)E(\epsilon_{ij}) + E(\tau))$$

- The analysis compares the right hand side and the left hand side to evaluate instances where arrival gaps is large enough to allow n departures

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

Expected Departures per Arrival Gap

- The analysis estimates the number of expected departures per hour per arrival gap

$$E(D_{ij}) = TG(P_{ij})(DG_{ij})$$

$E(D_{ij})$ is the expected number of departure per gap when aircraft i follows aircraft j

TG is the number of total gaps in one hour

P_{ij} is the probability that aircraft i follows aircraft j

DG_{ij} is the departures per gap when aircraft i follows aircraft j

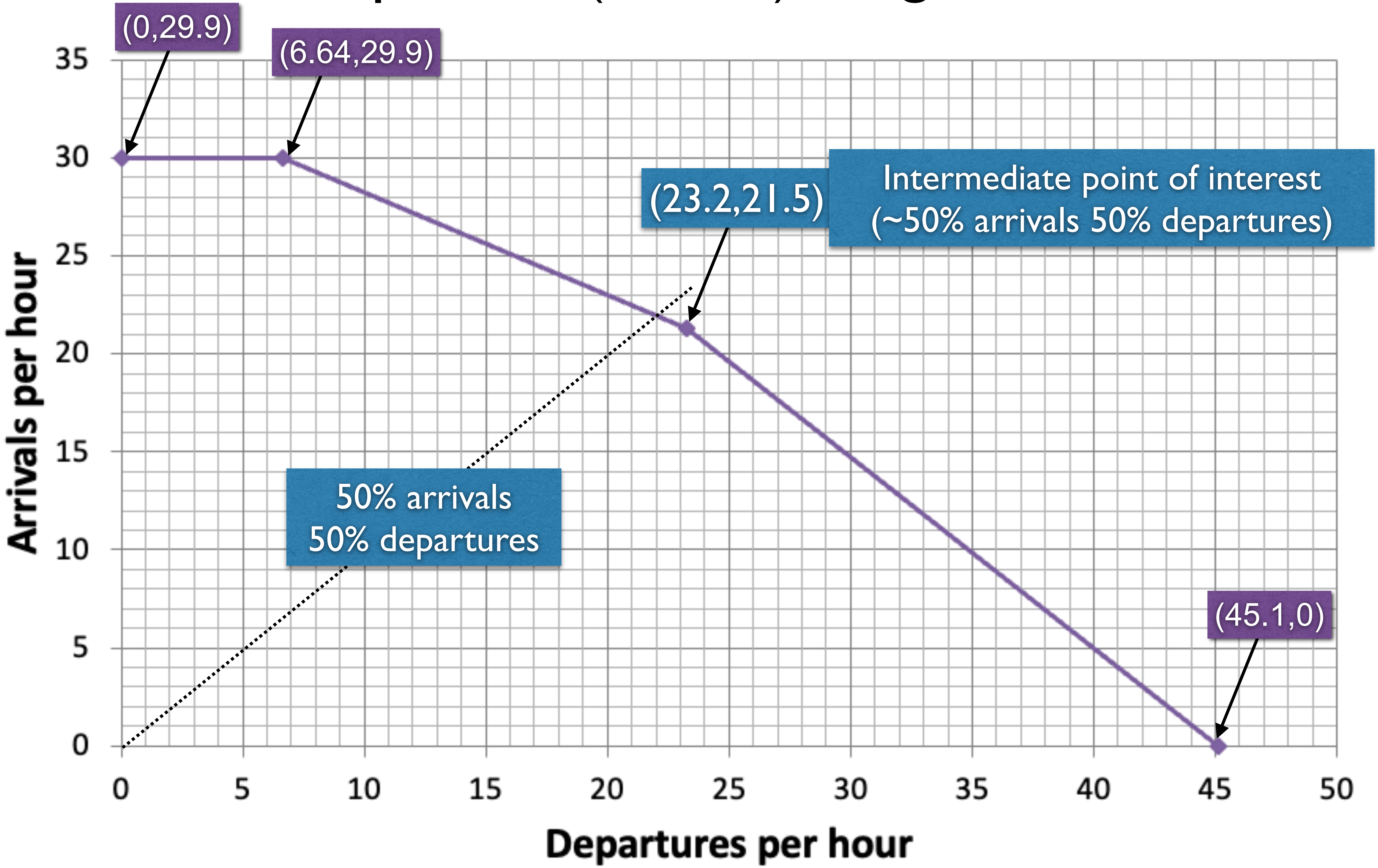
Departures for Each Arrival Gap

- The table summarizes the **expected number** of departures per arrival gap in one hour

	Trailing Aircraft (Header Columns)		
Lead Aircraft (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

- The total number of departures is 6.64 per hour while keeping the number of arrivals at 29.9 per hour

Collect Numbers and Create an Arrival-Departure (Pareto) Diagram

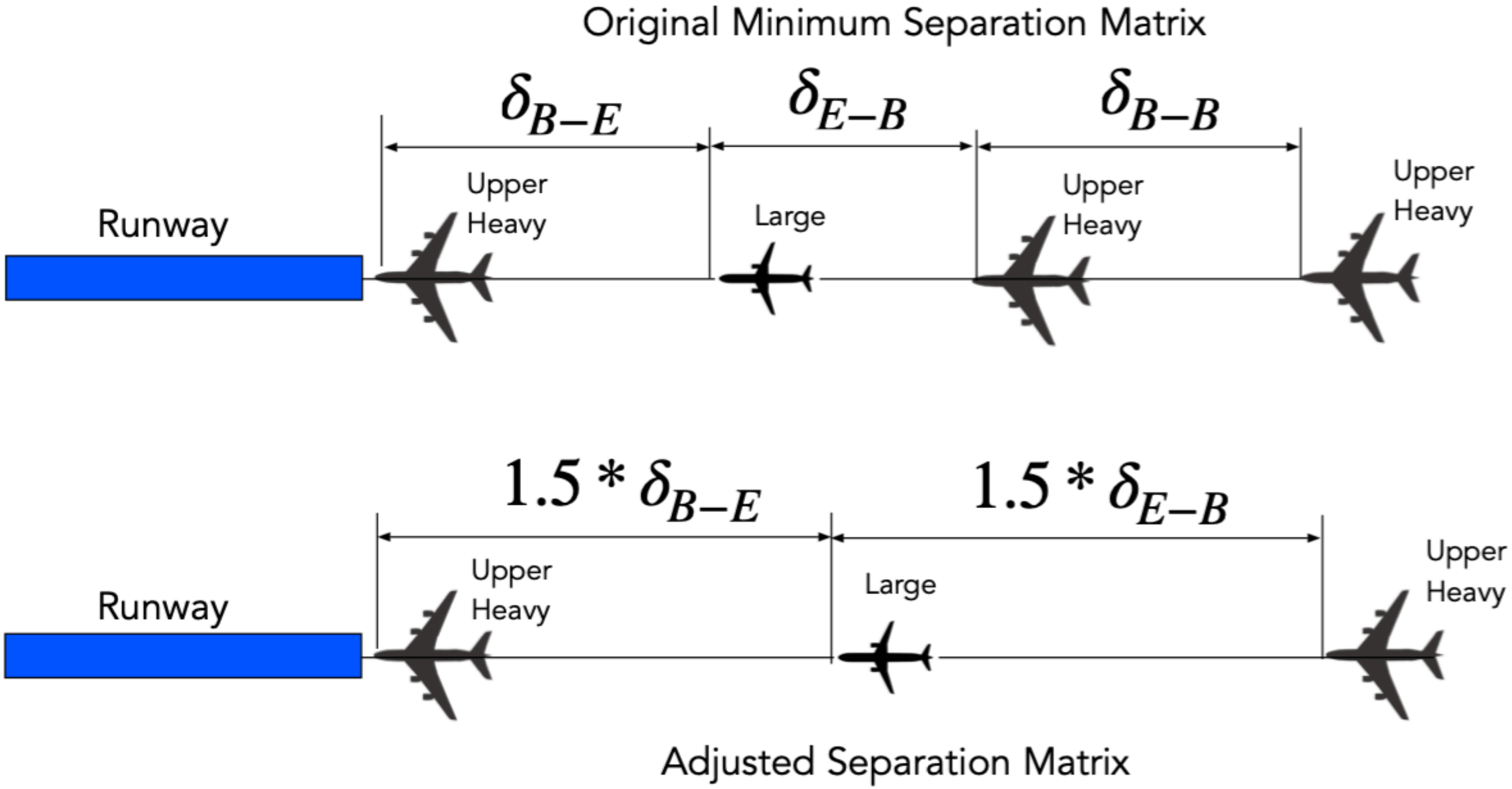


Intermediate point of interest (~50% arrivals 50% departures)

50% arrivals
50% departures

Calculating Other Points in the Arrival-Departure (Pareto) Diagram

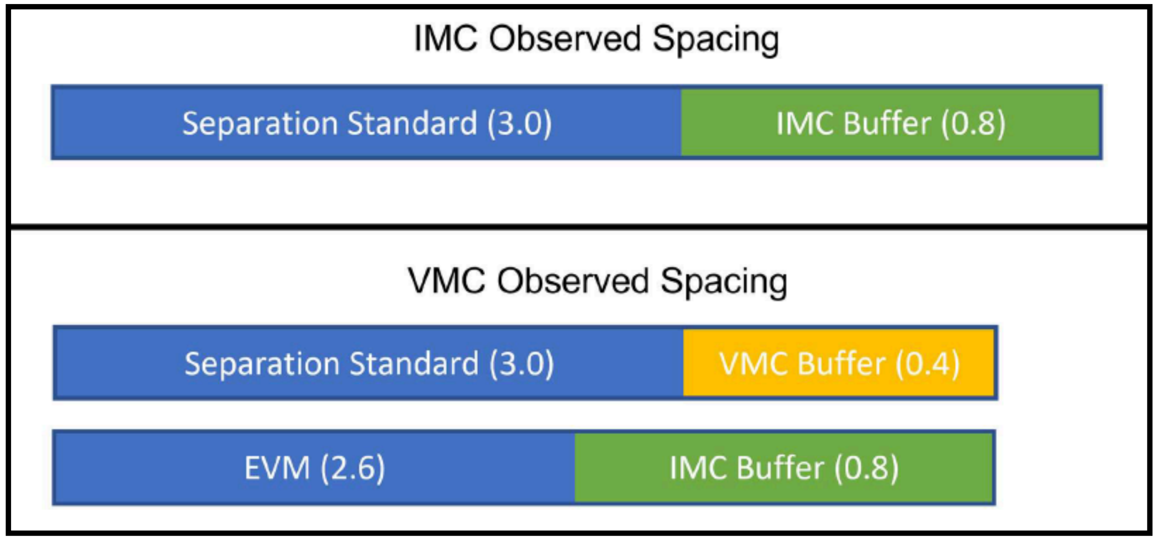
Adjust the minimum arrival-arrival separation matrix by a multiplier factor and recalculate the departure operations



FAA/MITRE Arrival Delivery Accuracy Updates

Recent work at the MITRE Corporation provides updated information about ATC arrival separation buffers and their standard deviation (σ_0)

The work also provides separations under visual conditions (called Equivalent Visual Minima)



MITRE | Center for Advanced Aviation System Development

MTR220403
MITRE TECHNICAL REPORT

Interarrival Separation Buffers and Equivalent Visual Minima for Airport Capacity Modeling

Sponsor: The Federal Aviation Administration
Dept. No.: P224
Project No.: 100339.10.104.1042.AP1
Outcome No: 1
PBWP Reference: 1_80-1.A.3-1) Update Critical Capacity Modeling Arrival Parameters

For Limited Release

The views, opinions and/or findings contained in this report are those of The MITRE Corporation and should not be construed as an official government position, policy, or decision, unless designated by other documentation.

©2022 The MITRE Corporation.
All rights reserved.

McLean, VA

Author(s):
Chris Roberts
Willie Weiss
Erin Catlett

September 2022

NAS-Wide ATC Arrival Buffers

- 5.3 million landings studied
- NAS-wide buffers are 29 seconds in IMC and 21 seconds in VMC
- Violation rates are 2.9% in VMC and 0.4% in IMC

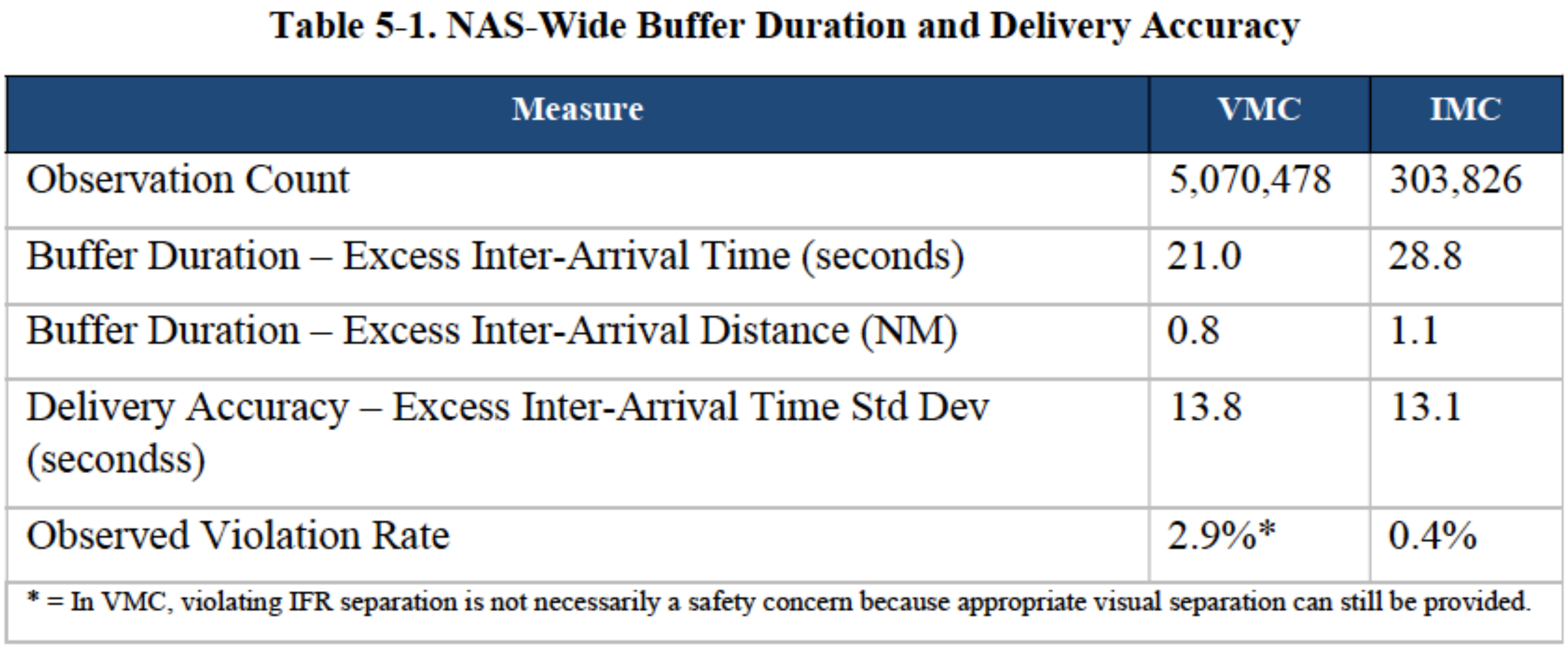


Table 5-1. NAS-Wide Buffer Duration and Delivery Accuracy

Measure	VMC	IMC
Observation Count	5,070,478	303,826
Buffer Duration – Excess Inter-Arrival Time (seconds)	21.0	28.8
Buffer Duration – Excess Inter-Arrival Distance (NM)	0.8	1.1
Delivery Accuracy – Excess Inter-Arrival Time Std Dev (secondss)	13.8	13.1
Observed Violation Rate	2.9%*	0.4%

* = In VMC, violating IFR separation is not necessarily a safety concern because appropriate visual separation can still be provided.

Source: Roberts, Weiss, and Catlett, 2022. Interarrival Separation Buffers and Equivalent Visual Minima for Airport Capacity Modeling

ATC Arrival-Arrival Buffers Vary by Airport

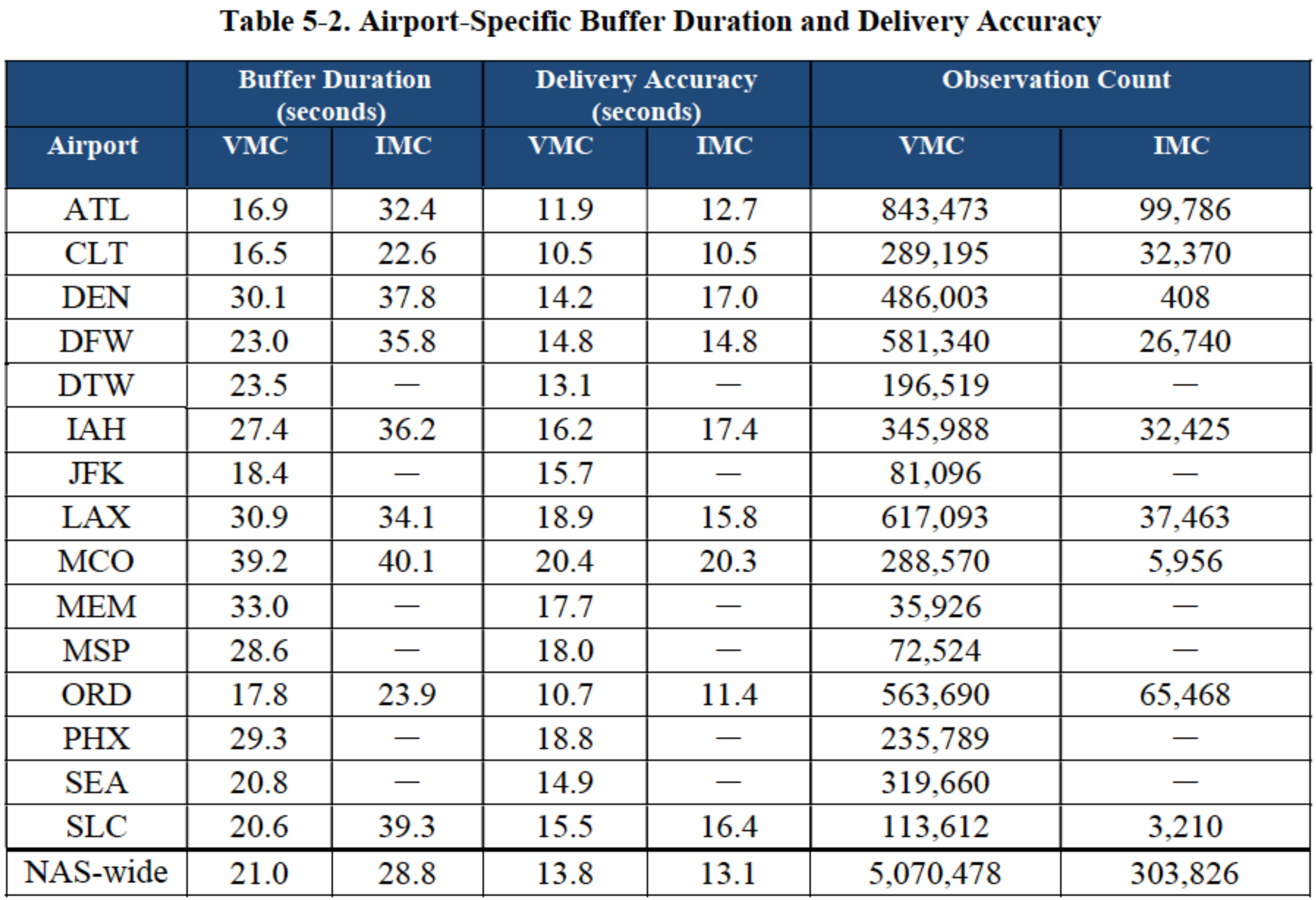


Table 5-2. Airport-Specific Buffer Duration and Delivery Accuracy

	Buffer Duration (seconds)		Delivery Accuracy (seconds)		Observation Count	
Airport	**VMC**	**IMC**	**VMC**	**IMC**	**VMC**	**IMC**
ATL	16.9	32.4	11.9	12.7	843,473	99,786
CLT	16.5	22.6	10.5	10.5	289,195	32,370
DEN	30.1	37.8	14.2	17.0	486,003	408
DFW	23.0	35.8	14.8	14.8	581,340	26,740
DTW	23.5	—	13.1	—	196,519	—
IAH	27.4	36.2	16.2	17.4	345,988	32,425
JFK	18.4	—	15.7	—	81,096	—
LAX	30.9	34.1	18.9	15.8	617,093	37,463
MCO	39.2	40.1	20.4	20.3	288,570	5,956
MEM	33.0	—	17.7	—	35,926	—
MSP	28.6	—	18.0	—	72,524	—
ORD	17.8	23.9	10.7	11.4	563,690	65,468
PHX	29.3	—	18.8	—	235,789	—
SEA	20.8	—	14.9	—	319,660	—
SLC	20.6	39.3	15.5	16.4	113,612	3,210
NAS-wide	21.0	28.8	13.8	13.1	5,070,478	303,826

Source: Roberts, Weiss, and Catlett, 2022. Interarrival Separation Buffers and Equivalent Visual Minima for Airport Capacity Modeling

NAS-Wide Equivalent Visual Minima (EVM)

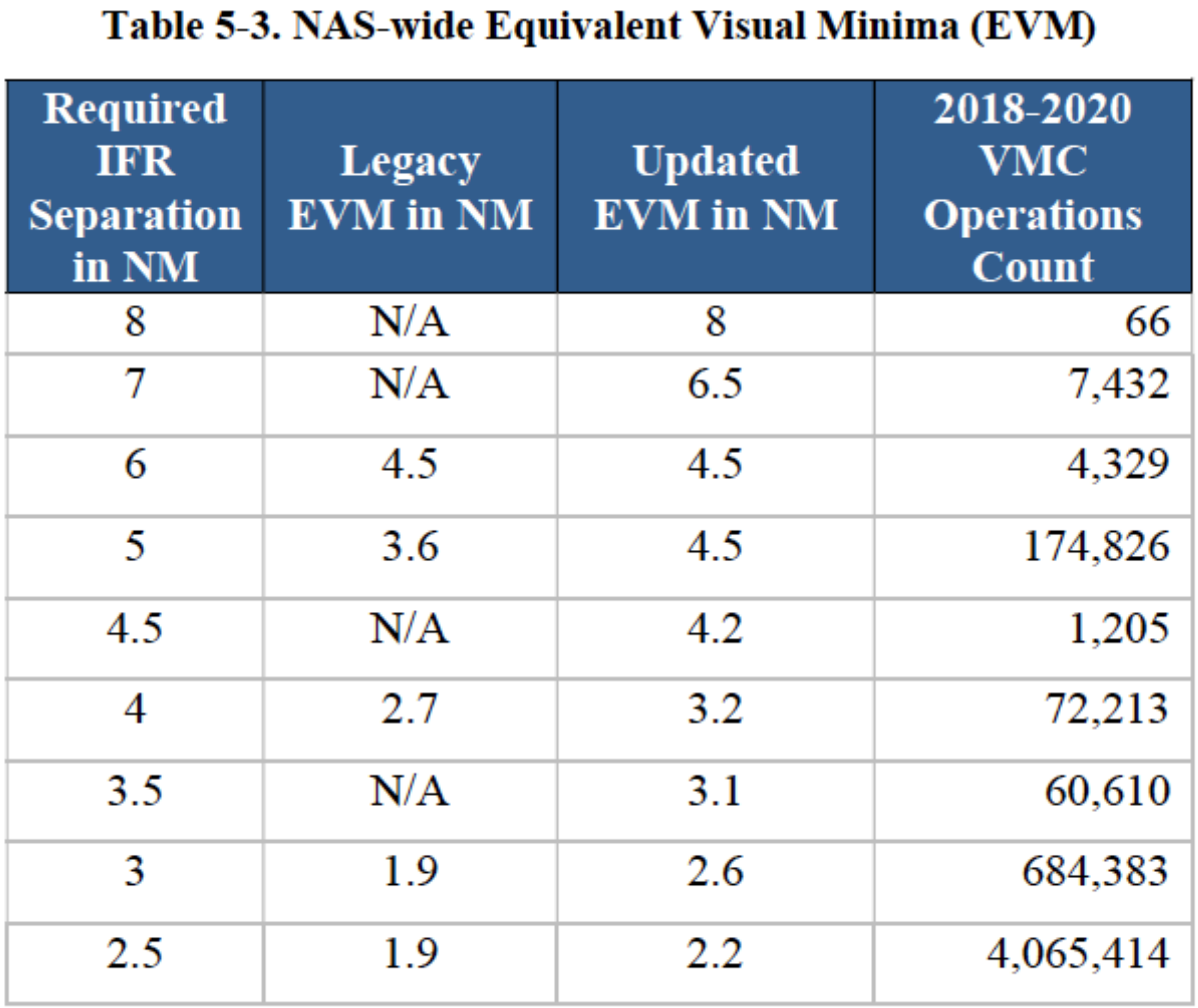


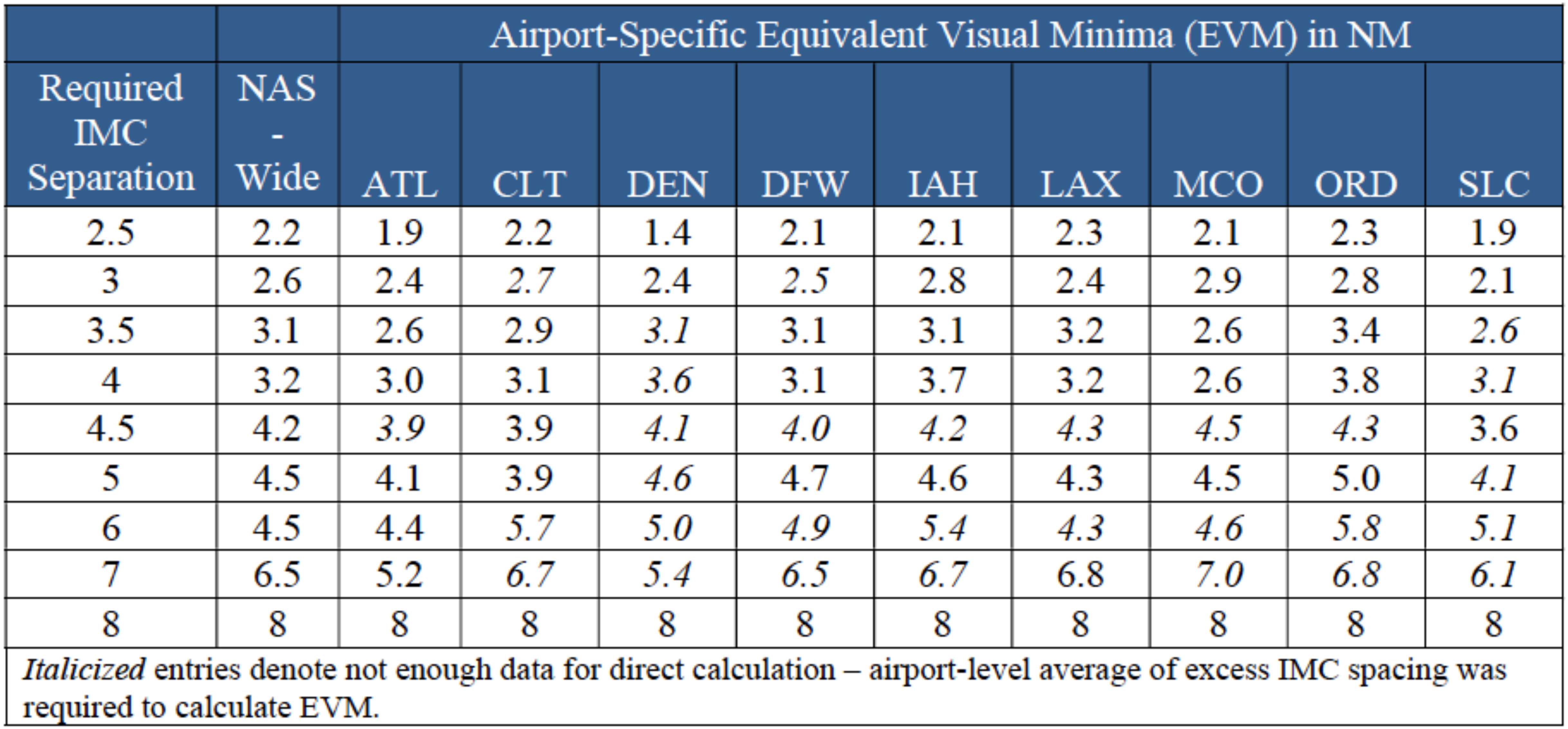
Table 5-3. NAS-wide Equivalent Visual Minima (EVM)

Required IFR Separation in NM	Legacy EVM in NM	Updated EVM in NM	2018-2020 VMC Operations Count
8	N/A	8	66
7	N/A	6.5	7,432
6	4.5	4.5	4,329
5	3.6	4.5	174,826
4.5	N/A	4.2	1,205
4	2.7	3.2	72,213
3.5	N/A	3.1	60,610
3	1.9	2.6	684,383
2.5	1.9	2.2	4,065,414

Source: Roberts, Weiss, and Catlett, 2022. Interarrival Separation Buffers and Equivalent Visual Minima for Airport Capacity Modeling

Airport-Specific Equivalent Visual Minima (EVM)

Table 5-4. Airport-Specific Equivalent Visual Minima

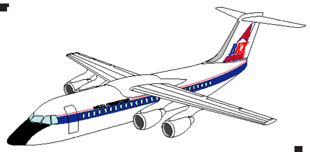


		Airport-Specific Equivalent Visual Minima (EVM) in NM								
Required IMC Separation	NAS - Wide	ATL	CLT	DEN	DFW	IAH	LAX	MCO	ORD	SLC
2.5	2.2	1.9	2.2	1.4	2.1	2.1	2.3	2.1	2.3	1.9
3	2.6	2.4	*2.7*	2.4	*2.5*	2.8	2.4	2.9	2.8	2.1
3.5	3.1	2.6	2.9	*3.1*	3.1	3.1	3.2	2.6	3.4	*2.6*
4	3.2	3.0	3.1	*3.6*	3.1	3.7	3.2	2.6	3.8	*3.1*
4.5	4.2	*3.9*	3.9	*4.1*	*4.0*	*4.2*	*4.3*	*4.5*	*4.3*	3.6
5	4.5	4.1	3.9	*4.6*	4.7	4.6	4.3	4.5	5.0	*4.1*
6	4.5	4.4	*5.7*	*5.0*	*4.9*	*5.4*	*4.3*	*4.6*	*5.8*	*5.1*
7	6.5	5.2	*6.7*	*5.4*	*6.5*	*6.7*	6.8	*7.0*	*6.8*	*6.1*
8	8	8	8	8	8	8	8	8	8	8

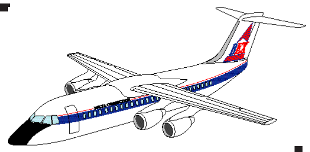
Italicized entries denote not enough data for direct calculation – airport-level average of excess IMC spacing was required to calculate EVM.

Source: Roberts, Weiss, and Catlett, 2022. Interarrival Separation Buffers and Equivalent Visual Minima for Airport Capacity Modeling

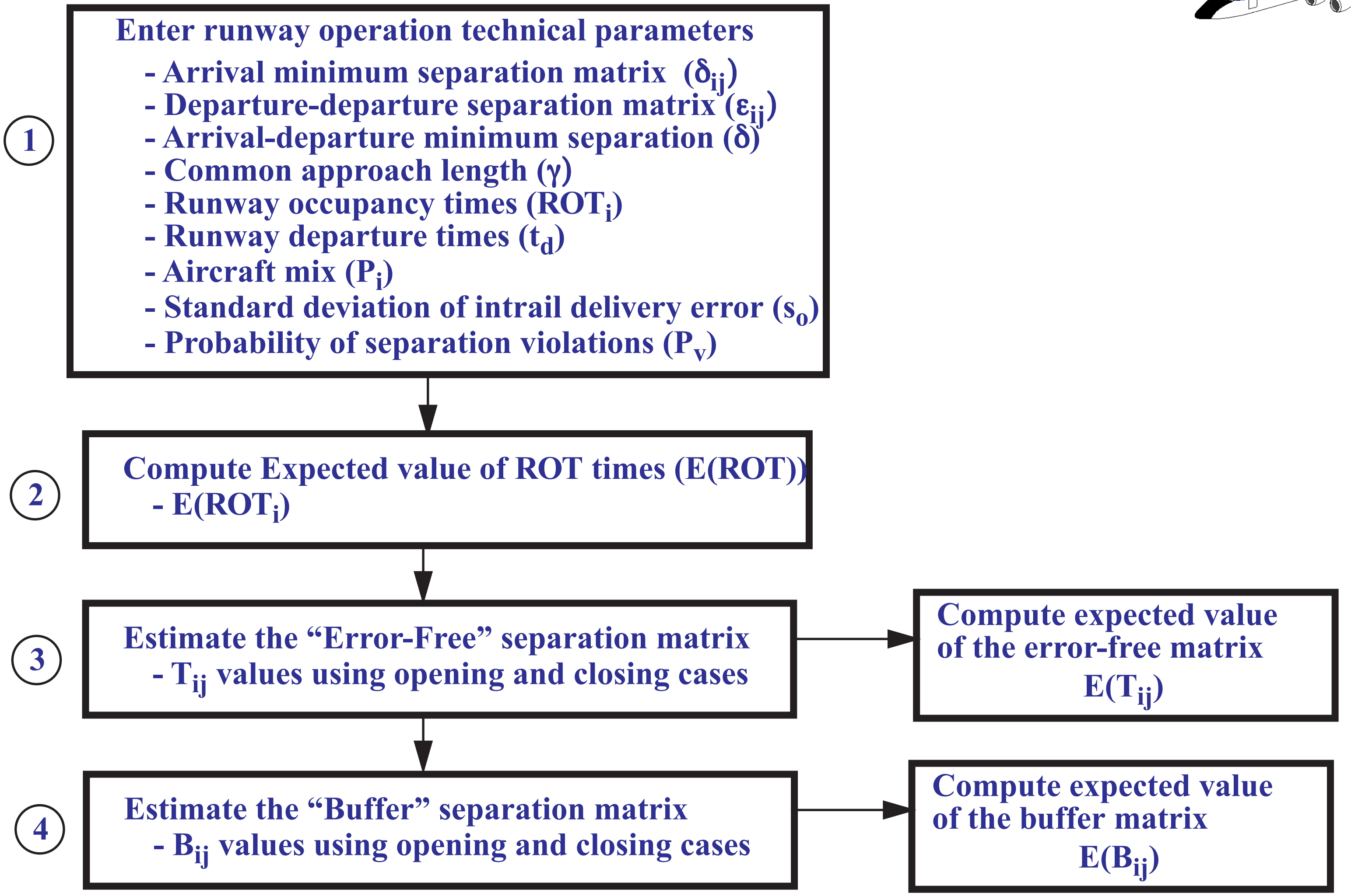
Review of Runway Capacity Excel Program



- The Excel template provided in class attempts to illustrate how the time-space diagram technique can be "programmed" in a standard spreadsheet
- You can extend the analysis provided in the basic template to more complex airport configurations
- The program, as it stands now, can only estimate the saturation capacity of a single runway. The program provides a simple graphical representation of the arrival -departure saturation diagram (sometimes called capacity Pareto frontier in the literature)
- The following pages illustrate the use of the program using the values of the previous runway example.



Excel Template Flowchart



① Enter runway operation technical parameters

- Arrival minimum separation matrix (δ_{ij})
- Departure-departure separation matrix (ε_{ij})
- Arrival-departure minimum separation (δ)
- Common approach length (γ)
- Runway occupancy times (ROT_i)
- Runway departure times (t_d)
- Aircraft mix (P_i)
- Standard deviation of intrail delivery error (s_o)
- Probability of separation violations (P_v)

② Compute Expected value of ROT times (E(ROT))

- $E(ROT_i)$

③ Estimate the "Error-Free" separation matrix

- T_{ij} values using opening and closing cases

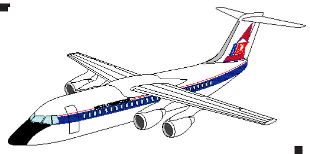
Compute expected value of the error-free matrix
$E(T_{ij})$

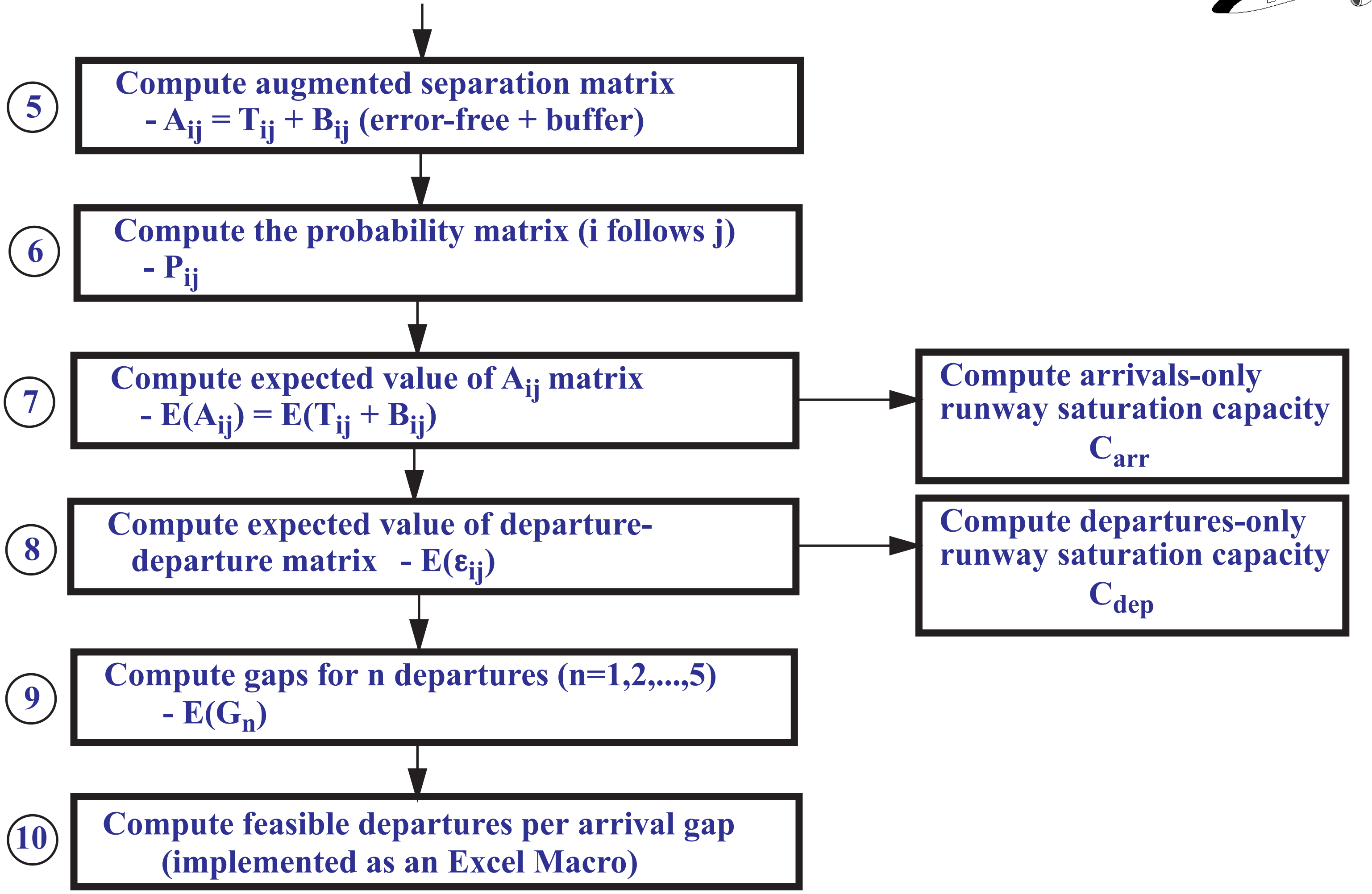
④ Estimate the "Buffer" separation matrix

- B_{ij} values using opening and closing cases

Compute expected value of the buffer matrix
$E(B_{ij})$

Excel Template Flowchart (continuation)





⑤ Compute augmented separation matrix
- $A_{ij} = T_{ij} + B_{ij}$ (error-free + buffer)

⑥ Compute the probability matrix (i follows j)
- P_{ij}

⑦ Compute expected value of A_{ij} matrix
- $E(A_{ij}) = E(T_{ij} + B_{ij})$

Compute arrivals-only runway saturation capacity
C_{arr}

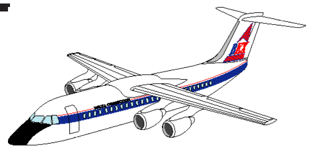
⑧ Compute expected value of departure-departure matrix - $E(\varepsilon_{ij})$

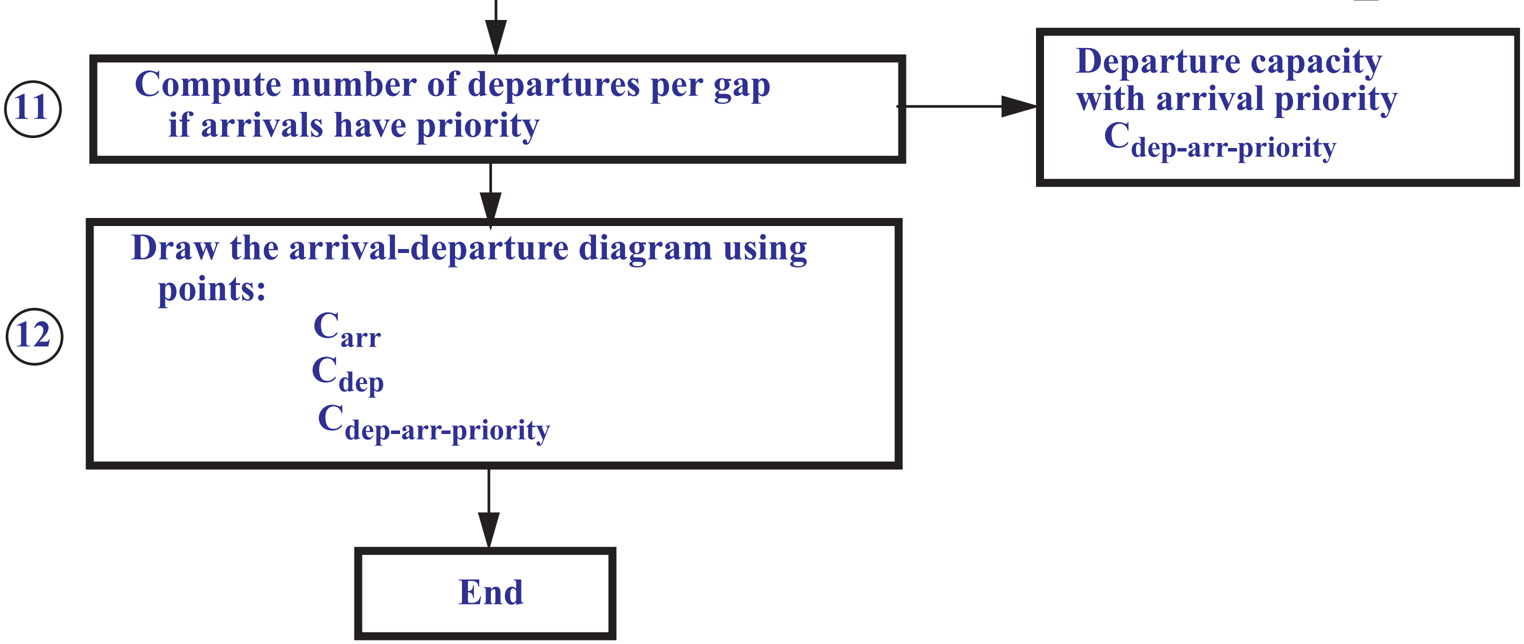
Compute departures-only runway saturation capacity
C_{dep}

⑨ Compute gaps for n departures (n=1,2,...,5)
- $E(G_n)$

⑩ Compute feasible departures per arrival gap
(implemented as an Excel Macro)

Excel Template Flowchart (continuation)





⑪ Compute number of departures per gap if arrivals have priority

Departure capacity with arrival priority $C_{dep-arr-priority}$

⑫ Draw the arrival-departure diagram using points:

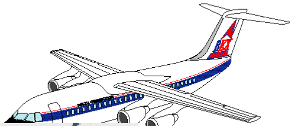
C_{arr}

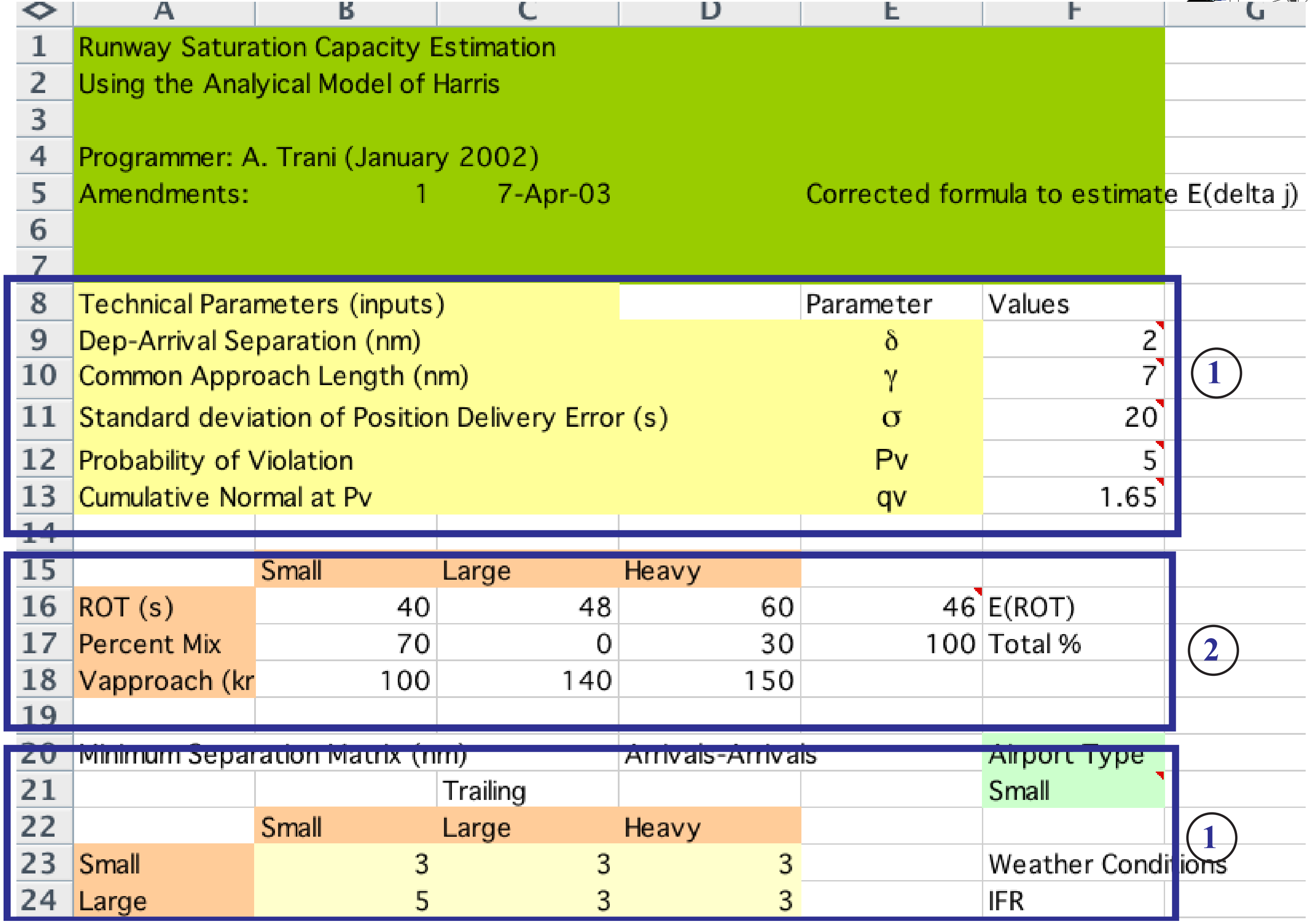
C_{dep}

$C_{dep-arr-priority}$

End

Computer Program Screen 1





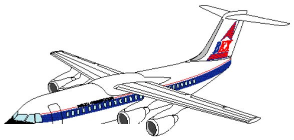
	A	B	C	D	E	F	G
1	Runway Saturation Capacity Estimation						
2	Using the Analyical Model of Harris						
3							
4	Programmer: A. Trani (January 2002)						
5	Amendments:	1	7-Apr-03		Corrected formula to estimate E(delta j)		
6							
7							
8	Technical Parameters (inputs)				Parameter	Values	
9	Dep-Arrival Separation (nm)				δ	2	
10	Common Approach Length (nm)				γ	7	
11	Standard deviation of Position Delivery Error (s)				σ	20	
12	Probability of Violation				Pv	5	
13	Cumulative Normal at Pv				qv	1.65	
14							
15		Small	Large	Heavy			
16	ROT (s)	40	48	60	46	E(ROT)	
17	Percent Mix	70	0	30	100	Total %	
18	Vapproach (kr	100	140	150			
19							
20	Minimum Separation Matrix (nm)			Arrivals-Arrivals		Airport Type	
21			Trailing			Small	
22		Small	Large	Heavy			
23	Small	3	3	3		Weather Conditions	
24	Large	5	3	3		IFR	

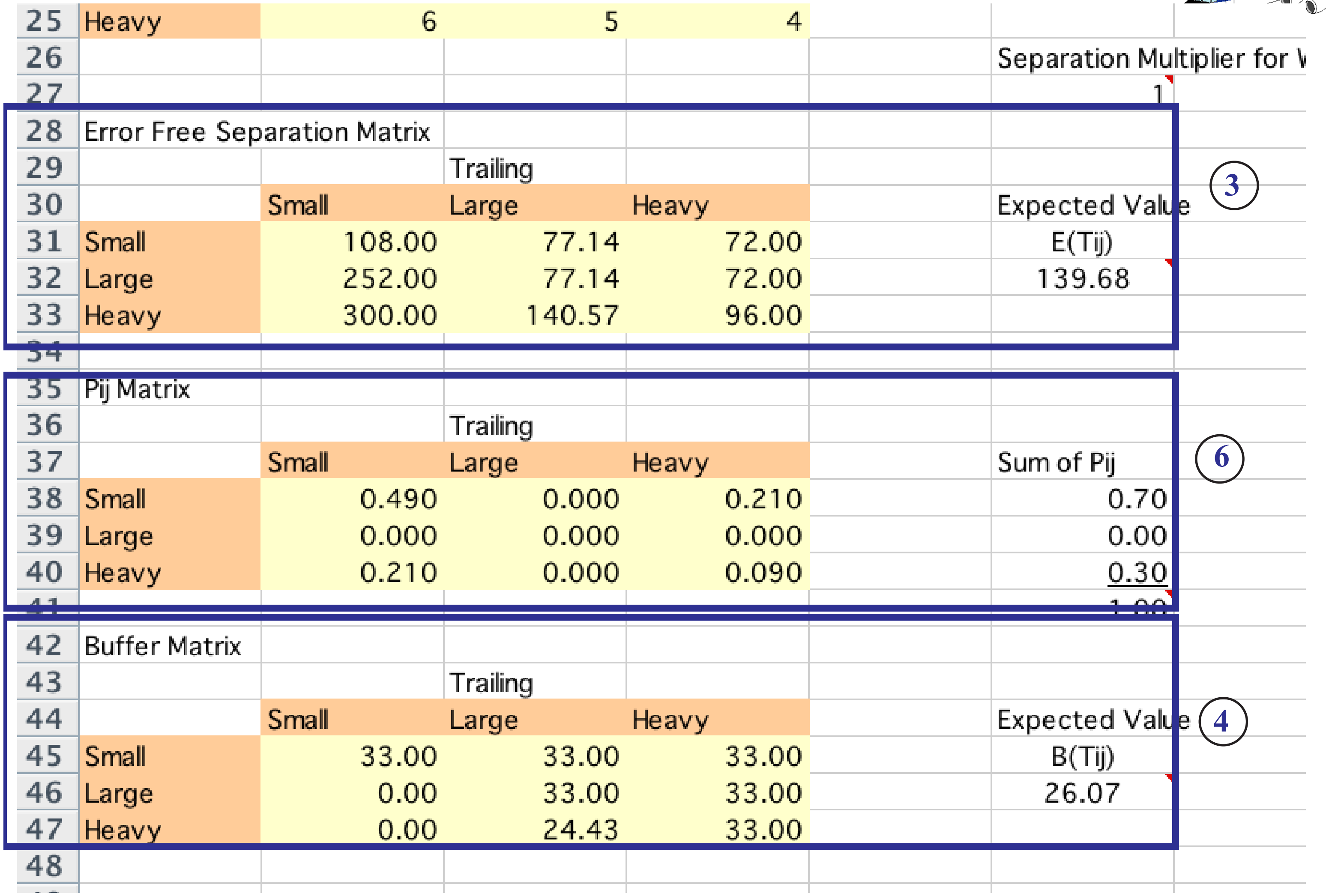
①

②

①

Computer Program (Screen 2)





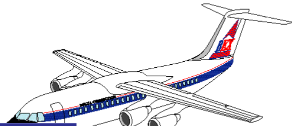
25	Heavy	6	5	4	
26					Separation Multiplier for W
27					1
28	Error Free Separation Matrix				
29			Trailing		
30		Small	Large	Heavy	Expected Value
31	Small	108.00	77.14	72.00	E(Tij)
32	Large	252.00	77.14	72.00	139.68
33	Heavy	300.00	140.57	96.00	
34					
35	Pij Matrix				
36			Trailing		
37		Small	Large	Heavy	Sum of Pij
38	Small	0.490	0.000	0.210	0.70
39	Large	0.000	0.000	0.000	0.00
40	Heavy	0.210	0.000	0.090	0.30
41					1.00
42	Buffer Matrix				
43			Trailing		
44		Small	Large	Heavy	Expected Value
45	Small	33.00	33.00	33.00	B(Tij)
46	Large	0.00	33.00	33.00	26.07
47	Heavy	0.00	24.43	33.00	
48					

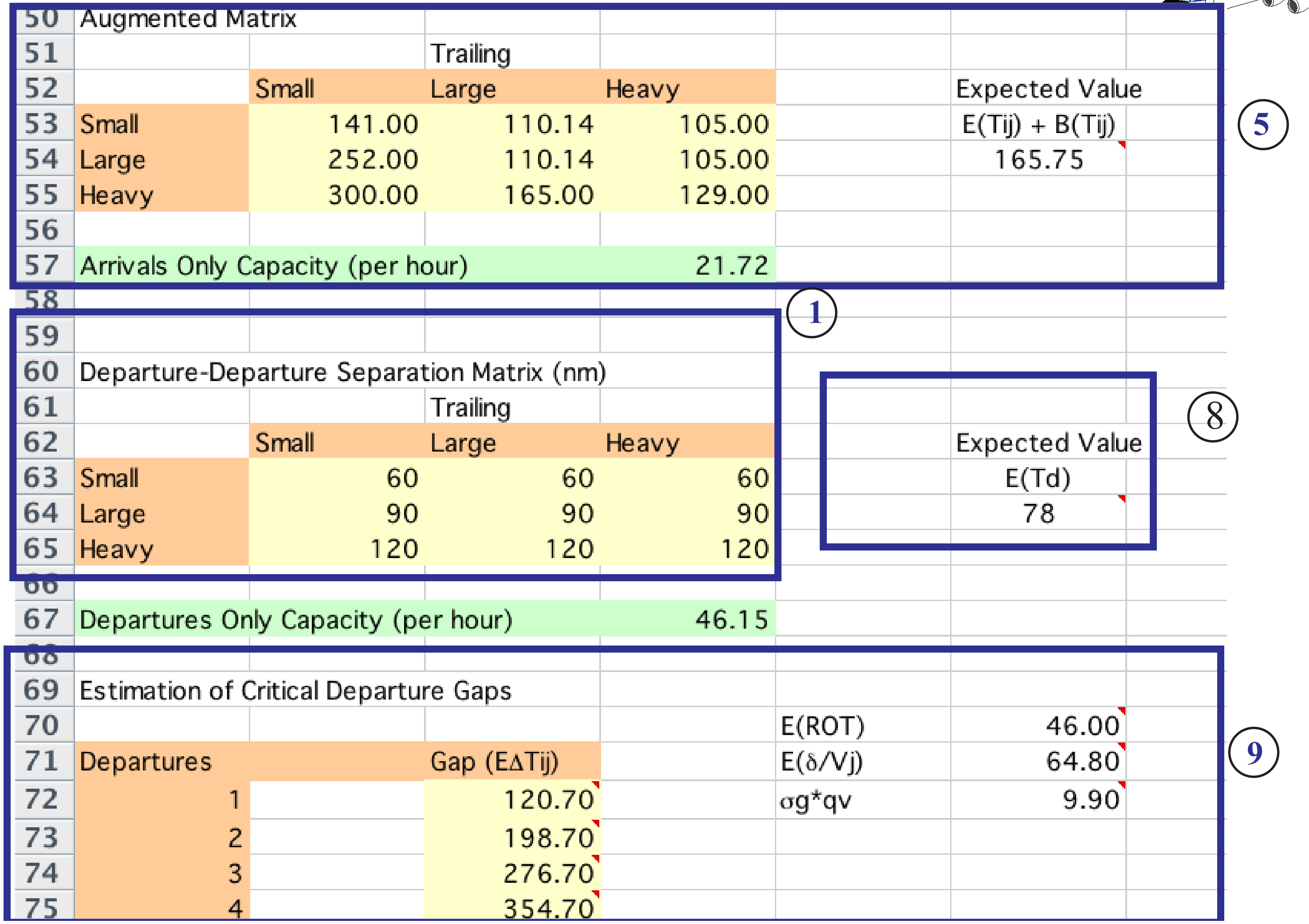
③

⑥

④

Computer Program (Screen 3)





Augmented Matrix

	Trailing		
	Small	Large	Heavy
Small	141.00	110.14	105.00
Large	252.00	110.14	105.00
Heavy	300.00	165.00	129.00

Expected Value

E(Tij) + B(Tij)

165.75

Arrivals Only Capacity (per hour) 21.72

Departure-Departure Separation Matrix (nm)

	Trailing		
	Small	Large	Heavy
Small	60	60	60
Large	90	90	90
Heavy	120	120	120

Expected Value

E(Td)

78

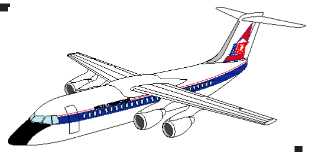
Departures Only Capacity (per hour) 46.15

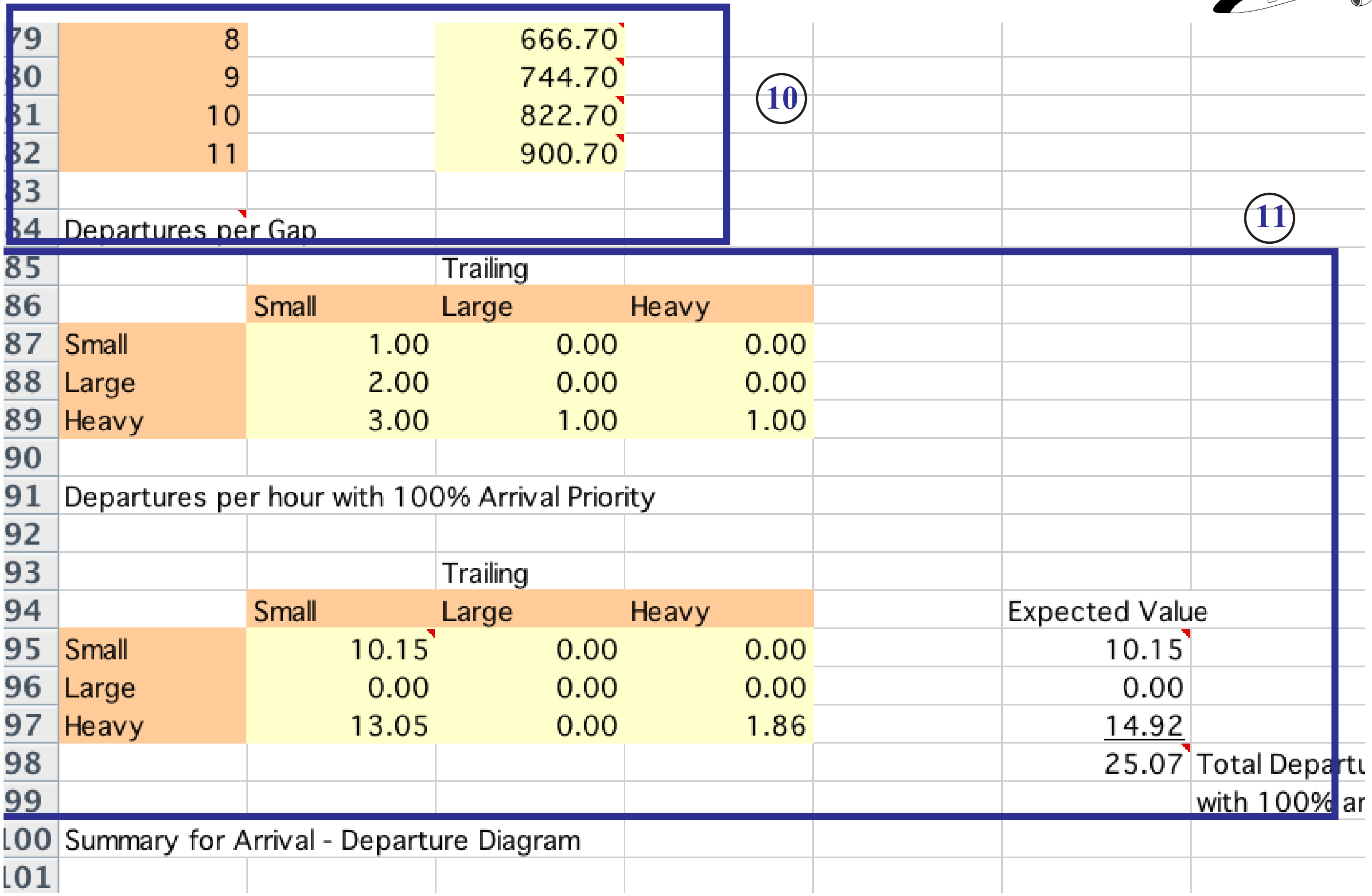
Estimation of Critical Departure Gaps

Departures	Gap (EΔTij)
1	120.70
2	198.70
3	276.70
4	354.70

E(ROT)	46.00
E(δ/Vj)	64.80
σg*qv	9.90

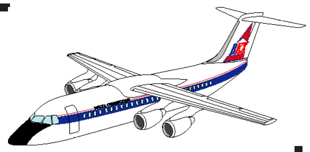
Computer Program (Screen 4)

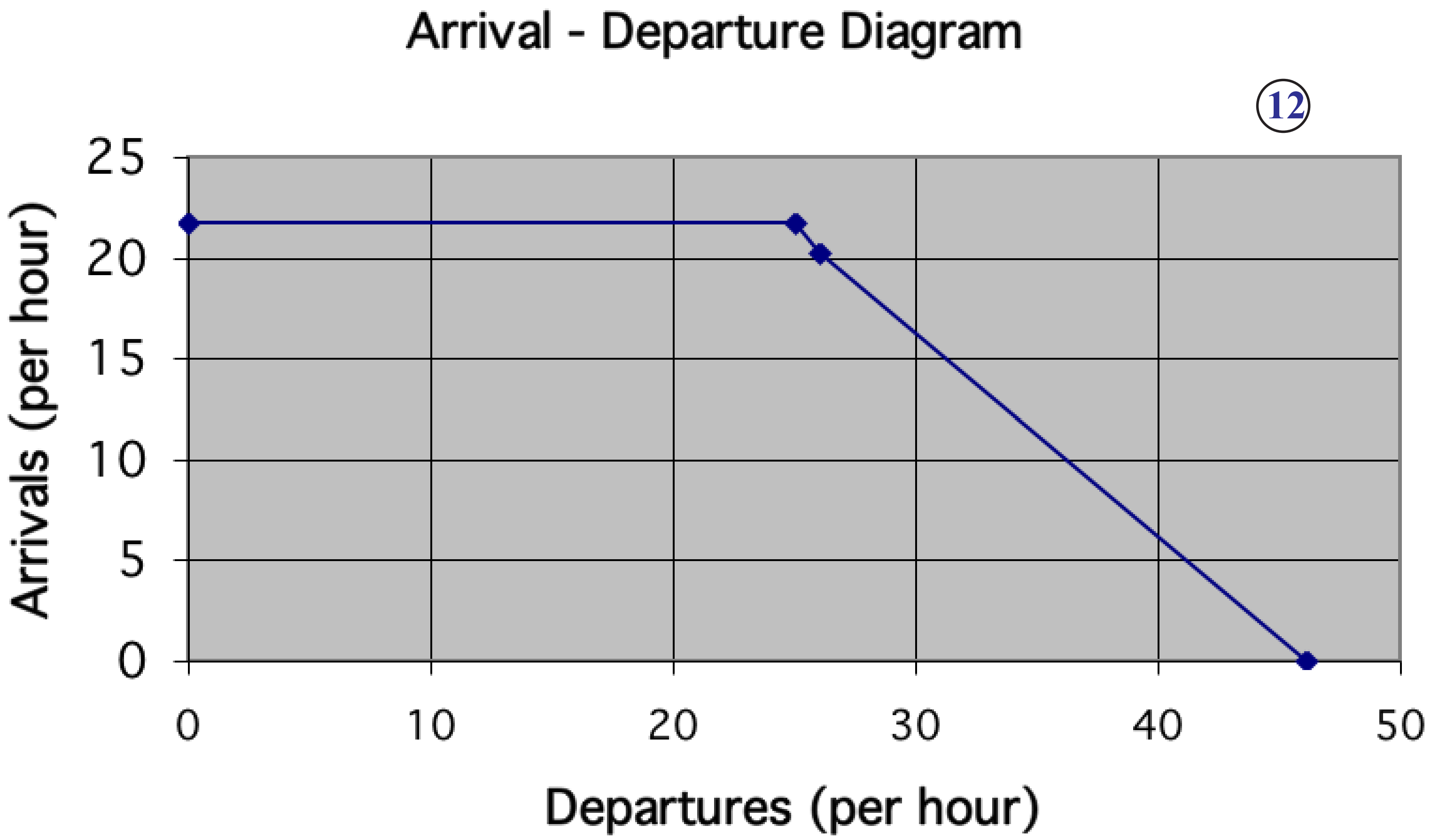




79	8		666.70				
80	9		744.70				
81	10		822.70				
82	11		900.70				
83							
84	Departures per Gap						
85			Trailing				
86		Small	Large	Heavy			
87	Small	1.00	0.00	0.00			
88	Large	2.00	0.00	0.00			
89	Heavy	3.00	1.00	1.00			
90							
91	Departures per hour with 100% Arrival Priority						
92							
93			Trailing				
94		Small	Large	Heavy		Expected Value	
95	Small	10.15	0.00	0.00		10.15	
96	Large	0.00	0.00	0.00		0.00	
97	Heavy	13.05	0.00	1.86		14.92	
98						25.07	Total Departu
99							with 100% ar
100	Summary for Arrival - Departure Diagram						
101							

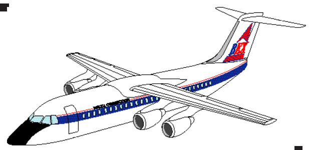
Computer Program (Screen 5)





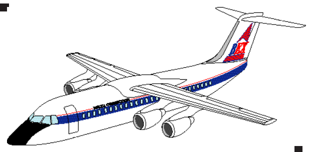
⑫

Estimating Runway Saturation Capacity for Complex Airport Configurations

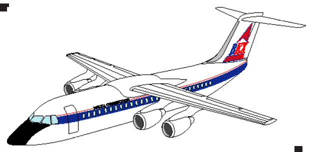


- The methodology explained in the previous handout addresses a simple Time-Space diagram technique to estimate the runway saturation capacity
- The time-space approach can also be used to estimate the saturation capacity of more complex runway configurations where interactions occur between runways
- Example problems taken from the FAA Airport Capacity benchmark document will be used to illustrate the points made

Methodology

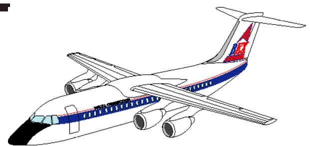


- Understand the runway use according to ATC operations
- Select a primary runway as the basis for your analysis
- Estimate the saturation capacity characteristics of the primary runway using the known time-space method
- Examine gaps in the runway operations at the primary runway. These gaps might exist naturally (i.e., large arrival-arrival separations) or might be forced by ATC controllers by imposing large in-trail separations allowing operations at other runways



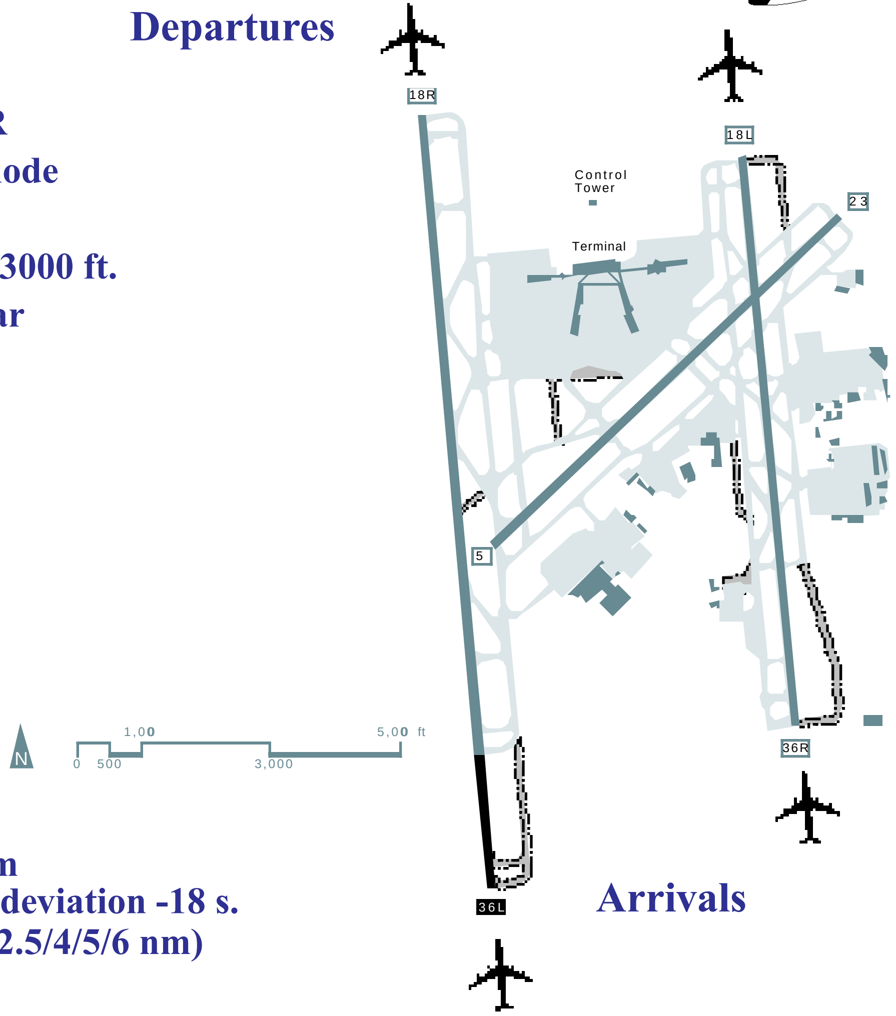
- If runway operations are independent you can estimate arrival and departure saturation capacities for each runway independently
- If the operations on runways are dependent estimate the runway occupancy times (both for arrivals and departures) very carefully and establish a logical order f operations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

Example 2 - Charlotte-Douglas Intl. Airport

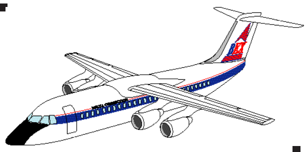


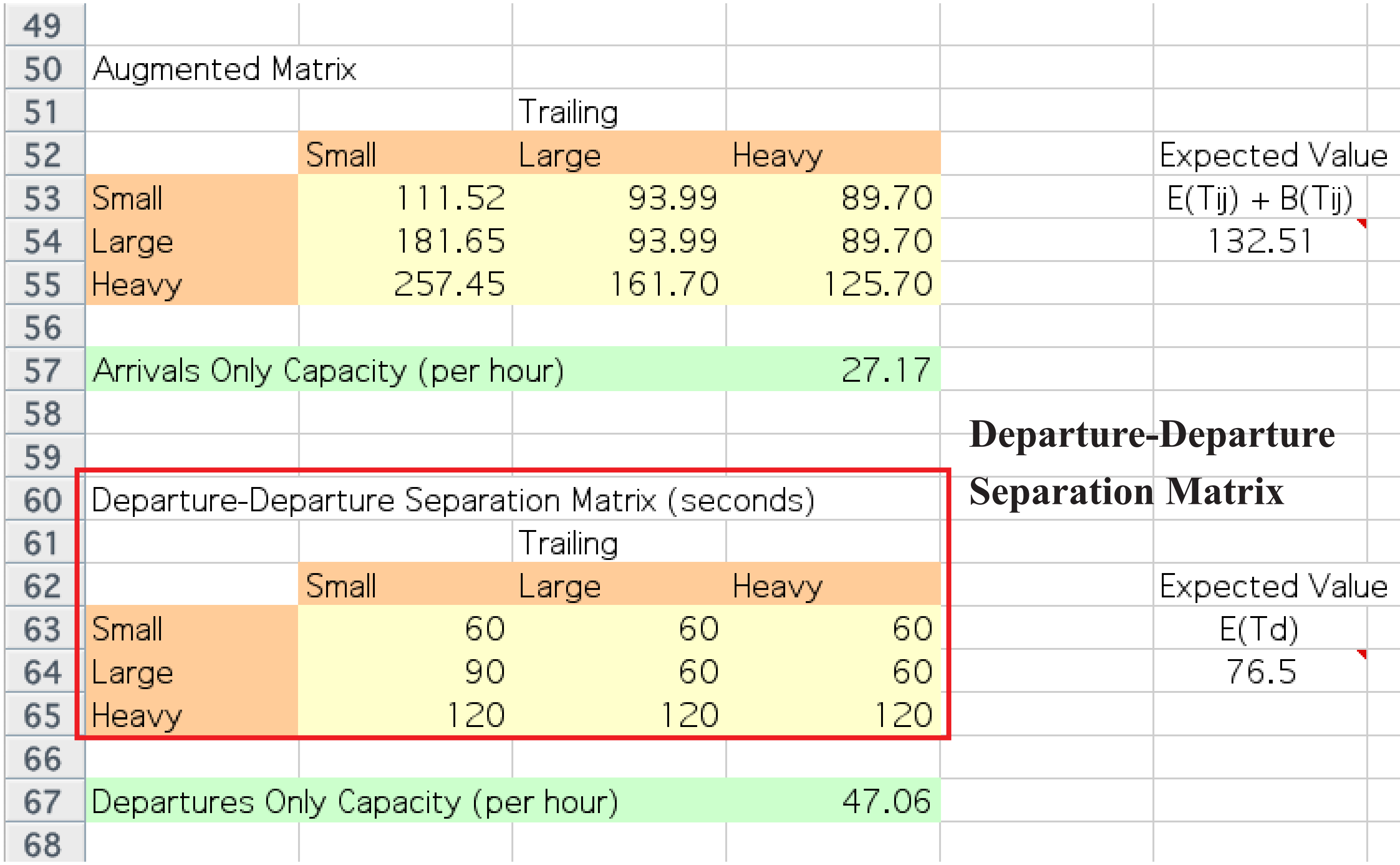
Operational Conditions

1) Runways 18R/36L and 18L/36R
   are used in mixed operations mode
2) Runway 5/23 is inactive
3) Parallel runway separation > 4,3000 ft.
4) ASR-9 airport surveillance radar
   (scan time 4.8 seconds)
5) Aircraft mix
   a) Heavy - 20%
   b) Large - 30%
   c) Small - 50%
6) Approach speeds
   a) Heavy - 150 knots
   b) Large - 140 knots
   c) Small - 110 knots
7) Runway occupancy times
   a) Heavy - 57 s.
   b) Large - 52 s.
   c) Small - 49 s.
8) Common approach length - 7 nm
9) In-trail delivery error standard deviation -18 s.
10) Large hub separation criteria (2.5/4/5/6 nm)
11) IMC weather conditions



Some Intermediate Results

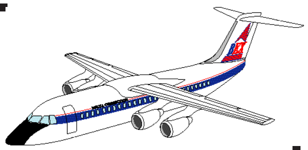




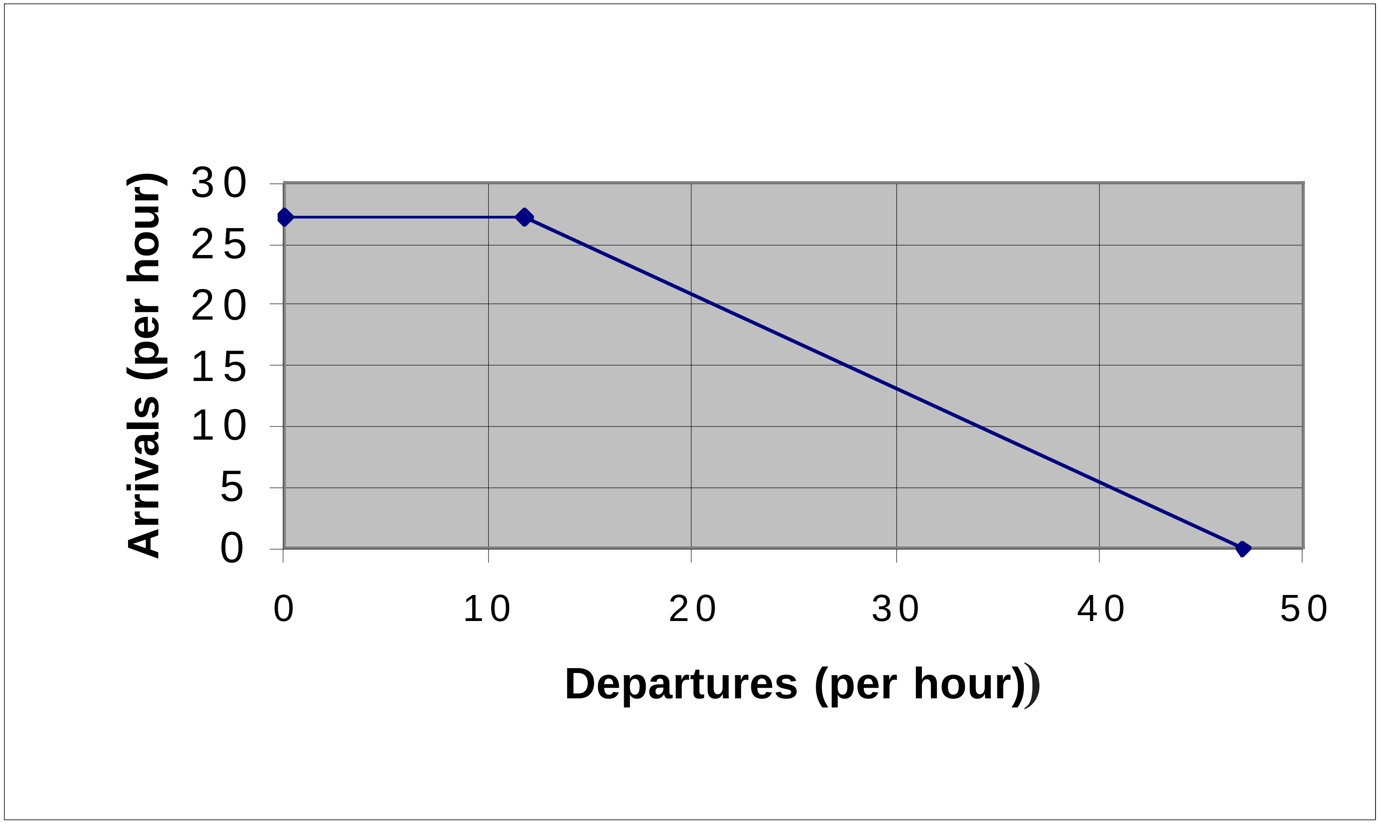
49						
50	Augmented Matrix					
51			Trailing			
52		Small	Large	Heavy		Expected Value
53	Small	111.52	93.99	89.70		E(Tij) + B(Tij)
54	Large	181.65	93.99	89.70		132.51
55	Heavy	257.45	161.70	125.70		
56						
57	Arrivals Only Capacity (per hour)			27.17		
58						
59						
60	Departure-Departure Separation Matrix (seconds)					
61			Trailing			
62		Small	Large	Heavy		Expected Value
63	Small	60	60	60		E(Td)
64	Large	90	60	60		76.5
65	Heavy	120	120	120		
66						
67	Departures Only Capacity (per hour)			47.06		
68						

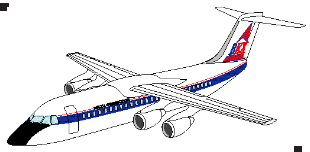
Departure-Departure Separation Matrix

Results of CLT Analysis



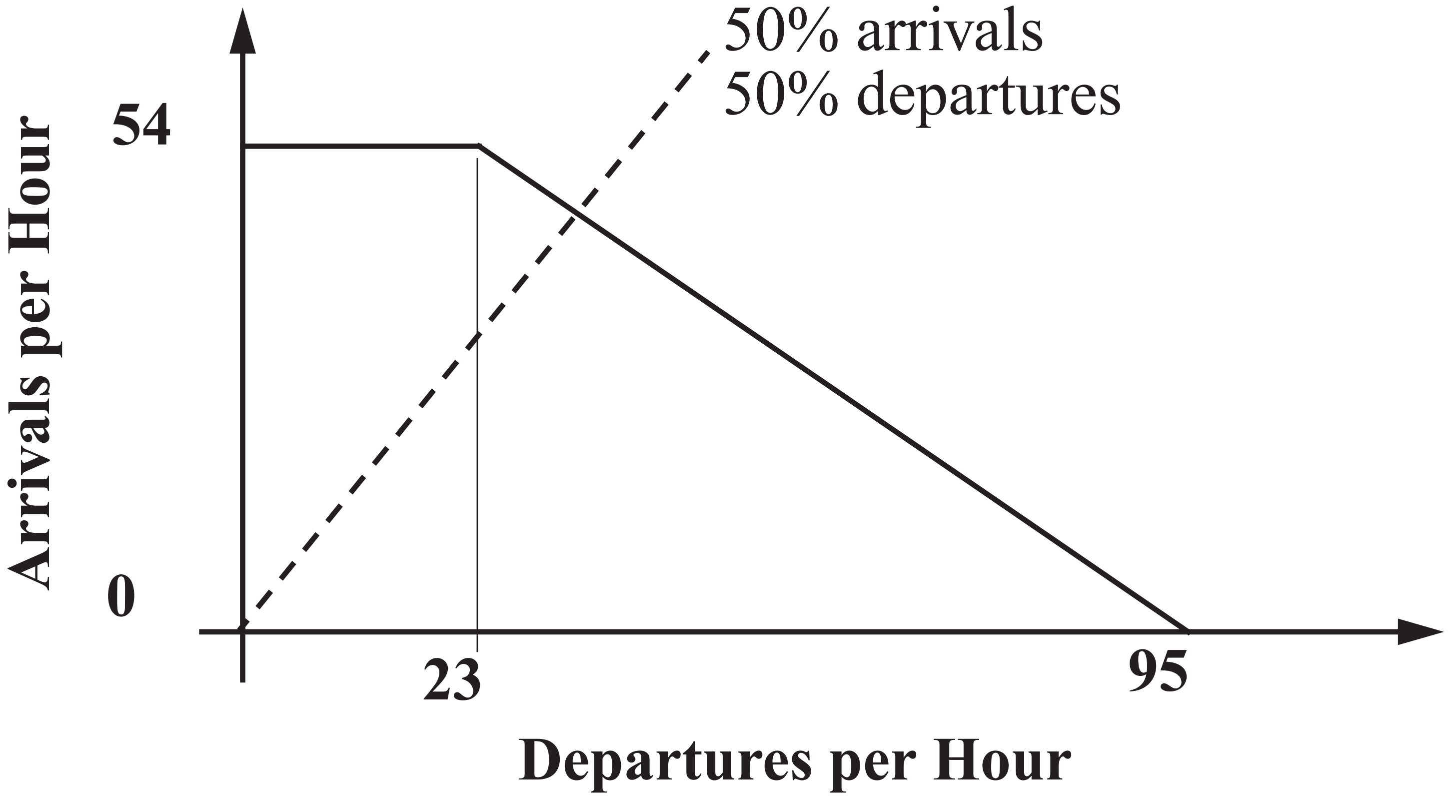
Single runway analysis - mixed operations



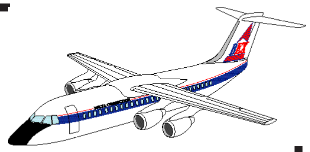


Results of CLT Analysis

Two-parallel runway analysis - mixed operations

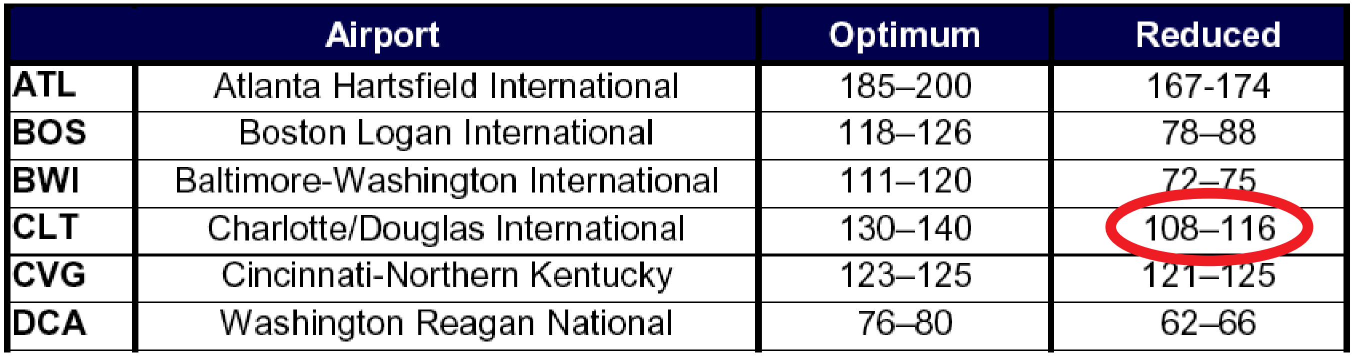


Capacity Benchmark Results



The FAA capacity benchmarks offer an assessment of the estimated capacity by the FAA

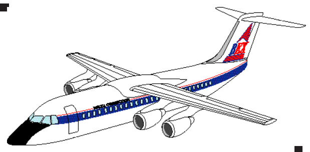
Table 1
Capacity Benchmarks for Today's Operations at 31 Airports

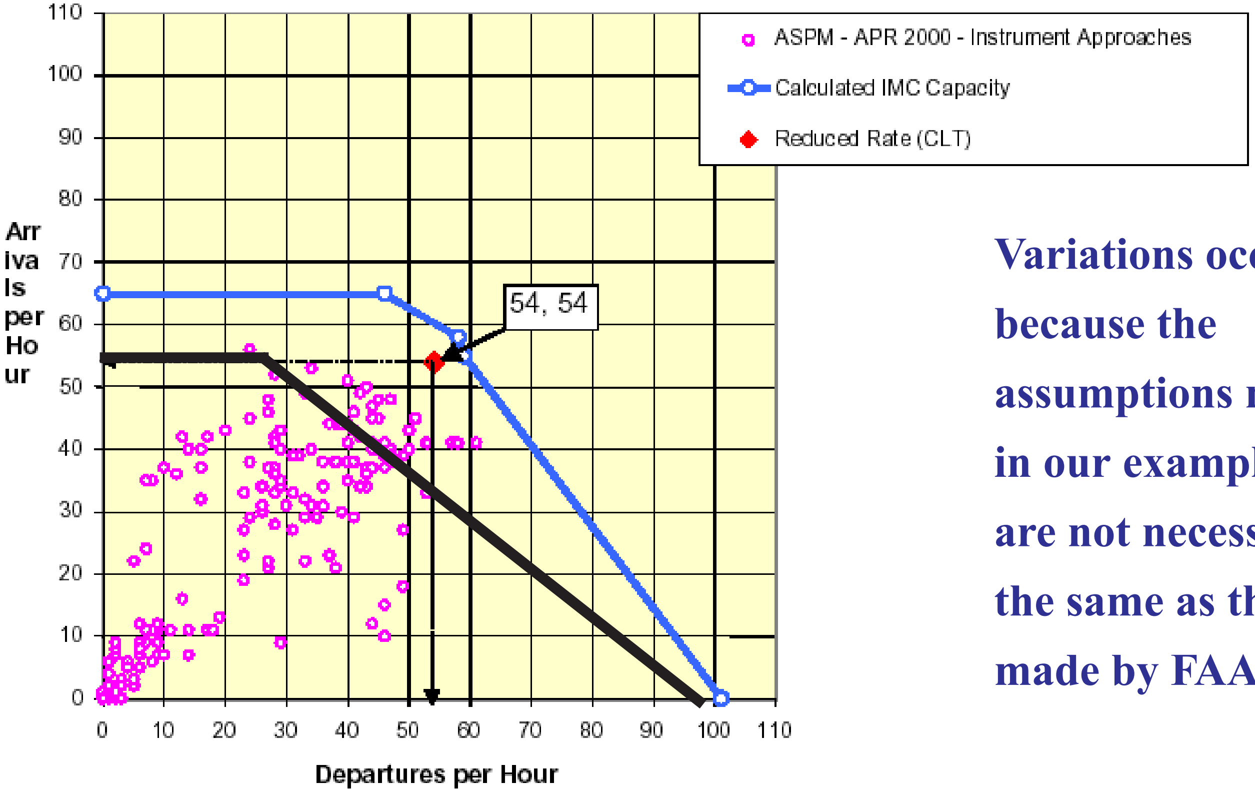


Airport		Optimum	Reduced
ATL	Atlanta Hartsfield International	185–200	167-174
BOS	Boston Logan International	118–126	78–88
BWI	Baltimore-Washington International	111–120	72–75
CLT	Charlotte/Douglas International	130–140	108–116
CVG	Cincinnati-Northern Kentucky	123–125	121–125
DCA	Washington Reagan National	76–80	62–66

Reduced capacity = IMC conditions

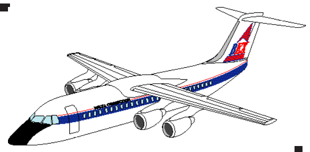
FAA Benchmark Results vs. Our Analysis





Variations occur because the assumptions made in our example are not necessarily the same as those made by FAA

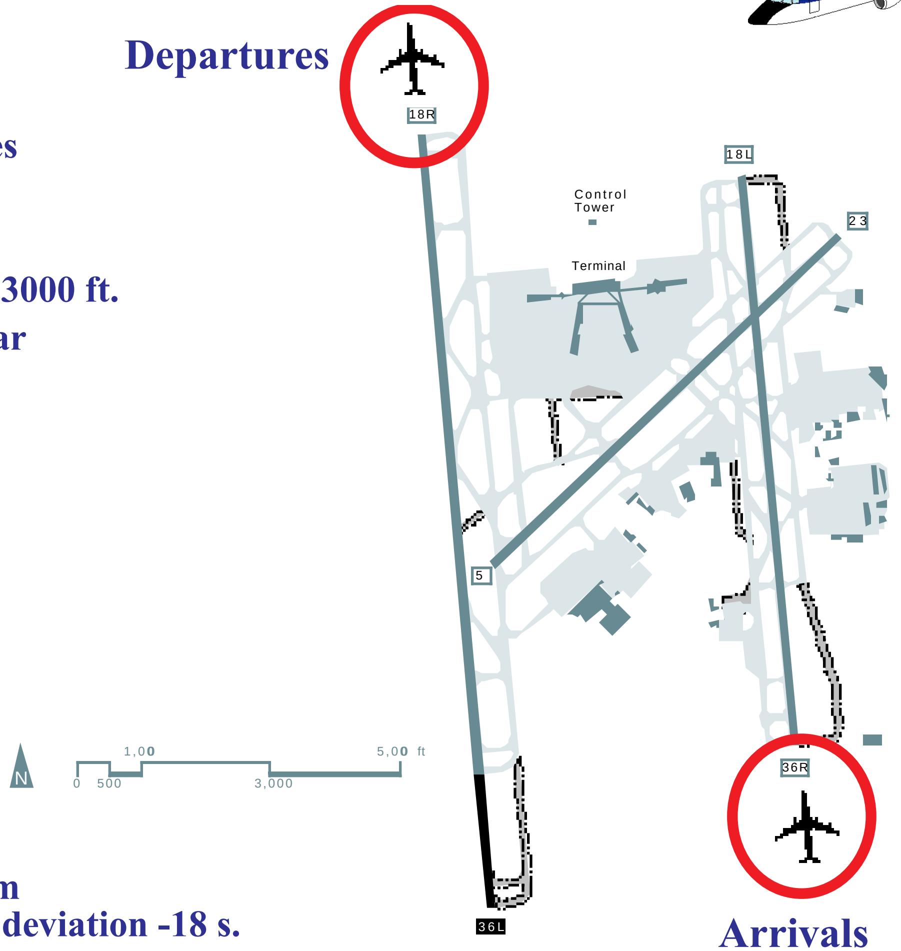
Example 3 - Charlotte-Douglas Intl. Airport



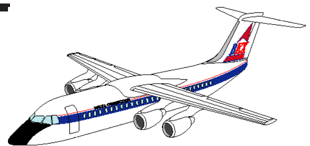
Operational Conditions

1) Runway 18R/36L for departures
   Runway 18L/36R for arrivals
2) Runway 5/23 is inactive
3) Parallel runway separation > 4,3000 ft.
4) ASR-9 airport surveillance radar
   (scan time 4.8 seconds)
5) Aircraft mix
   a) Heavy - 20%
   b) Large - 30%
   c) Small - 50%
6) Approach speeds
   a) Heavy - 150 knots
   b) Large - 140 knots
   c) Small - 110 knots
7) Runway occupancy times
   a) Heavy - 57 s.
   b) Large - 52 s.
   c) Small - 49 s.
8) Common approach length - 7 nm
9) In-trail delivery error standard deviation -18 s.
10) Large hub separation criteria (2.5/4/5/6 nm)
11) IMC weather conditions

Departures

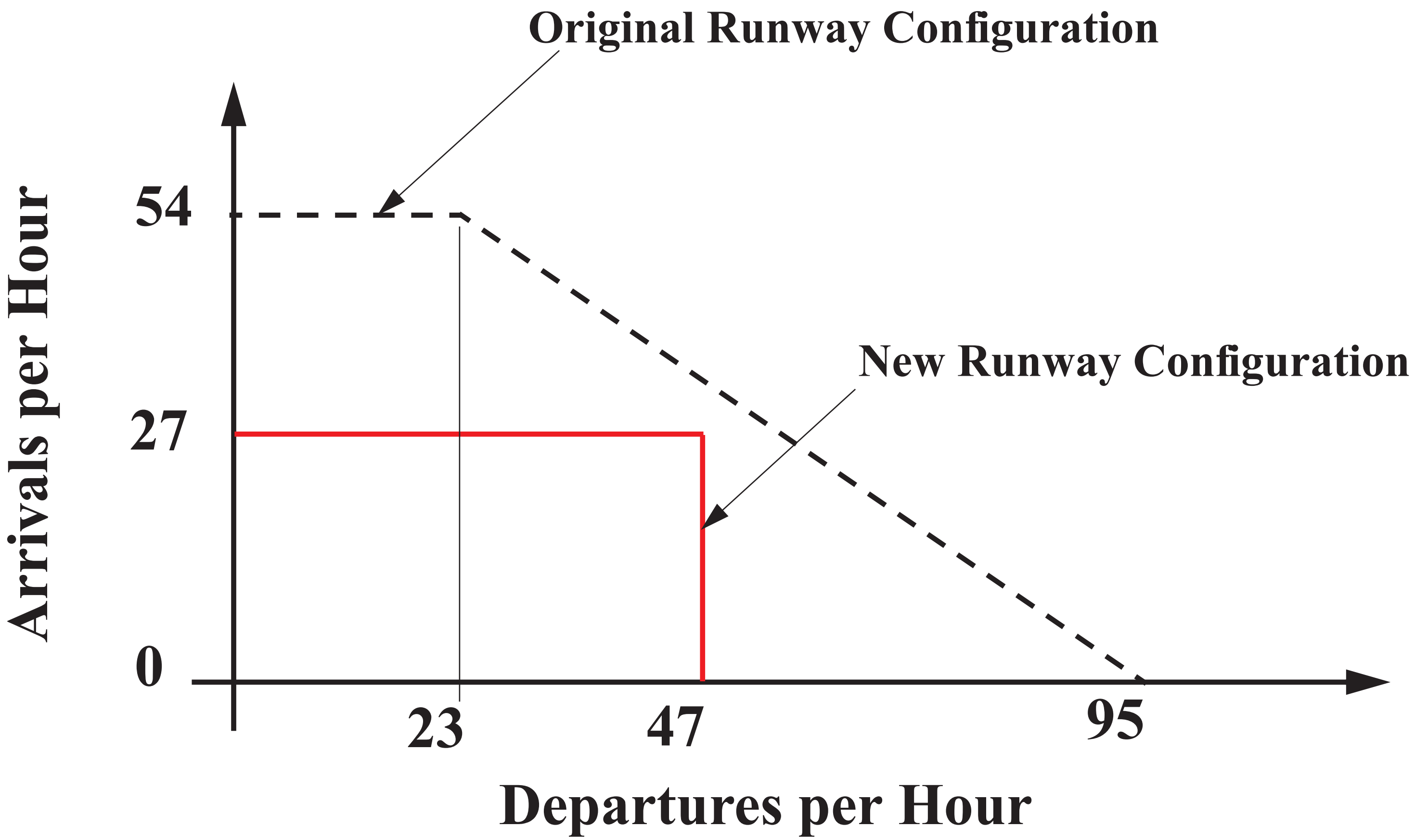


Arrivals

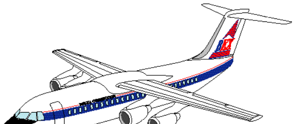


Results of CLT Analysis

Two-parallel runway analysis - segregated operations

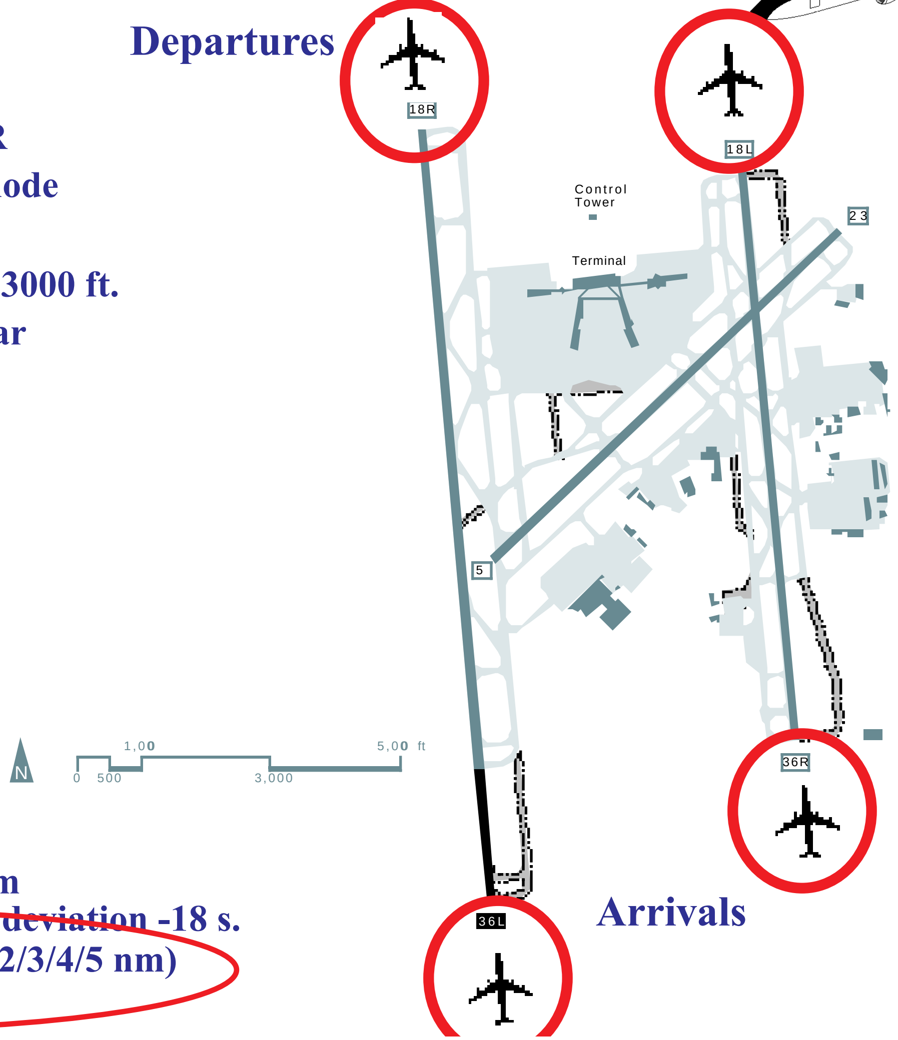


Example 4 - Charlotte-Douglas Intl. Airport

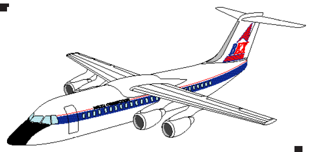


Operational Conditions

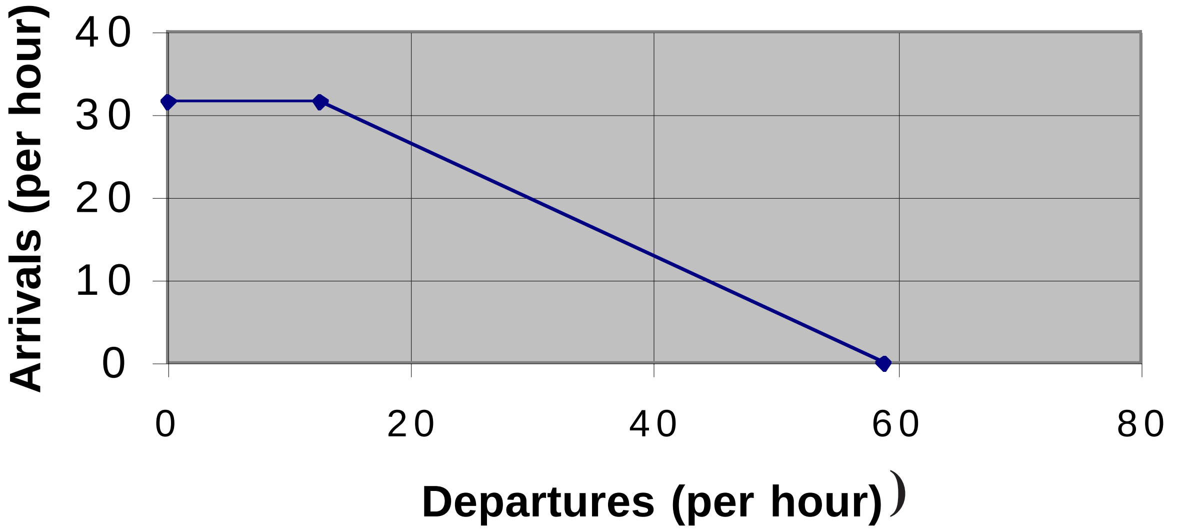
1) Runways 18R/36L and 18L/36R
are used in mixed operations mode
2) Runway 5/23 is inactive
3) Parallel runway separation > 4,3000 ft.
4) ASR-9 airport surveillance radar
(scan time 4.8 seconds)
5) Aircraft mix
   a) Heavy - 20%
   b) Large - 30%
   c) Small - 50%
6) Approach speeds
   a) Heavy - 150 knots
   b) Large - 140 knots
   c) Small - 110 knots
7) Runway occupancy times
   a) Heavy - 57 s.
   b) Large - 52 s.
   c) Small - 49 s.
8) Common approach length - 7 nm
9) In-trail delivery error standard deviation -18 s.
10) Large hub separation criteria (2/3/4/5 nm)
11)VMC weather conditions



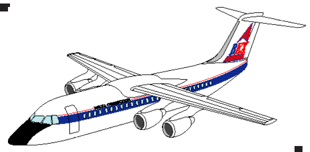
Results for CLT VMC Scenario



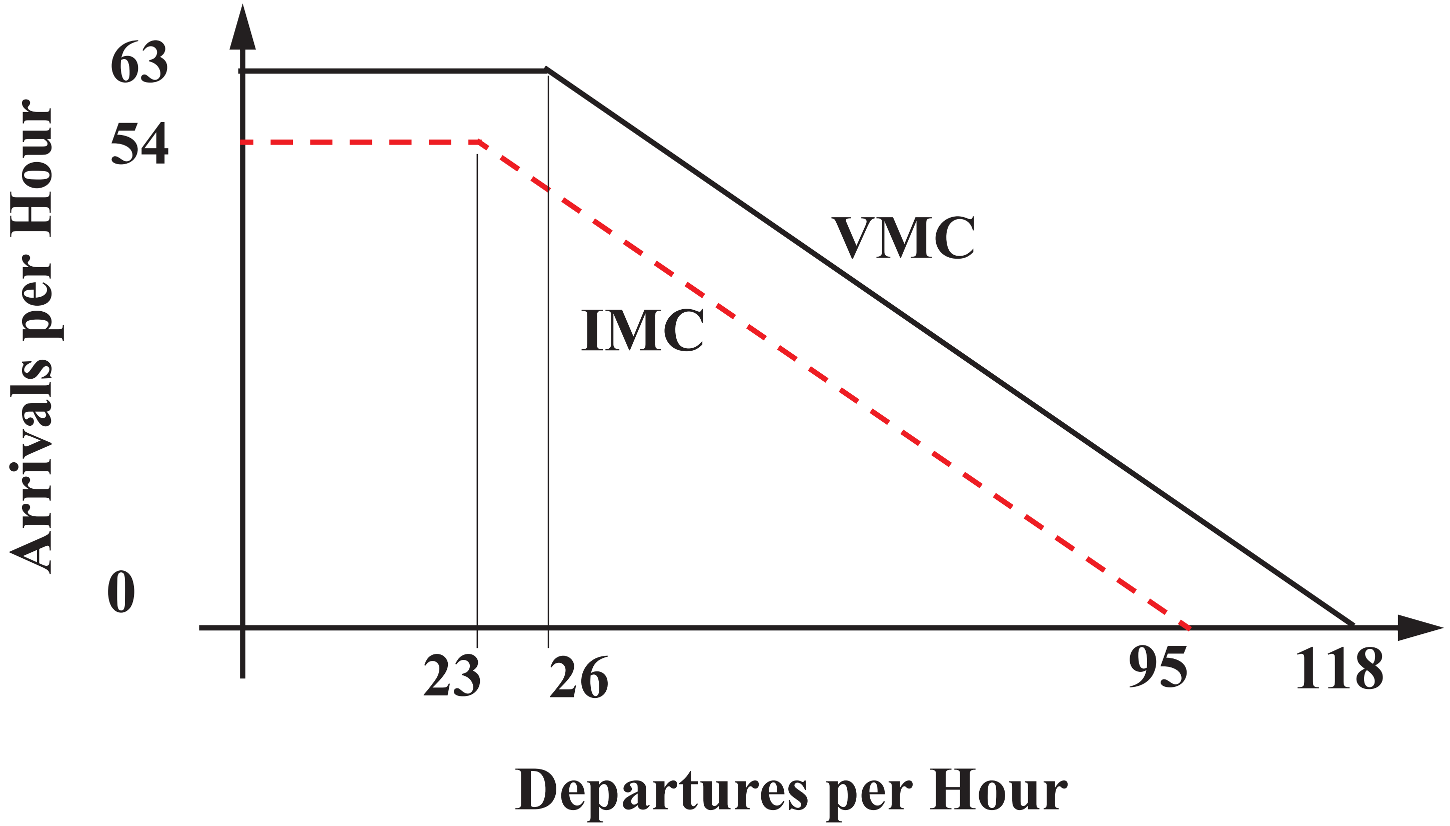
Single runway analysis - mixed operations



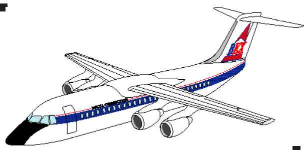
Results of CLT VMC Analysis



Two-parallel runway analysis - mixed operations

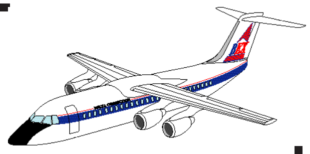


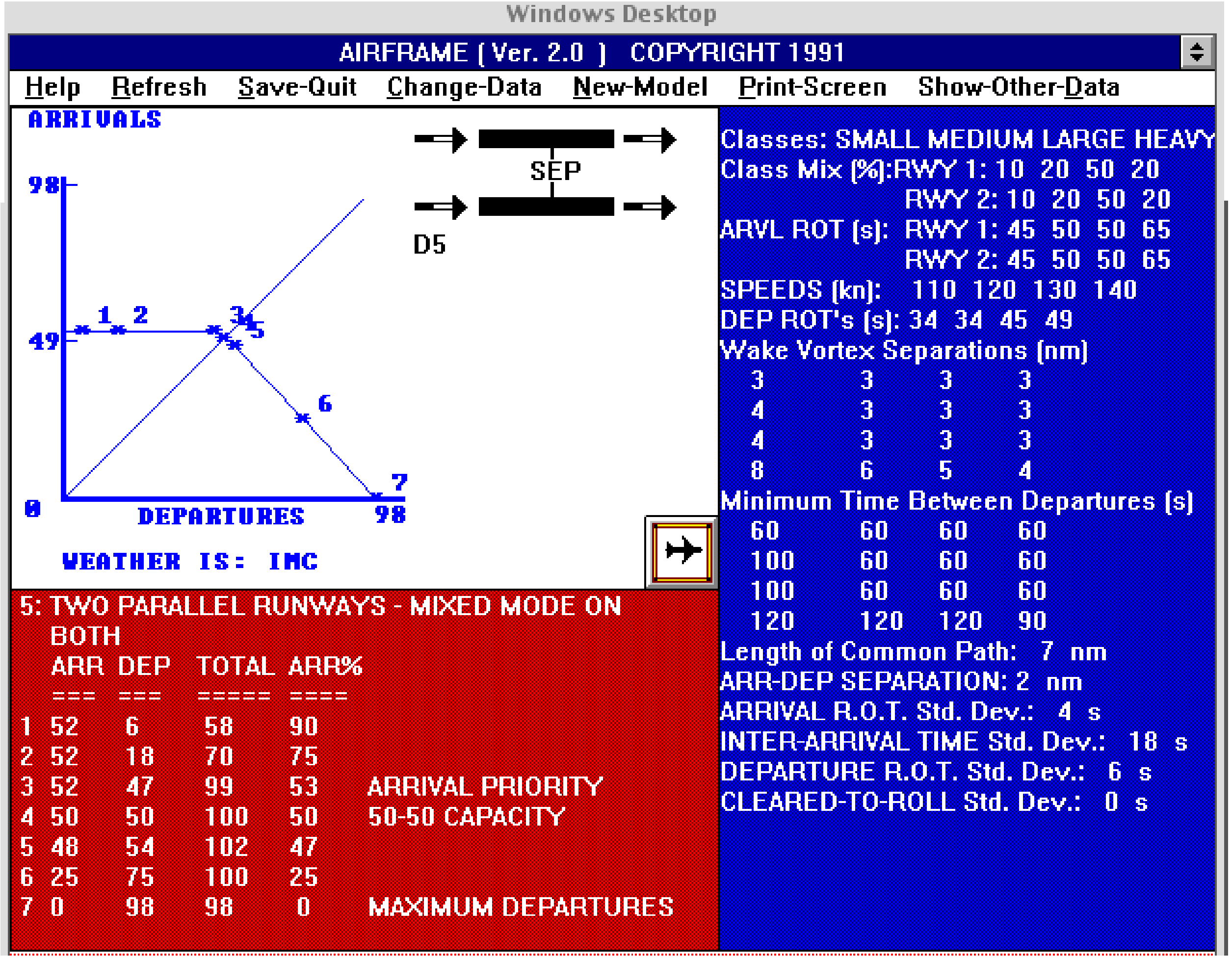
Airport Capacity Model (ACM)



- Model developed by FAA to expedite computations of runway saturation capacity
- Later modified by MITRE to be more user friendly
- Inputs and output of the model are similar to those included in the spreadsheet shown in class
- Provides 7-9 data points to plot the arrival-capacity saturation capacity envelope (Pareto frontier)

Sample Enhanced ACM Results





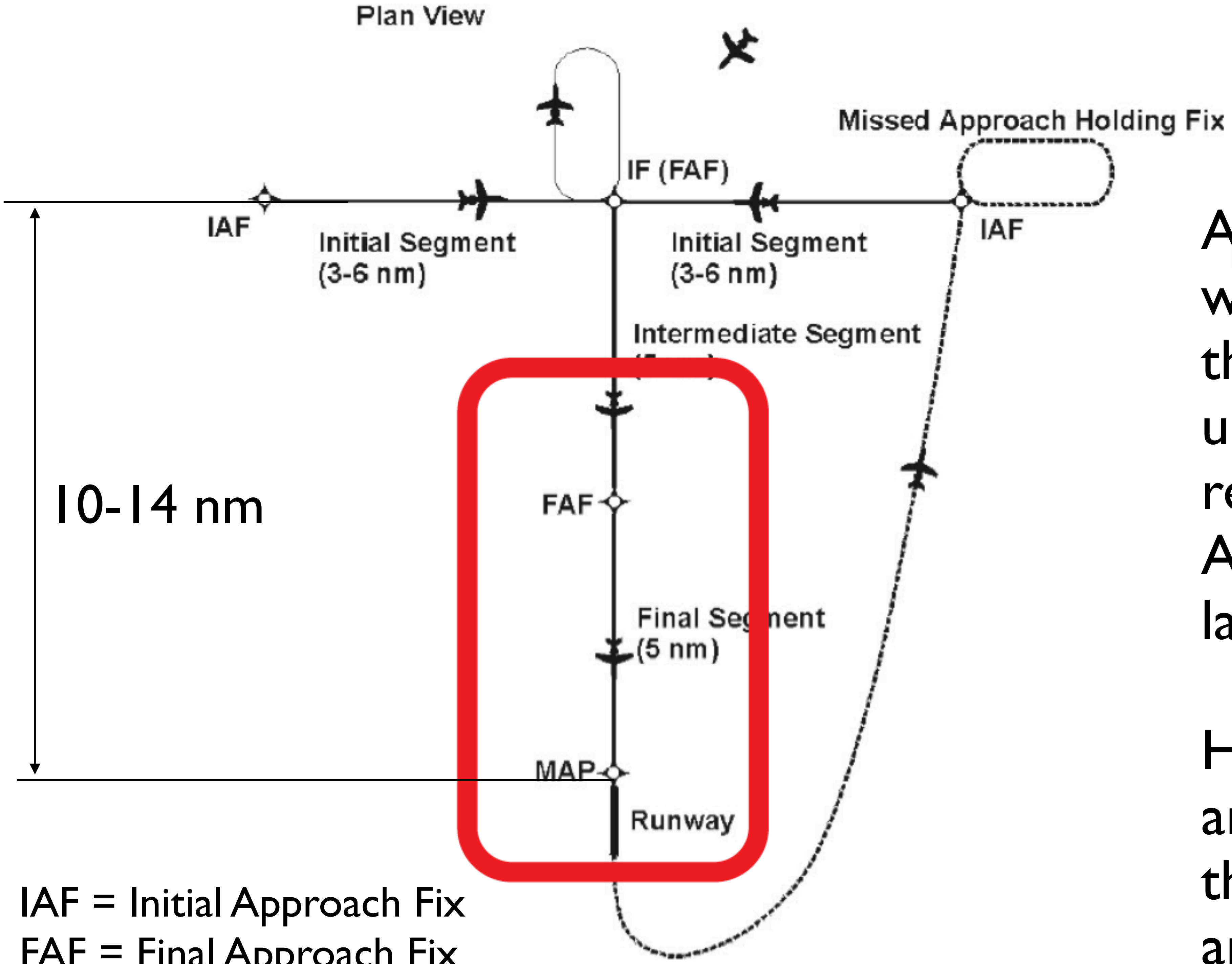
```
5: TWO PARALLEL RUNWAYS - MIXED MODE ON
   BOTH
   ARR  DEP   TOTAL  ARR%
   ===  ===   =====  ====
1  52    6     58     90
2  52   18     70     75
3  52   47     99     53    ARRIVAL PRIORITY
4  50   50    100     50    50-50 CAPACITY
5  48   54    102     47
6  25   75    100     25
7  0    98     98      0    MAXIMUM DEPARTURES
```

```
Classes: SMALL MEDIUM LARGE HEAVY
Class Mix [%]:RWY 1: 10  20  50  20
              RWY 2: 10  20  50  20
ARVL ROT (s):  RWY 1: 45  50  50  65
               RWY 2: 45  50  50  65
SPEEDS (kn):   110  120  130  140
DEP ROT's (s): 34  34  45  49
Wake Vortex Separations (nm)
   3        3      3      3
   4        3      3      3
   4        3      3      3
   8        6      5      4
Minimum Time Between Departures (s)
   60       60     60     60
   100      60     60     60
   100      60     60     60
   120      120    120    90
Length of Common Path:  7  nm
ARR-DEP SEPARATION: 2  nm
ARRIVAL R.O.T. Std. Dev.:  4  s
INTER-ARRIVAL TIME Std. Dev.:  18  s
DEPARTURE R.O.T. Std. Dev.:  6  s
CLEARED-TO-ROLL Std. Dev.:  0  s
```

Capacity of Non-tower Airports

- Existing airports without a control tower have lower runway capacities
  - In IMC (Instrument Meteorological Conditions) perhaps 5-9 arrivals per hour
  - In VMC (Visual Meteorological Conditions) around 15-20 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)
- Automated Dependance Surveyance (ADS-B) can help provide better situational awareness

Typical Arrival Geometry of Uncontrolled Airports

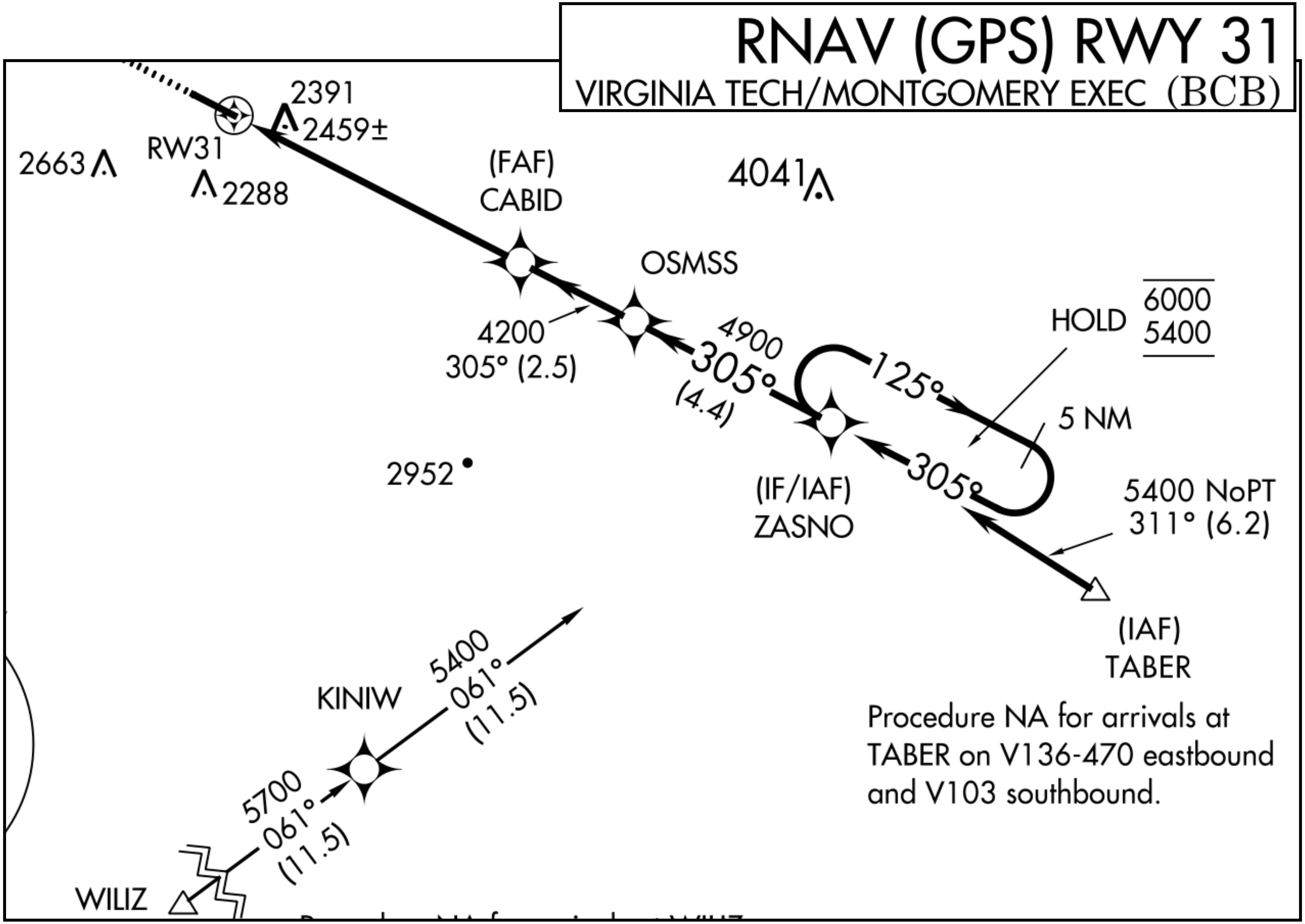


IAF = Initial Approach Fix
FAF = Final Approach Fix
MAP = Missed Approach Point

ATC controllers will hold aircraft at the Initial Fix (IF) until the lead arrival reports back to ATC that they have landed

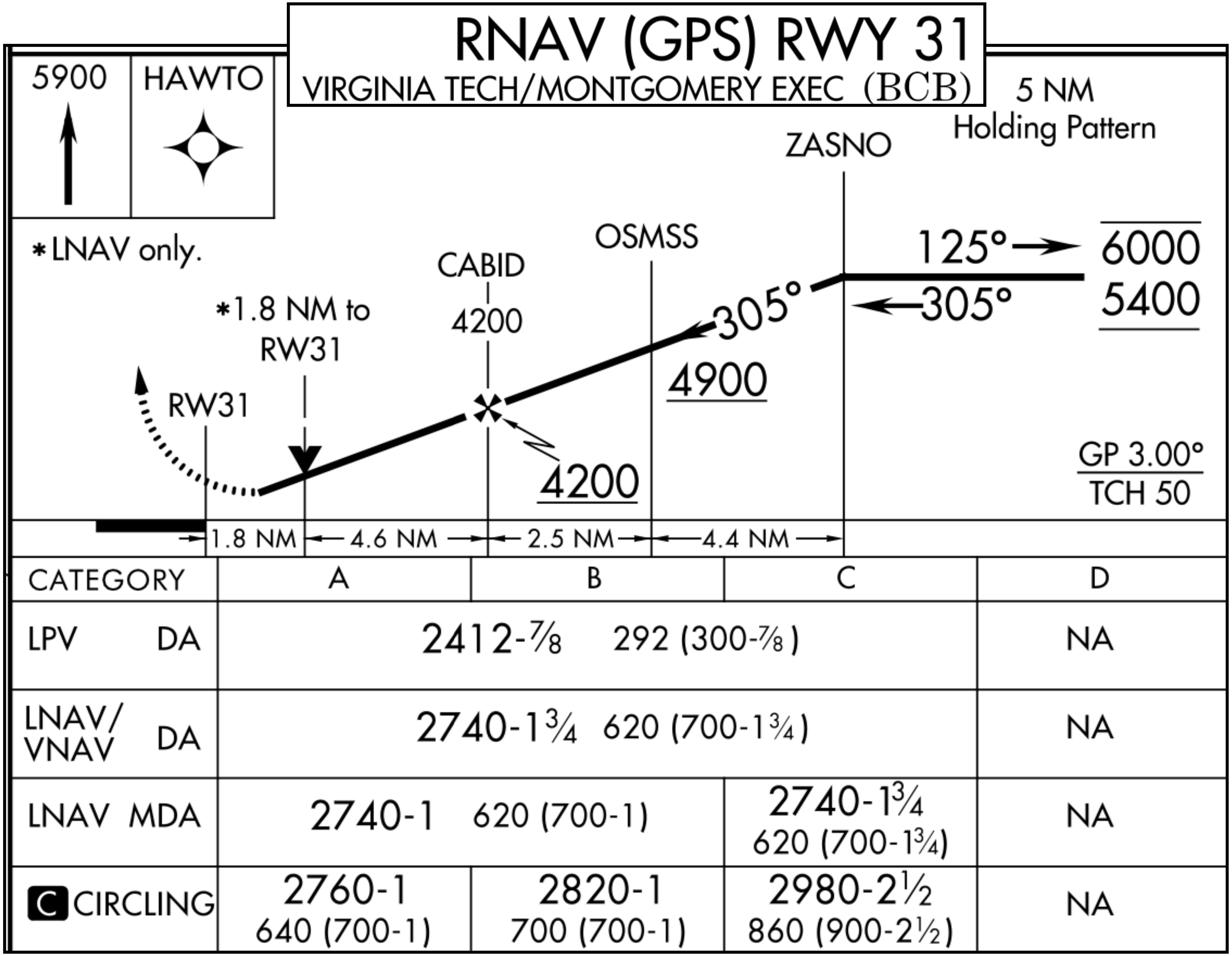
Holding patterns are used to control the inbound flow of arrivals

Typical Arrival Geometry of Uncontrolled Airports



Procedure NA for arrivals at TABER on V136-470 eastbound and V103 southbound.

Typical Arrival Geometry of Uncontrolled Airports

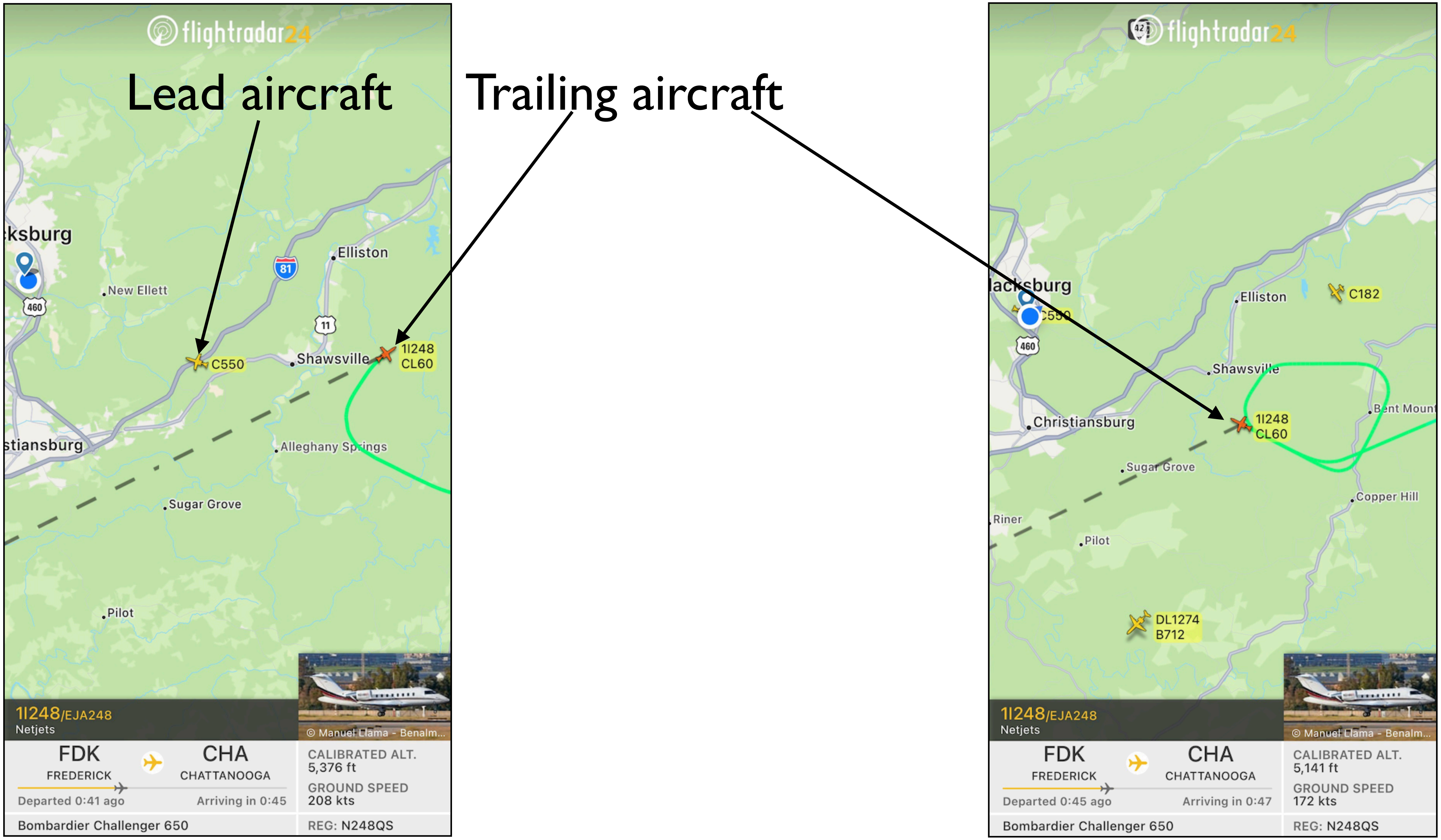


RNAV (GPS) RWY 31
VIRGINIA TECH/MONTGOMERY EXEC (BCB)

CATEGORY	A	B	C	D
LPV DA	2412-⅞ 292 (300-⅞)			NA
LNAV/VNAV DA	2740-1¾ 620 (700-1¾)			NA
LNAV MDA	2740-1 620 (700-1)		2740-1¾ 620 (700-1¾)	NA
C CIRCLING	2760-1 640 (700-1)	2820-1 700 (700-1)	2980-2½ 860 (900-2½)	NA

Example Problem: BCB Airport

- Example of vectoring and 360 degree turn to establish separation



11248/EJA248
Netjets
FDK FREDERICK → CHA CHATTANOOGA
Departed 0:41 ago
Arriving in 0:45
CALIBRATED ALT. 5,376 ft
GROUND SPEED 208 kts
Bombardier Challenger 650
REG: N248QS

11248/EJA248
Netjets
FDK FREDERICK → CHA CHATTANOOGA
Departed 0:45 ago
Arriving in 0:47
CALIBRATED ALT. 5,141 ft
GROUND SPEED 172 kts
Bombardier Challenger 650
REG: N248QS

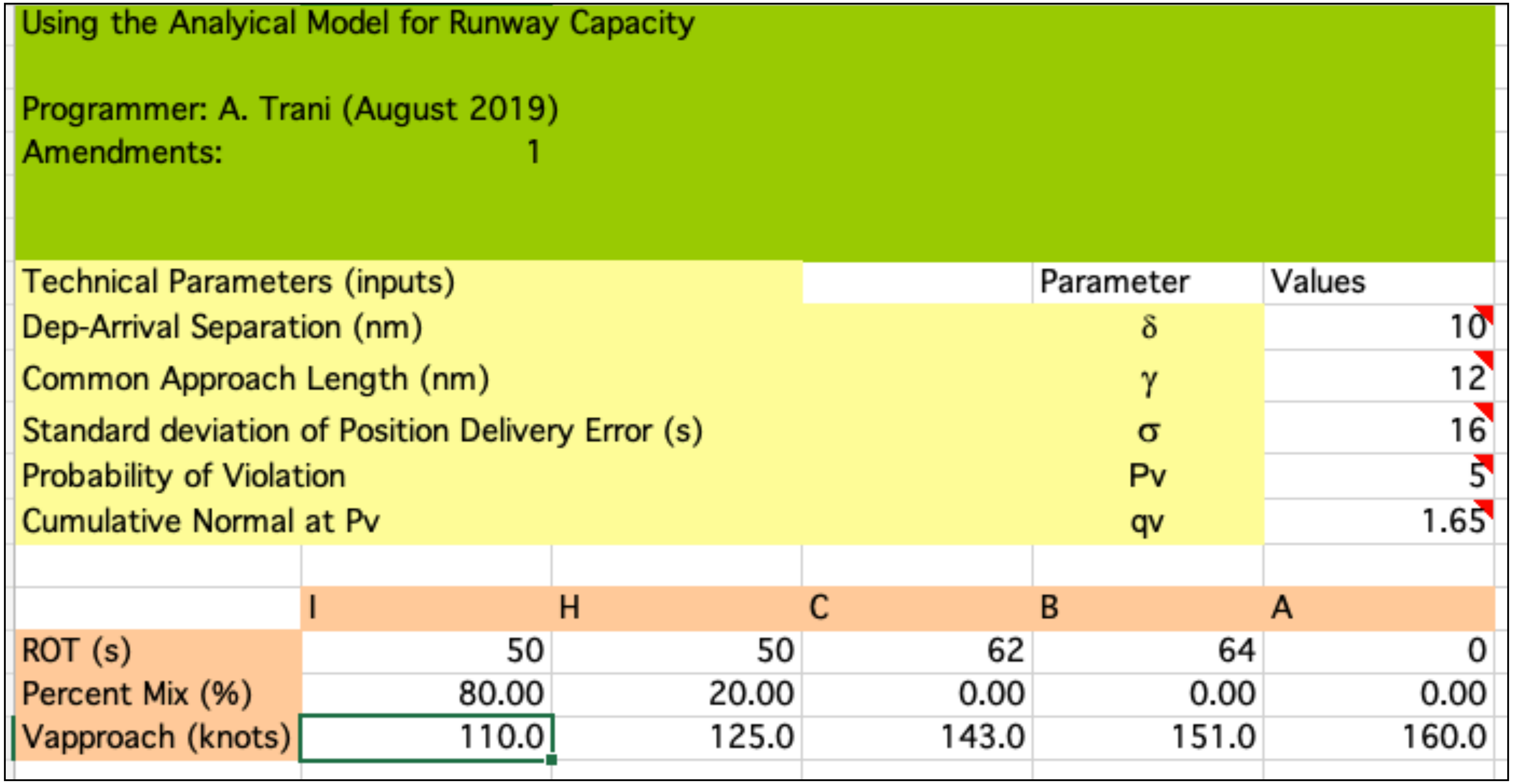
Example Problem: BCB Airport

- Virginia Tech Airport
- Two aircraft CWT groups operating at the airport

Aircraft CWT Group	H	I
ROT (s)	50	52
Percent Mix (%)	80	20
Vapproach (knots)	110	125

Example Problem: BCB Airport

- Virginia Tech Airport
- IMC Conditions



Using the Analyical Model for Runway Capacity

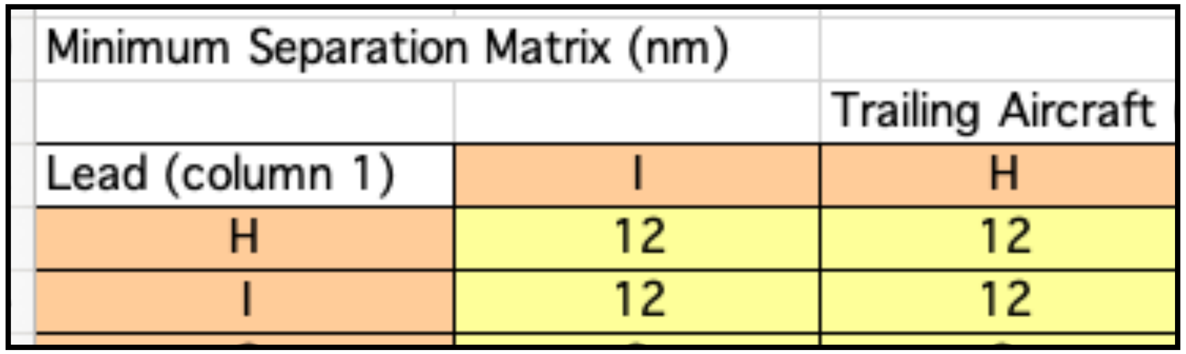
Programmer: A. Trani (August 2019)
Amendments: 1

Technical Parameters (inputs)	Parameter	Values
Dep-Arrival Separation (nm)	δ	10
Common Approach Length (nm)	γ	12
Standard deviation of Position Delivery Error (s)	σ	16
Probability of Violation	Pv	5
Cumulative Normal at Pv	qv	1.65

	I	H	C	B	A
ROT (s)	50	50	62	64	0
Percent Mix (%)	80.00	20.00	0.00	0.00	0.00
Vapproach (knots)	110.0	125.0	143.0	151.0	160.0

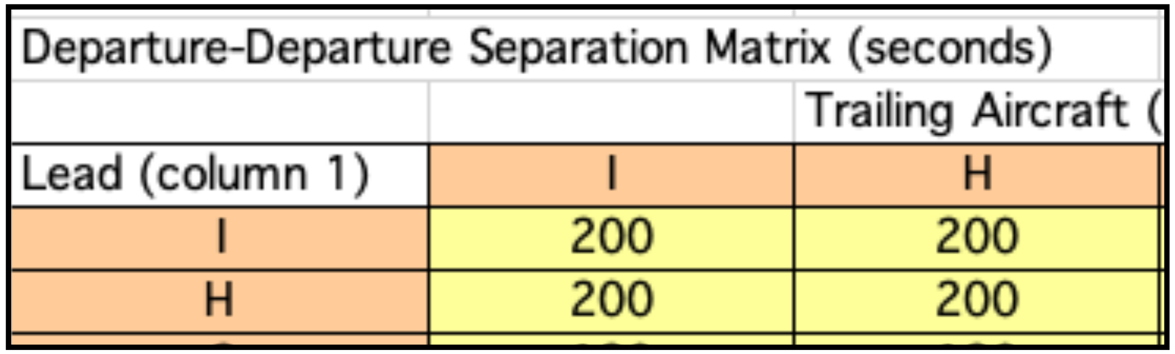
Example Problem: BCB Airport

- IMC Conditions



Minimum Separation Matrix (nm)		
		Trailing Aircraft
Lead (column 1)	I	H
H	12	12
I	12	12

Distance to Initial Fix

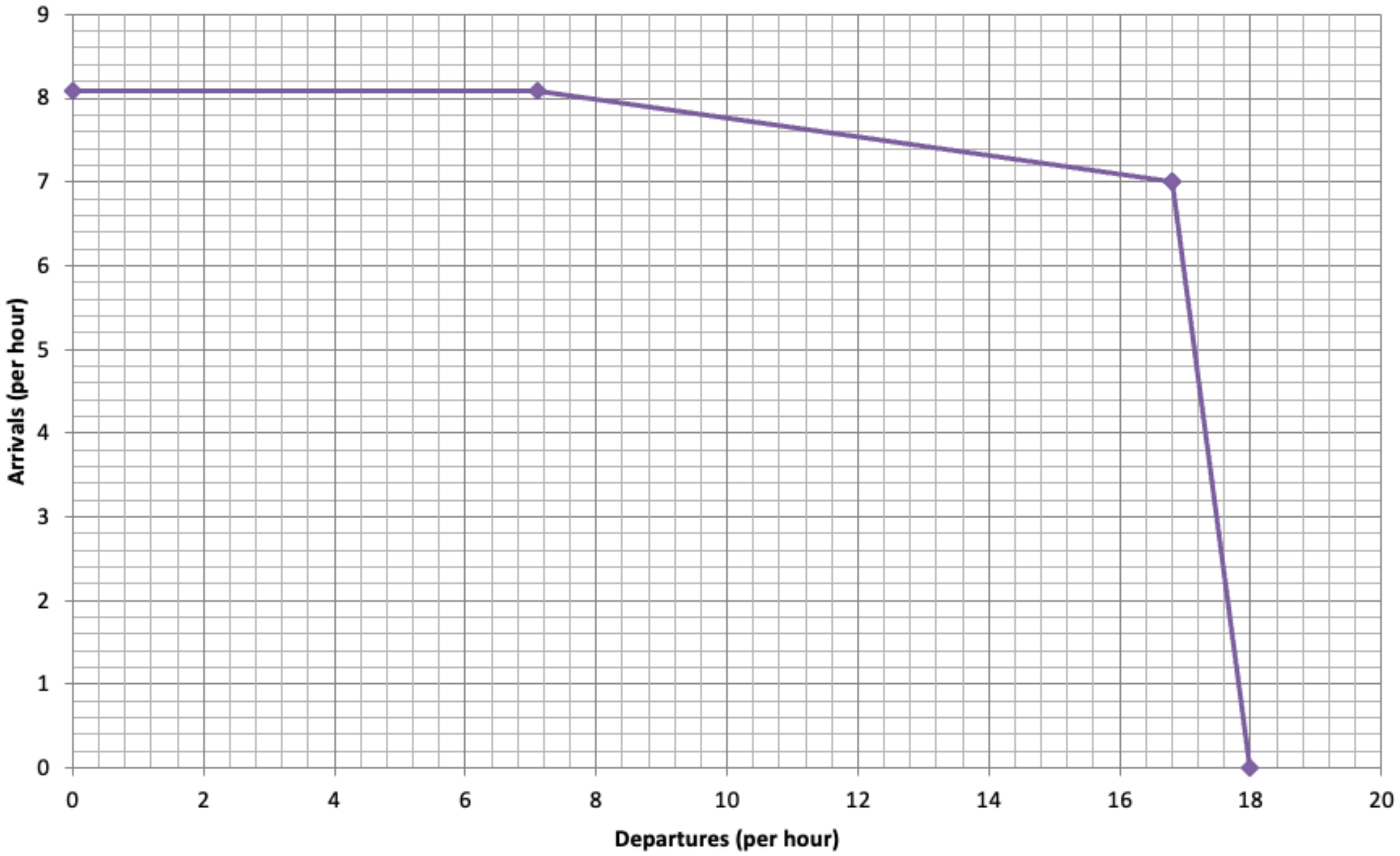


Departure-Departure Separation Matrix (seconds)		
		Trailing Aircraft (
Lead (column 1)	I	H
I	200	200
H	200	200

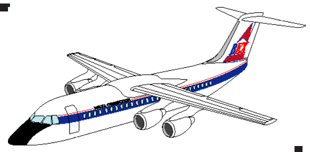
Time to climb out of BCB and aircraft to be in radar contact

Example Problem: BCB Airport

- IMC Conditions runway capacity

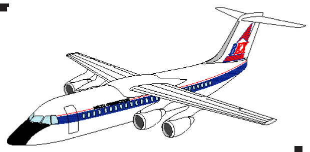


Summary of Results



- The saturation capacity of an airport with HVO (ADS-B) technology depends on the safety buffers allowed and the delivery accuracy of pilots/AMM system
- 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 seems consistent with analyses done by TSAA in 2003 (Milsaps, 2003)
- The results compare well with those obtained using the FAA Airport Capacity Model
- The availability of a parallel taxiway has a large influence in the mixed mode saturation capacities

Recapitulation



- The saturation capacity of an airport depends on the runway configuration used
- The saturation capacity during VMC conditions is higher than during 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 seems very conservative
- The time-space analysis does not provide with delay results (use deterministic queueing theory or FAA AC 150/5060 to estimate delay)