CEE 4674 Airport Planning and Design

Geometric Design: Part 2
Runway Exit Design and Exit Locations

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Geometric Design of Runway Exits

Sources of information:

- FAA AC 150/5300-13B (Chapter 4)
  - Sections 4.8.2 through 4.8.6
- ICAO Aerodrome Manual Volumes 1 and 2

Design principles:

- Provide ample space for aircraft to maneuver out of the runway
- Locate runway exits consistent with aircraft landing performance

Important Issues about Runway Exits

- Runway exits are responsible for making operations more efficient on the ground
- Poorly designed runway exits add valuable service time (i.e., runway occupancy time)
- Poorly placed runway exits can contribute to go-arounds and runway incursions
- Runway occupancy time and its standard deviation are critical parameters for runway capacity estimation

Runway Occupancy Time

- The time elapsed between the aircraft crossing the runway threshold and the time when the same aircraft crosses the imaginary plane of a runway exit paved area (aircraft wingtip or tailtip)
- Issues about ROT
  - The definition of ROT has been used inconsistently throughout the years
  - Many early ROT studies failed to recognize that when an aircraft starts turning towards the runway exit, the aircraft is still using the runway until its wingtip clears the runway edge plane

Factors Affecting Runway Occupancy Time

- Aircraft type (AAC group)
- Runway geometric design factors
  - Runway width
  - Pavement condition (wet, dry, contaminated)
- Taxiway geometry design factors
  - Number of runway exits on the runway
  - Taxiway type
  - Taxiway network interaction
- Pilot technique
- Traffic pressure (i.e., having another aircraft on short final behind)
- Gate location

Source of Runway Occupancy Time Data FAA and Virginia Tech Landing Event Database

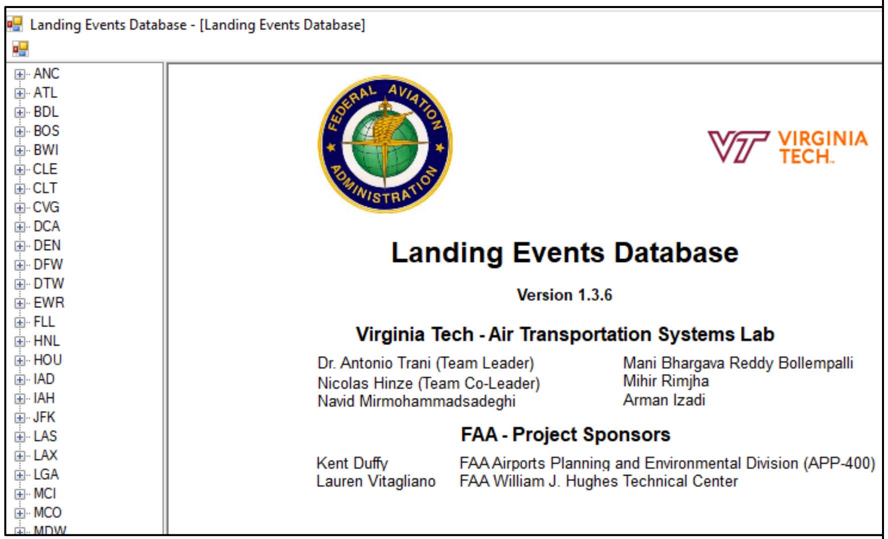
Landing Events Database

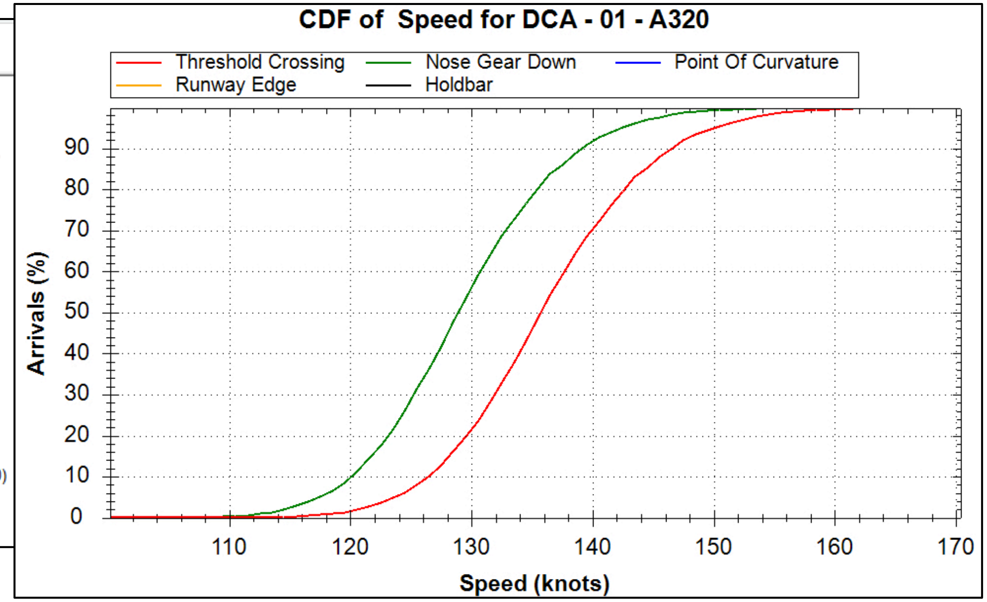
- **Landing Events Database** archives 36 million landing records from ASDE-X data (all landings at 43 U.S. airports during for years 2015-2020)
  - Stand-alone product (client software)
- Tabular and graphical data on runway exit utilization at 43 U.S. airports

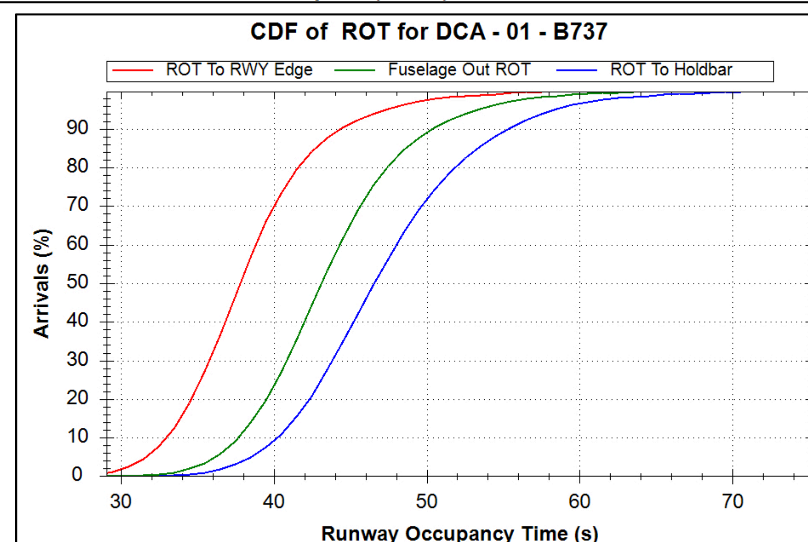
Landing database client can be downloaded at:

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

Landing Event Database Tool Versions 1.3.6-1.3.7







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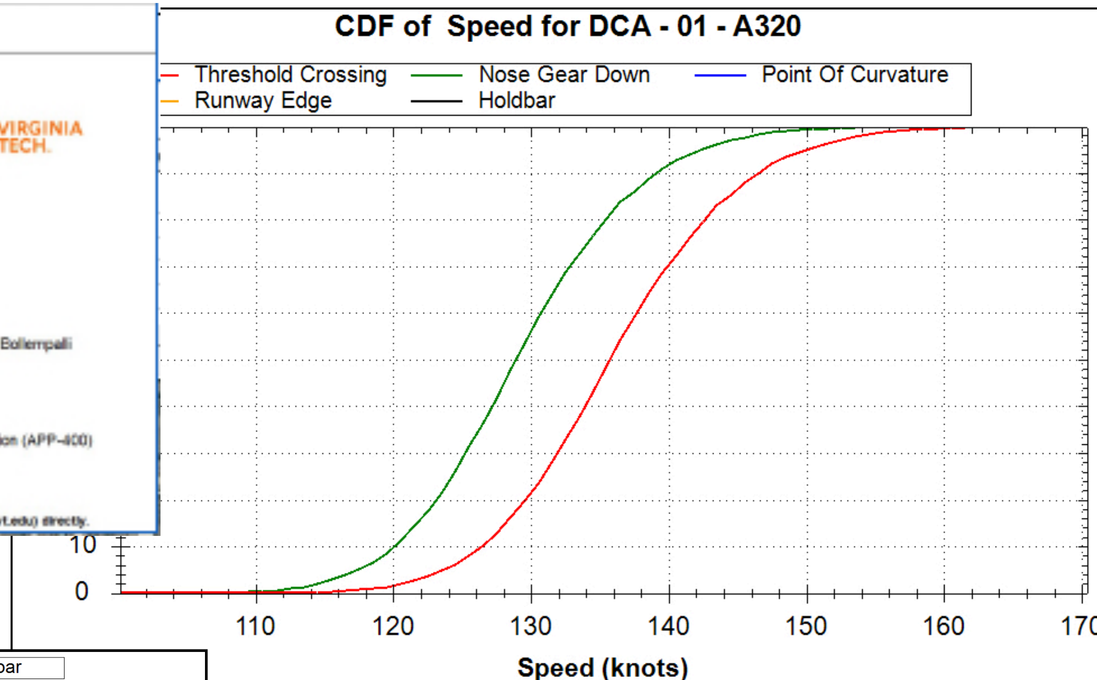
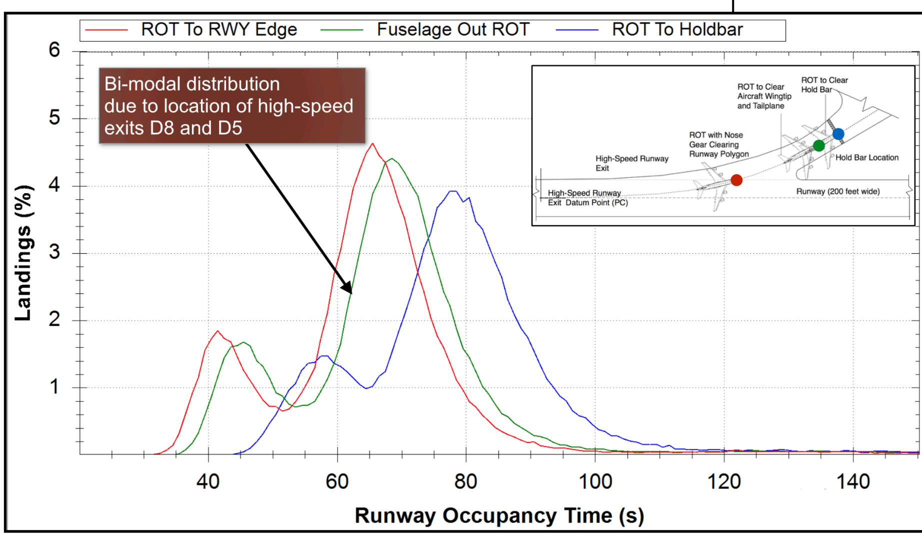
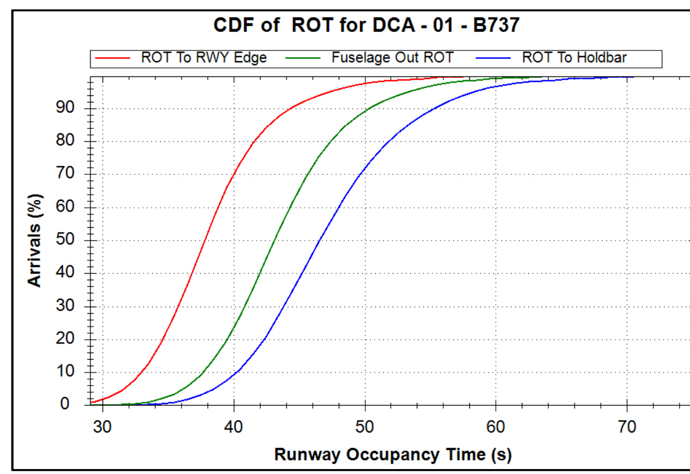
Landing Event Database Tool : Screen Shots







Landing Event Database Tool (1)

Analysis	Purpose	Metrics and Ready-Made Query Options
Aircraft Mix	Provides an overview of aircraft fleet mix in the form of a pie chart with the top 10 aircraft in the fleet mix presented.	By runway By runway exit
Runway Occupancy Time	Provides three values of runway occupancy time measured at three locations: 1.Runway edge 2.Fuselage out 3.At hold bar	1.Average ROT (in seconds) by runway, runway exit and aircraft 2.Median ROT (in seconds) by runway, runway exit and aircraft 3.Probability Density Function (PDF) of ROT (dim) by runway, runway exit and aircraft 4.Cumulative density function of ROT by runway, runway exit and aircraft 5.Runway exit utilization (percentage) by runway exit and aircraft
Speed	Provides information about five aircraft ground speeds at different locations of the landing profile: 1.Threshold 2.Nose gear down 3.Point of curvature 4.Runway edge 5.Hold bar	1.Average ROT (in seconds) by runway, runway exit and aircraft 2.Median ROT (in seconds) by runway, runway exit and aircraft 3.Probability Density Function (PDF) of ROT (dim) by runway, runway exit and aircraft 4.Cumulative density function of ROT by runway, runway exit and aircraft 5.Detailed speed profiles as a function of distance by aircraft, runway and runway exit 6.Detailed speed profiles as a function of time by aircraft, runway and runway exit
Nose Gear Location	Provides estimates of nose gear distance. The nose gear distance is estimated in the landing algorithm to initiate the nominal deceleration.	1.Nose gear distance from runway landing threshold by runway, aircraft and runway exit 2.Probability Density Function (PDF) of nose gear distance (feet or meters) by runway, runway exit and aircraft 3.Cumulative density function of nose gear distance (feet or meters) by runway, runway exit and aircraft

Landing Event Database Tool (2)

Analysis	Purpose	Metrics and Ready-Made Query Options
Deceleration	Provides two values of aircraft deceleration on the runway: Nominal Nominal location to point of curvature (Nominal to PC)	Average deceleration (in m/s2) by runway, runway exit and aircraft Median deceleration (in m/s2) by runway, runway exit and aircraft Probability Density Function (PDF) of deceleration (in m/s2) by runway, runway exit and aircraft (both average and median values can be plotted) Cumulative density function of aircraft deceleration (in m/s2) by runway, runway exit and aircraft (both average and median values can be plotted)
Raw Data	Provides detailed information (in a table) on 30 key parameters for every landing contained in the Landing Events Database. Provides graphical information of every landing in the database. Provides a graphical depiction of individual landings in a Microsoft NAVTEQ map layer (bottom viewport)	30 key parameters defining the landing profile of each landing operation. Parameters include: flight ID, aircraft type, runway, runway exit use, time of operation, nose gear touchdown distance and time, nominal deceleration, deceleration from nominal point to PC, exit speed, and airport wind conditions. Speed-distance profile of each landing event Speed-time profile of each landing event Acceleration-time profile of each landing event Acceleration-distance profile of each landing event Processed numerical data with speed, acceleration, distance and time for individual landings.
Statistics	Summarizes the landing statistics processed by airport by month.	Total landing records Valid records Number of records with missing parameters Number of records with unreasonable parameters Records with no associated runway Go-around records

Landing Database **Raw Data Viewer**

26R | Exit | A320 | Arrival | Valid Flights | Query | Export

Flight 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)	Nominal Speed (kts)	Exiting Speed (kts)	ROT Edge Speed (kts)	ROT Fuselage Speed (kts)
DAL1639	A320	26R	B3	1/1/2015 9:3...	1/1/2015 9:...	13.7	3,040	30.2	5,603	37.2	6,280	42.9	47.3	52.1	132.0	125.4	70.0	48.6	41.1	34.8
DAL2133	A320	26R	B3	1/1/2015 9:4...	1/1/2015 9:...	12.4	2,741	28.2	5,110	42.3	6,280	49.8	55.3	63.2	131.3	124.7	70.0	37.0	29.0	25.2
NKS165	A320	26R	B3	1/1/2015 9:4...	1/1/2015 9:...	12.6	2,844	28.3	5,381	39.1	6,280	47.1	52.2	62.2	136.9	130.0	70.0	38.7	28.1	25.6
DAL390	A320	26R	B3	1/1/2015 11:...	1/1/2015 1...	11.2	2,629	28.9	5,522	37.3	6,280	45.3	52.3	62.3	142.0	134.9	70.0	42.5	23.6	22.2
DAL1799	A320	26R	B3	1/2/2015 1:3...	1/2/2015 1:...	10.7	2,400	28.5	5,328	41.1	6,280	49.9	56.4	66.1	135.7	128.9	70.0	32.5	26.0	19.6
DAL1702	A320	26R	B3	1/2/2015 9:5...	1/2/2015 9:...	11.4	2,657	27.0	5,288	40.0	6,280	47.8	51.3	58.9	141.6	134.6	70.0	35.2	31.9	30.8

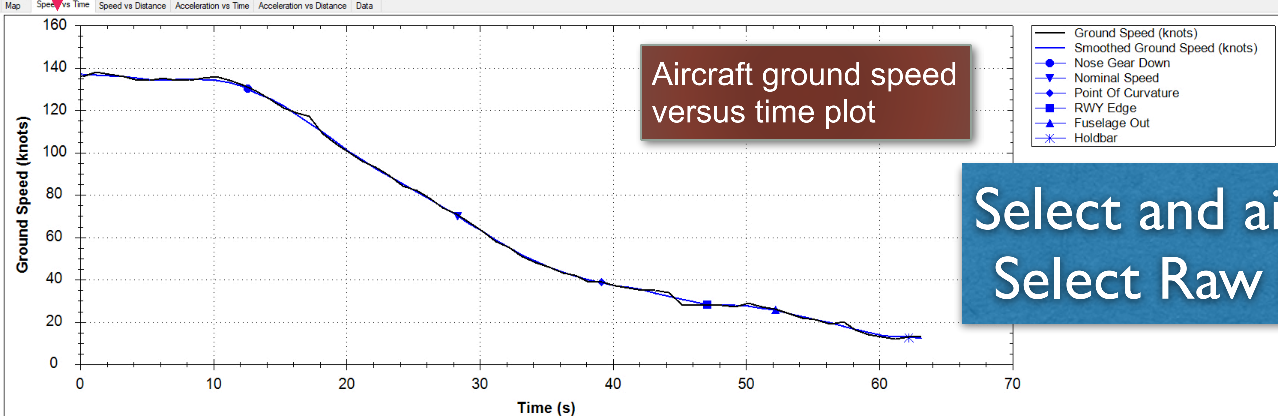
Map | Speed vs Time | Speed vs Distance | Acceleration vs Time | Acceleration vs Distance | Data

ATL Raw Data

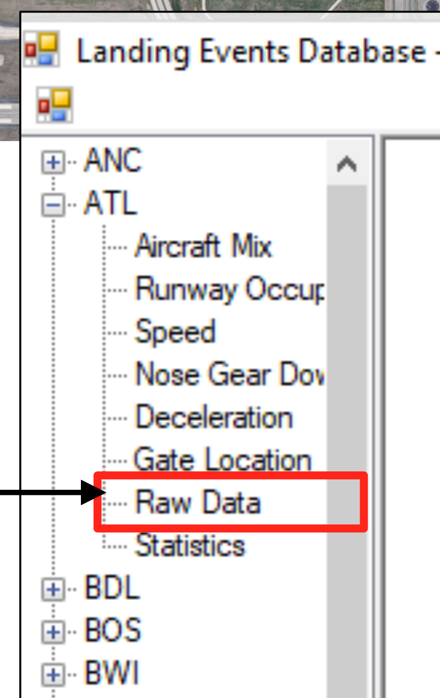
26R | Exit | A320 | Arrival | Valid Flights | Query | Export

Flight 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)
DAL9[illegible]	A320	26R	B3	1/1/2015 12:...	1/1/2015 1...	13.2	2,894	28.7	5,347	40.7	6,280	49.6	55.9	69.1	131.3	124.7
DAL1[illegible]91	A320	26R	B3	1/1/2015 2:2...	1/1/2015 2:...	12.7	2,902	29.3	5,576	38.4	6,280	46.1	52.4	58.9	137.8	130.9

Map | Speed vs Time | Speed vs Distance | Acceleration vs Time | Acceleration vs Distance | Data



Select and airport
Select Raw Data



Landing Database Raw Data Viewer

26R | Exit | A320 | Arrival | Valid Flights | Query | Export

Flight 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)	Nominal Speed (kts)	Exiting Speed (kts)	ROT Edge Speed (kts)	ROT Fuselage Speed (kts)
DAL1639	A320	26R	B3	1/1/2015 9:3...	1/1/2015 9:...	13.7	3,040	30.2	5,603	37.2	6,280	42.9	47.3	52.1	132.0	125.4	70.0	48.6	41.1	34.8
DAL2133	A320	26R	B3	1/1/2015 9:4...	1/1/2015 9:...	12.4	2,741	28.2	5,110	42.3	6,280	49.8	55.3	63.2	131.3	124.7	70.0	37.0	29.0	25.2
NKS165	A320	26R	B3	1/1/2015 9:4...	1/1/2015 9:...	12.6	2,844	28.3	5,381	39.1	6,280	47.1	52.2	62.2	136.9	130.0	70.0	38.7	28.1	25.6
DAL390	A320	26R	B3	1/1/2015 11:...	1/1/2015 1...	11.2	2,629	28.9	5,522	37.3	6,280	45.3	52.3	62.3	142.0	134.9	70.0	42.5	23.6	22.2
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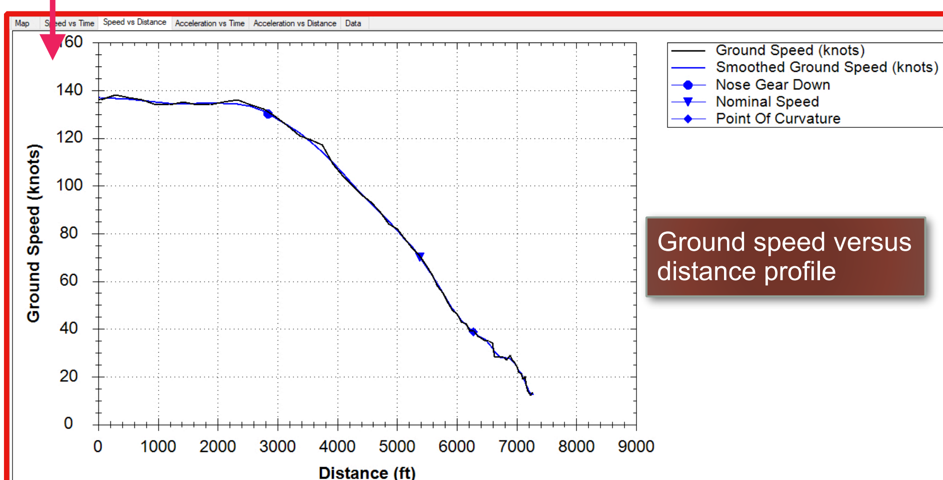
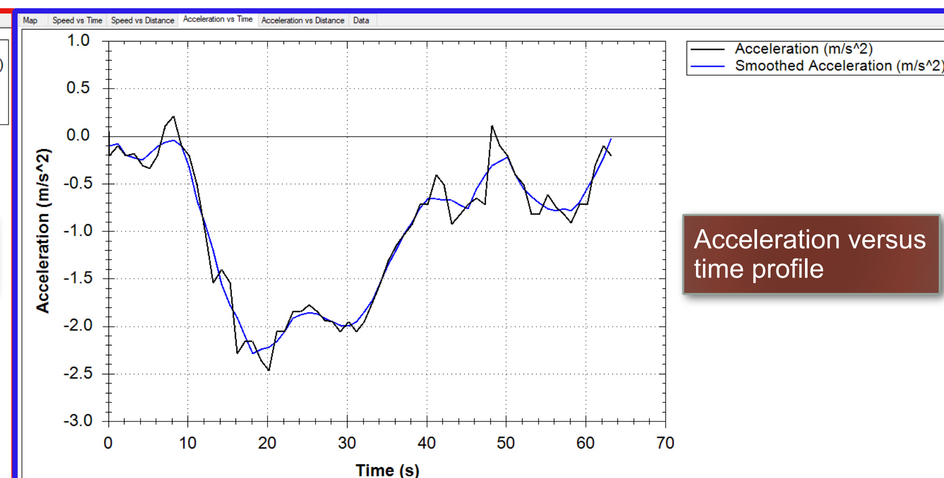
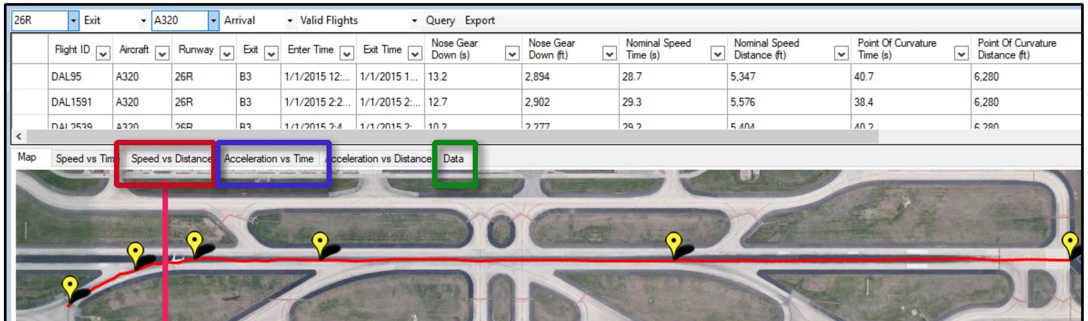
DAL1702	A320	26R	B3	1/2/2015 9:5...	1/2/2015 9:...	11.4	2,657	27.0	5,288	40.0	6,280	47.8	51.3	58.9	141.6	134.6	70.0	35.2	31.9	30.8

Map | Speed vs Time | Speed vs Distance | Acceleration vs Time | Acceleration vs Distance | Data



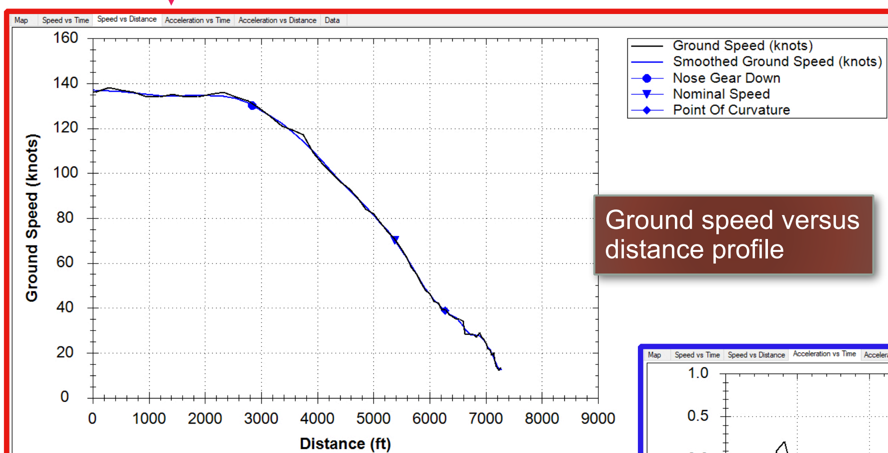


Landing Database Raw Data Viewer (2)

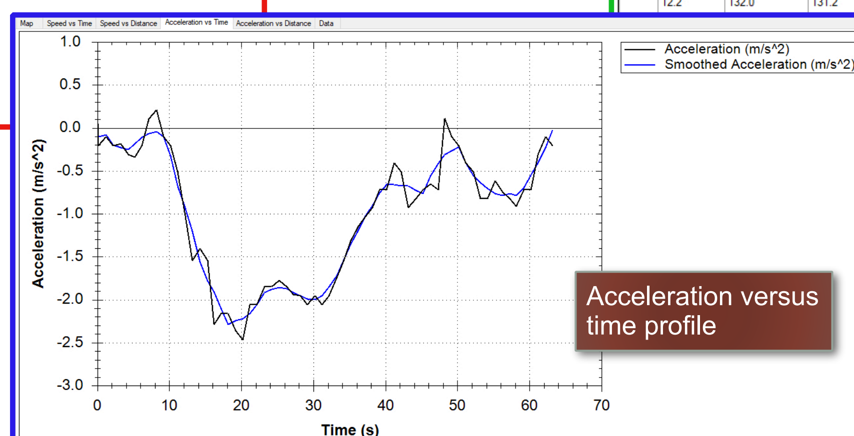


Spirit Airlines Airbus A320

Time (s)	Speed (kts)	Smoothed Speed (kts)	Distance (ft)	Acceleration (m/s^2)	Smoothed Acceleration (m/s^2)
0.0	136.0	136.9	0	0.3	-0.1
0.2	136.0	136.8	46	-0.2	-0.1
1.2	138.0	136.6	286	-0.1	-0.1
2.2	137.0	136.2	516	-0.2	-0.2
3.3	136.0	135.8	741	-0.2	-0.2
4.3	134.0	135.2	965	-0.3	-0.3
5.2	134.0	134.6	1,190	-0.3	-0.2
6.2	135.0	134.2	1,419	-0.2	-0.1
7.2	134.0	134.4	1,645	0.1	-0.1
8.2	134.0	134.8	1,870	0.2	0.0
9.2	135.0	134.6	2,100	-0.1	-0.1
10.2	136.0	134.2	2,331	-0.2	-0.3
11.2	134.0	133.2	2,550	-0.5	-0.7
12.2	132.0	131.2	2,765	-1.0	-0.9
			2,973	-1.5	-1.2
			3,171	-1.4	-1.6
			3,367	-1.5	-1.8
			3,561	-2.3	-1.9
			3,752	-2.2	-2.1
			3,922	-2.2	-2.3
			4,090	-2.4	-2.2
			4,253	-2.5	-2.2



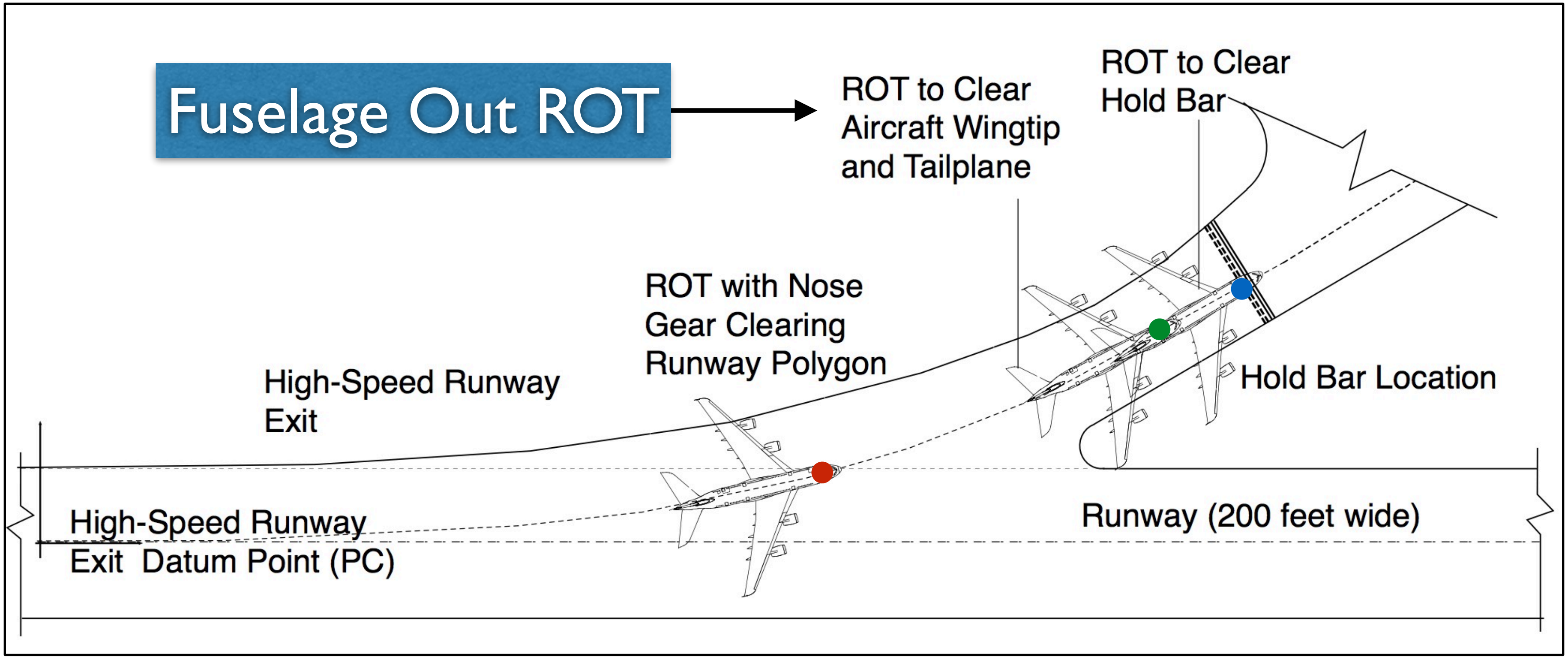
Ground speed versus distance profile



Acceleration versus time profile

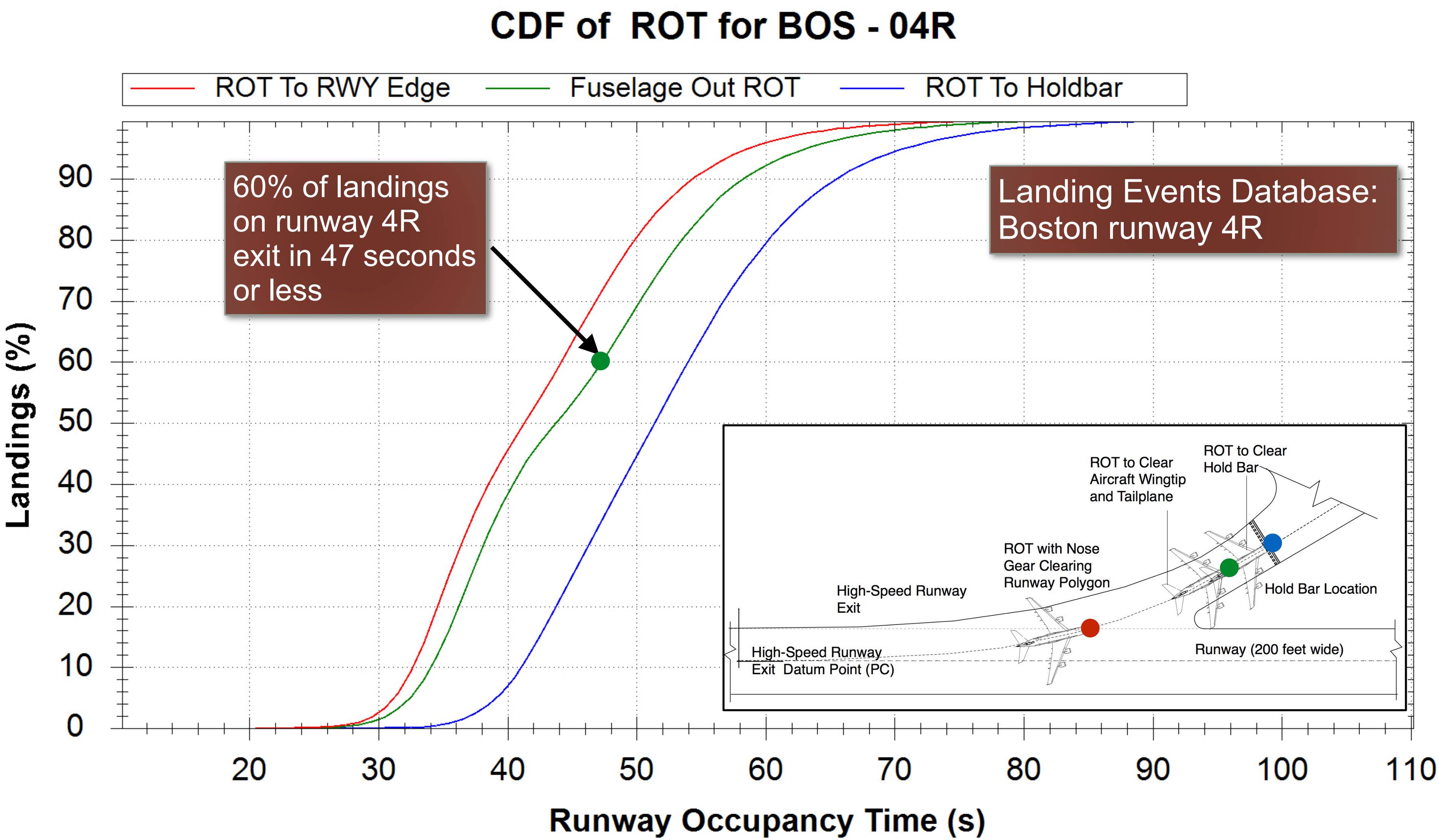
Every landing can be examined in detail (Airbus A320 example)

Definitions of Runway Occupancy Time

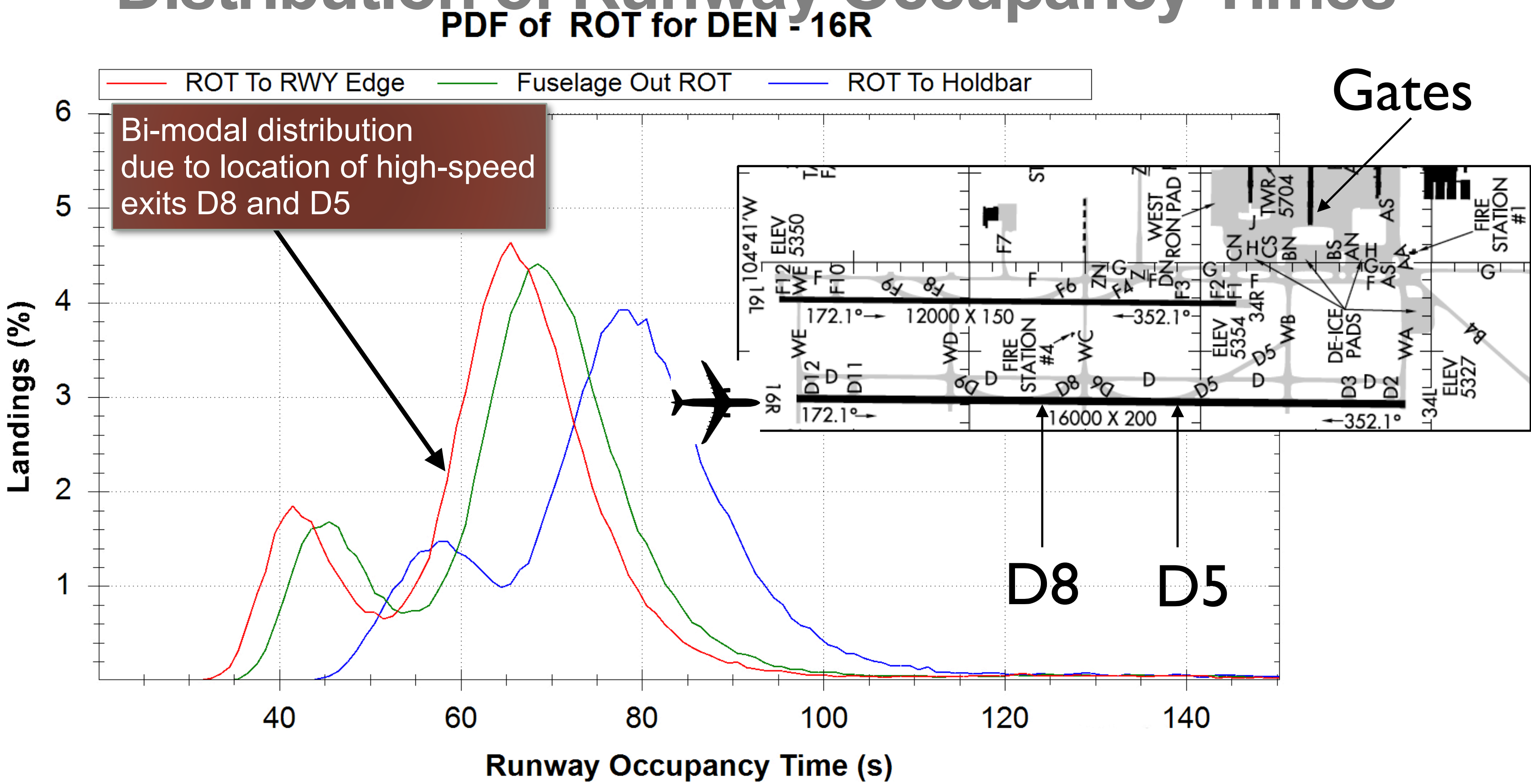


- In the US the definition of ROT is usually the time to vacate the runway with fuselage out
- In Europe and other countries ROT is interpreted as the time to reach the hold bar

Runway Occupancy Time Information in Landing Events Database



Distribution of Runway Occupancy Times



Pilots are motivated to use high-speed runway exit **D5** because it reduces the taxiing time to the gate

Runway Occupancy Time Tables

Step 1
Runway Occupancy Time

Step 2
Select runway

Step 3
Select ROT Table
1) ROT to runway edge
2) ROT to clear runway
3) ROT to hold bar

Step 4
Plot (query)

Landing Events Database

- ATL
  - Aircraft Mix
  - Runway Occupancy Time
  - Speed
  - Nose Gear Down Location
  - Deceleration
  - Raw Data
  - Statistics
- BDL
- BOS
- BWI
- CLE
- CLT
- DCA
- DEN
- DFW
- DTW
- EWR
- FLL
- HNL
- HOU
- MSP
- ORD
- PHL
- PHX
- PVD
- SAN
- SDF
- SEA
- SFO
- SLC
- SNA
- STL

ATL - Runway Occupancy Time (ROT) Analysis

Runway: 08L | ROT Type: Fuselage Out | Query

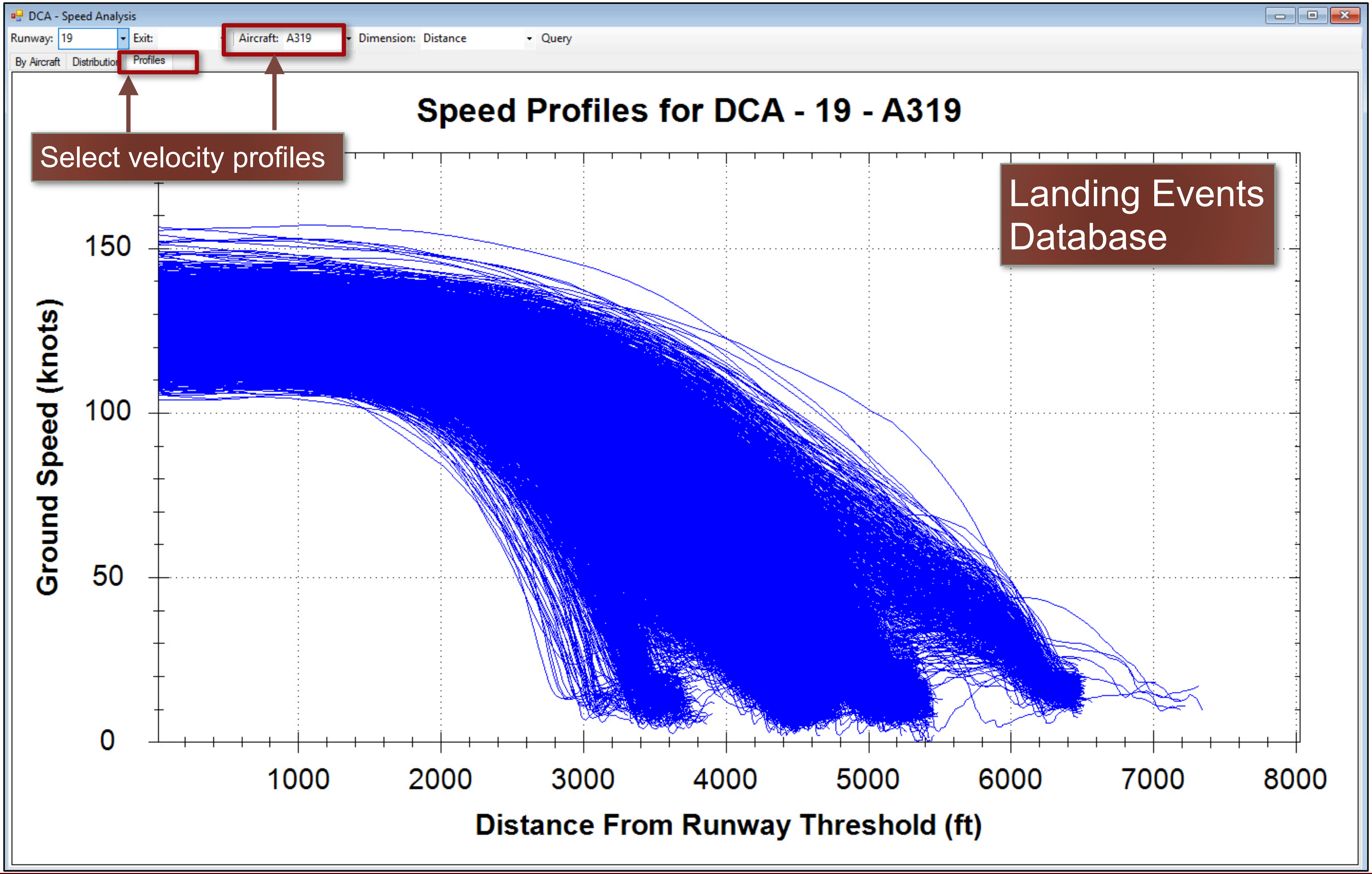
By Aircraft | Distribution | Table

Fuselage Out ROT for ATL - 08L

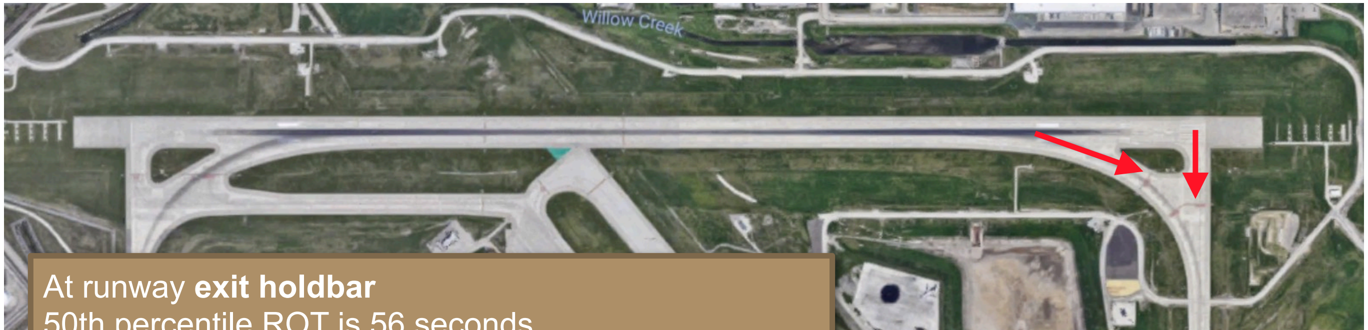
Aircraft	A	A4	A6-1	A6-2	B11	B13	B15	B5	B7	C-L	C-R	D-L	D-R	Average
A124						114.2s 100.0%								114.2s
A306	90.0s 3.0%		62.2s 33.3%	61.8s 53.3%	44.5s 0.3%					47.6s 2.0%		52.7s 8.1%		61.7s
A310			62.5s 45.5%	60.6s 34.1%						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
A319	75.6s 0.0%			59.8s 0.2%	50.5s 77.3%	71.2s 1.2%	78.7s 0.0%	36.2s 0.0%	41.3s 14.9%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
A320	81.9s 0.0%			54.4s 0.1%	48.7s 89.4%	70.3s 3.1%	69.3s 0.1%		40.6s 5.0%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
A321	83.0s 0.1%		57.3s 0.1%	53.8s 0.3%	47.8s 81.3%	69.4s 14.2%	75.7s 0.4%		39.8s 3.0%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
A332					56.2s 77.8%	78.3s 20.4%	72.1s 1.9%			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
A333					54.0s 81.1%	75.0s 16.3%	80.8s 1.1%		48.4s [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
A343					56.3s 67.1%	79.1s 30.4%	[illegible] 1.3%		49.8s 1.3%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
A346					54.5s 71.6%	80.0s 28.4%				[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AC50										[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AC90										[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AC95										[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AEST				68.3s 16.7%						70.3s 33.3%		69.8s 50.0%		69.7s
ASTR				53.1s 31.3%						43.4s 18.8%		45.8s 50.0%		47.6s
AT43		34.1s 16.7%								47.1s 16.7%		51.8s 66.7%		48.1s
AT72										44.1s 50.0%		49.0s 50.0%		46.5s
B190				61.1s 0.4%						47.2s 53.6%		50.2s 45.9%		48.7s
B350		38.0s 8.8%								50.5s 59.3%		53.5s 31.9%		50.3s
B712	72.0s 0.0%			48.1s 0.1%	46.3s 94.6%	66.6s 0.8%	65.9s 0.0%		38.8s 3.7%		40.6s 0.2%		42.8s 0.6%	46.2s
B732				51.1s 100.0%										51.1s
B733				53.9s 0.1%	47.7s 68.9%	67.7s 0.4%			39.5s 20.7%		41.6s 3.1%	45.8s 0.1%	43.0s 6.8%	45.6s
B734	70.6s 5.1%			52.2s 79.5%	51.5s 1.7%	71.7s 0.9%	78.3s 0.9%			43.2s 3.4%		45.8s 8.5%		52.7s
B735				55.6s 33.3%	48.6s 33.3%								43.1s 33.3%	49.1s

Cells in table show:
1) Average runway occupancy time by runway exit at the selected runway
2) Percent of aircraft using each runway exit

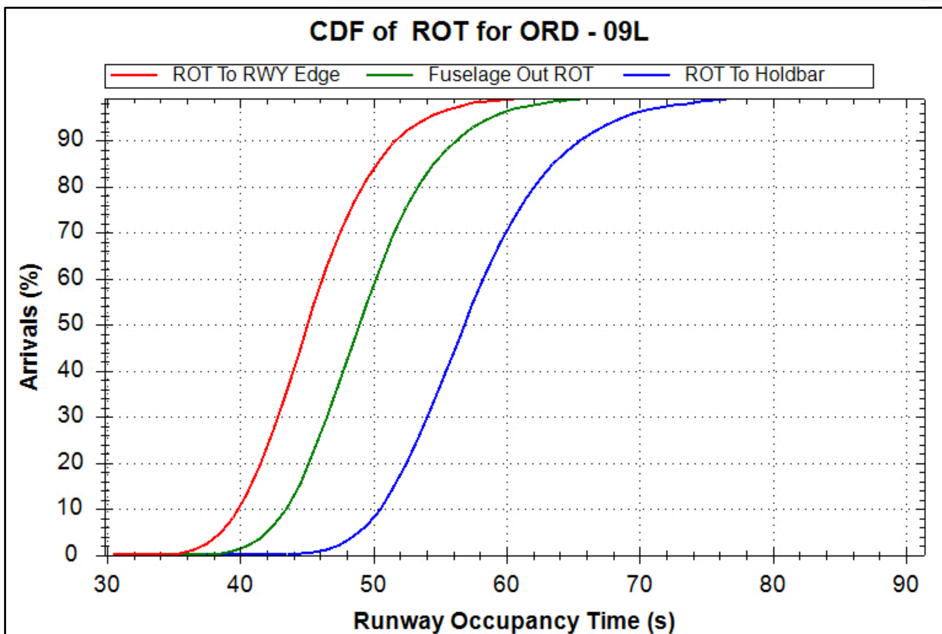
Aircraft Velocity Profiles : Airbus A319 at DCA Runway 19

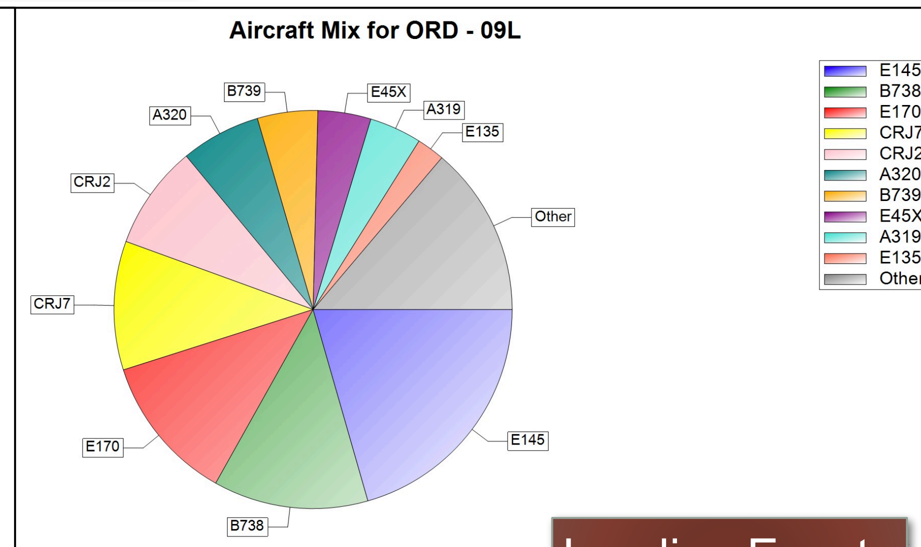


ORD Airport Runway 9L (Two Usable Exits)



At runway **exit holdbar**
50th percentile ROT is 56 seconds
95th percentile ROT is 71 seconds
Relatively high ROT value due to few runway exits

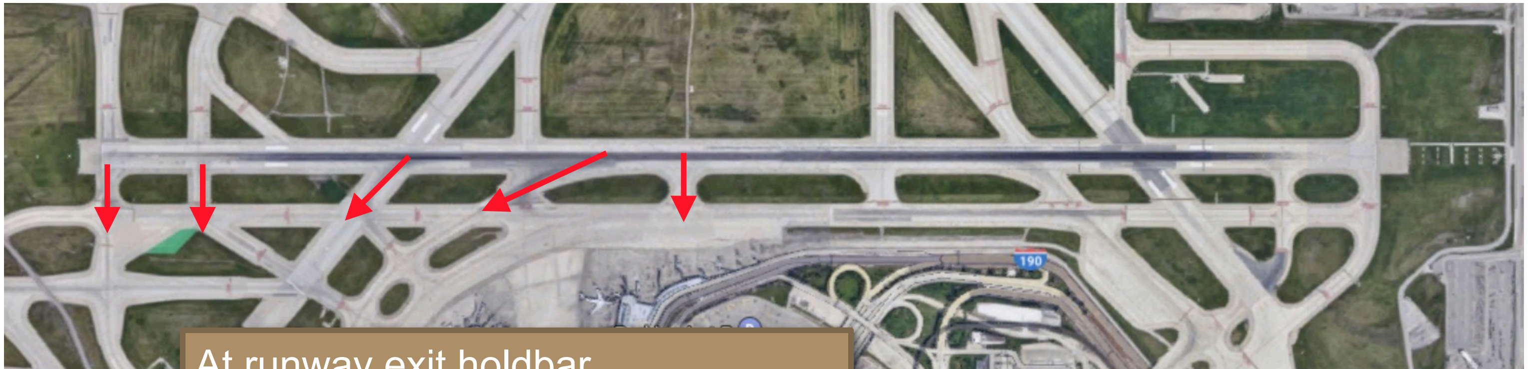




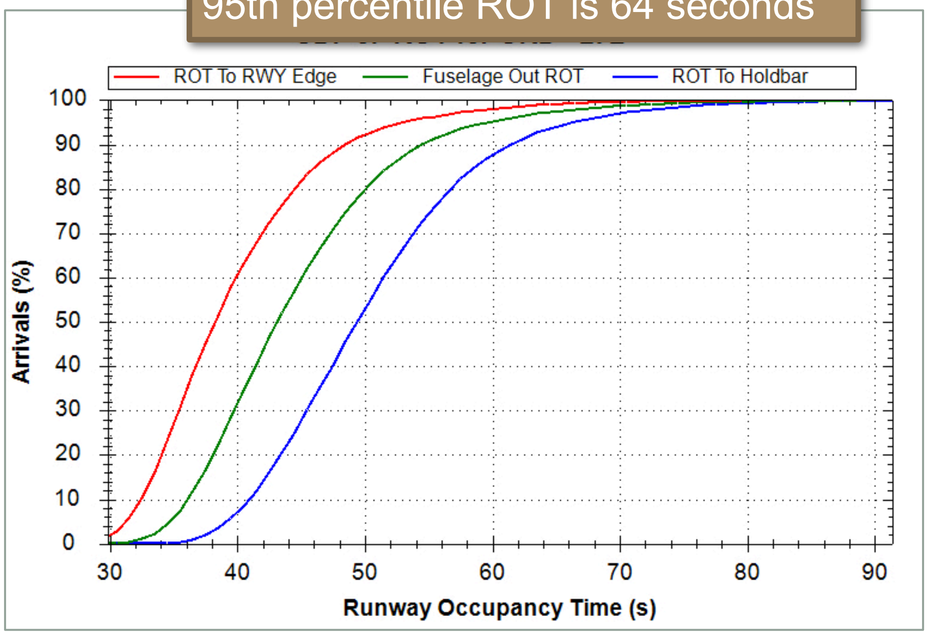
Landing Events Database

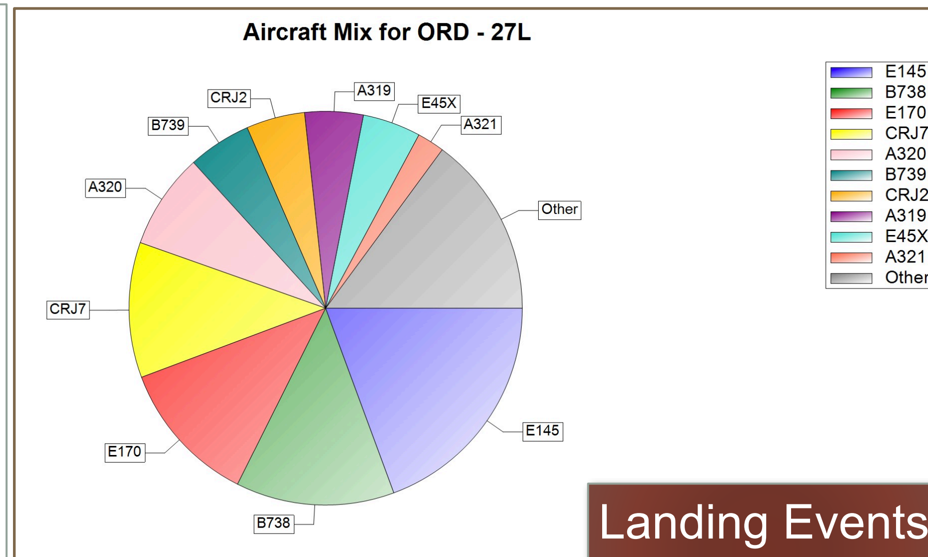
Virginia Tech
Invent the Future

ORD Airport Runway 27L (Five Usable Exits)



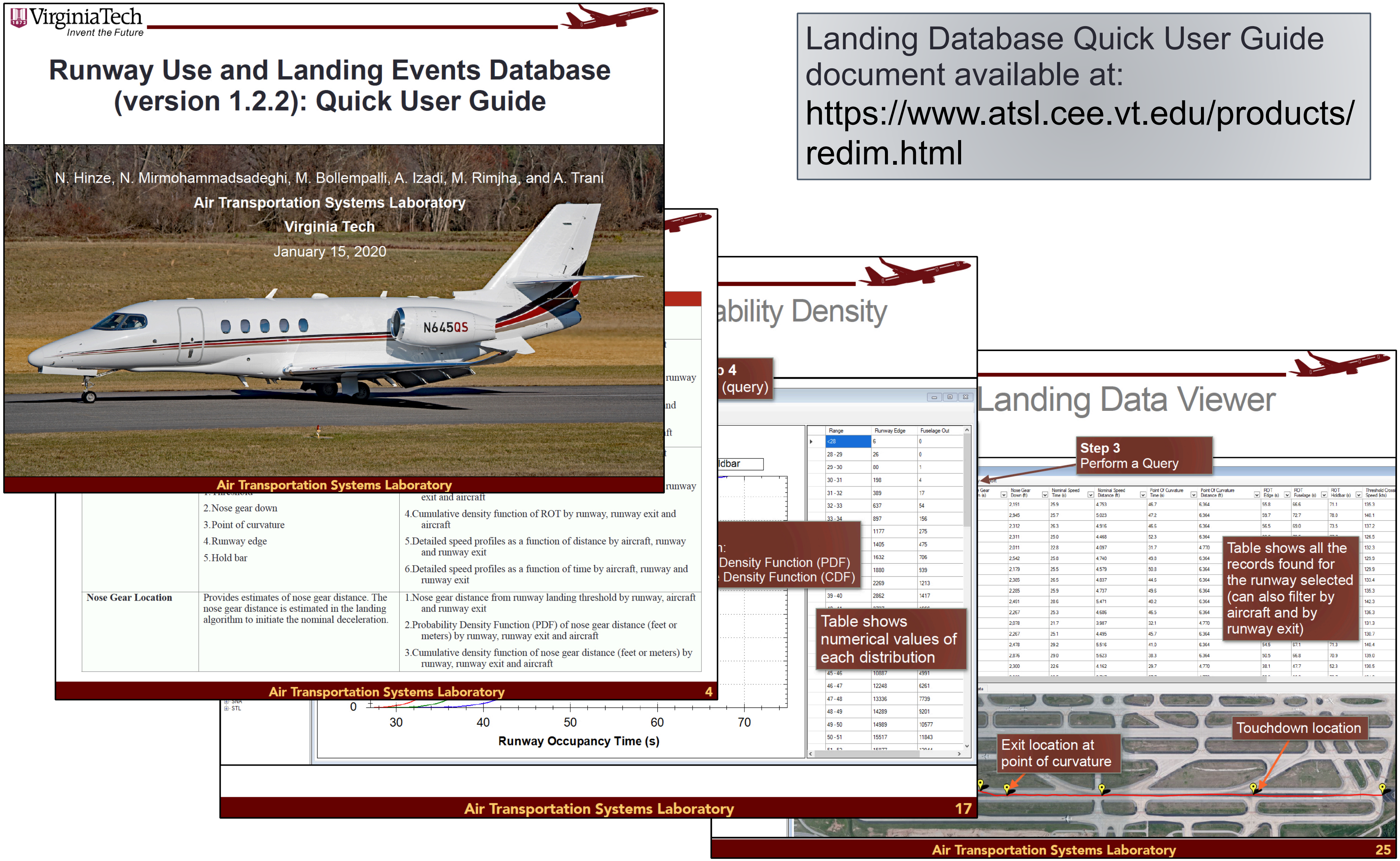
At runway exit holdbar
50th percentile ROT is 49 seconds
95th percentile ROT is 64 seconds





Landing Events Database

Landing Event Database Quick User Guide



Landing Database Quick User Guide document available at:
https://www.atsl.cee.vt.edu/products/redim.html

Runway Exit Design

Geometric Design Standards for Runway Exits

Sources:

- FAA AC 5300-13B (Chapter 4)
  - Sections 4.8.2 through 4.8.6
- ICAO Aerodrome Manual Volumes 1 and 2

Design principle:

- Provide ample space for aircraft to maneuver out of the runway
- Make the runway exits easily identifiable and usable

What is the Issue with Runway Exits?

- Runway exits are responsible for making operations more efficient on the ground
- Poorly designed runway exits add valuable service time (i.e., runway occupancy time)
- Poorly placed runway exits can contribute to go-arounds and runway incursions
- Runway occupancy time and its standard deviation are critical parameters for runway capacity estimation

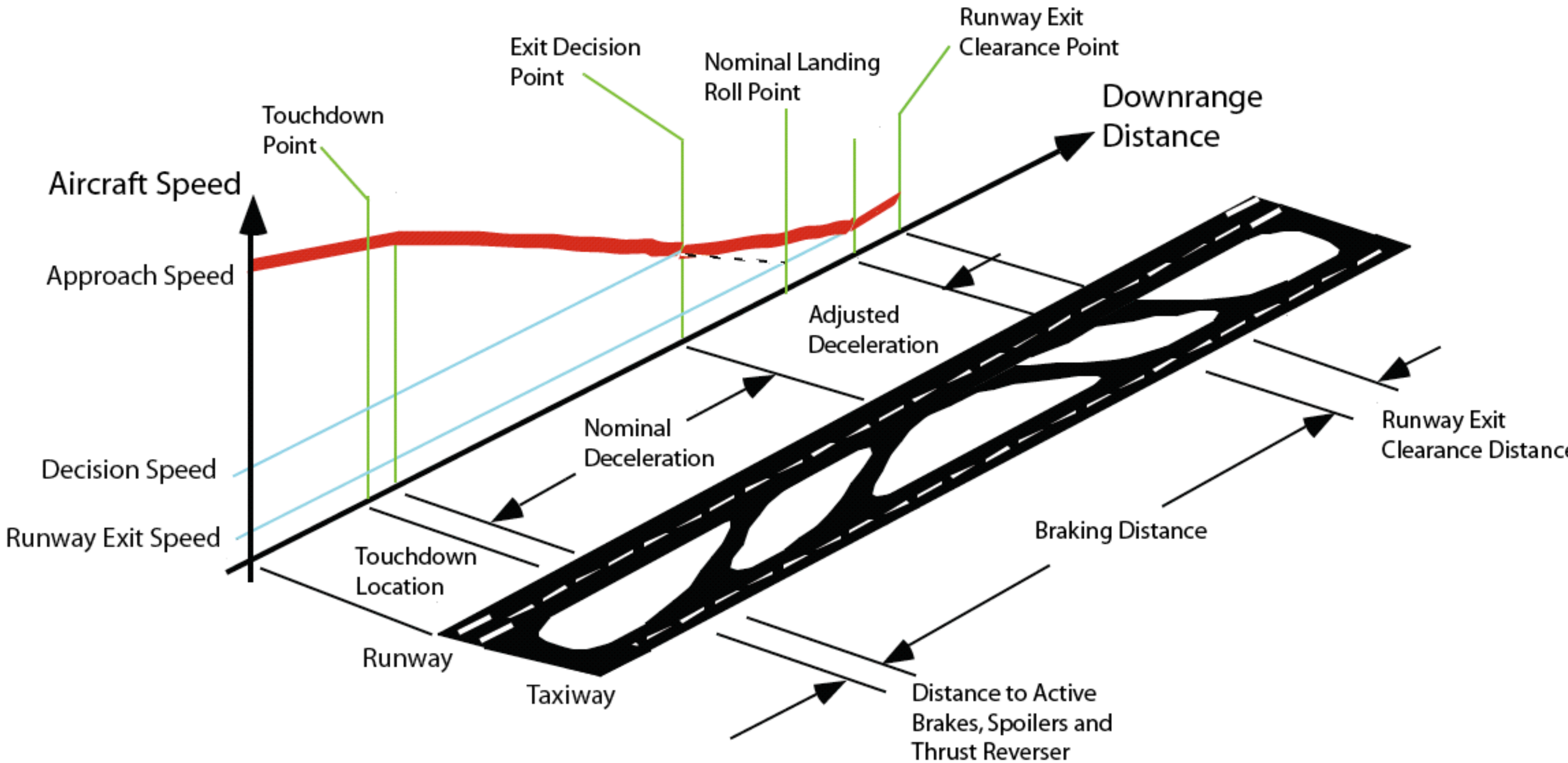
Definitions

- **Runway Occupancy Time (ROT)**
  - The time elapsed between an aircraft crossing the runway threshold and the time when the same aircraft crosses the imaginary plane of a runway exit paved area
- Issues about ROT
  - The definition of ROT has been used inconsistently throughout the years
  - Many early ROT studies failed to recognize that when an aircraft starts turning towards the runway exit, the aircraft is still using the runway until its wingtip clears the runway edge plane

Factors Affecting ROT

- Aircraft mix
  - Percent of aircraft in various runway performance groups
- Runway and runway exit geometric design factors
  - Runway width
  - Pavement condition (wet, dry, contaminated)
- Taxiway geometry design factors
  - Number of runway exits within the aircraft mix acceptability requirements
  - Taxiway type
  - Taxiway network interaction
- Pilot technique
  - Traffic pressure (i.e., having another aircraft on short final behind)
  - Gate location
  - Airport familiarity

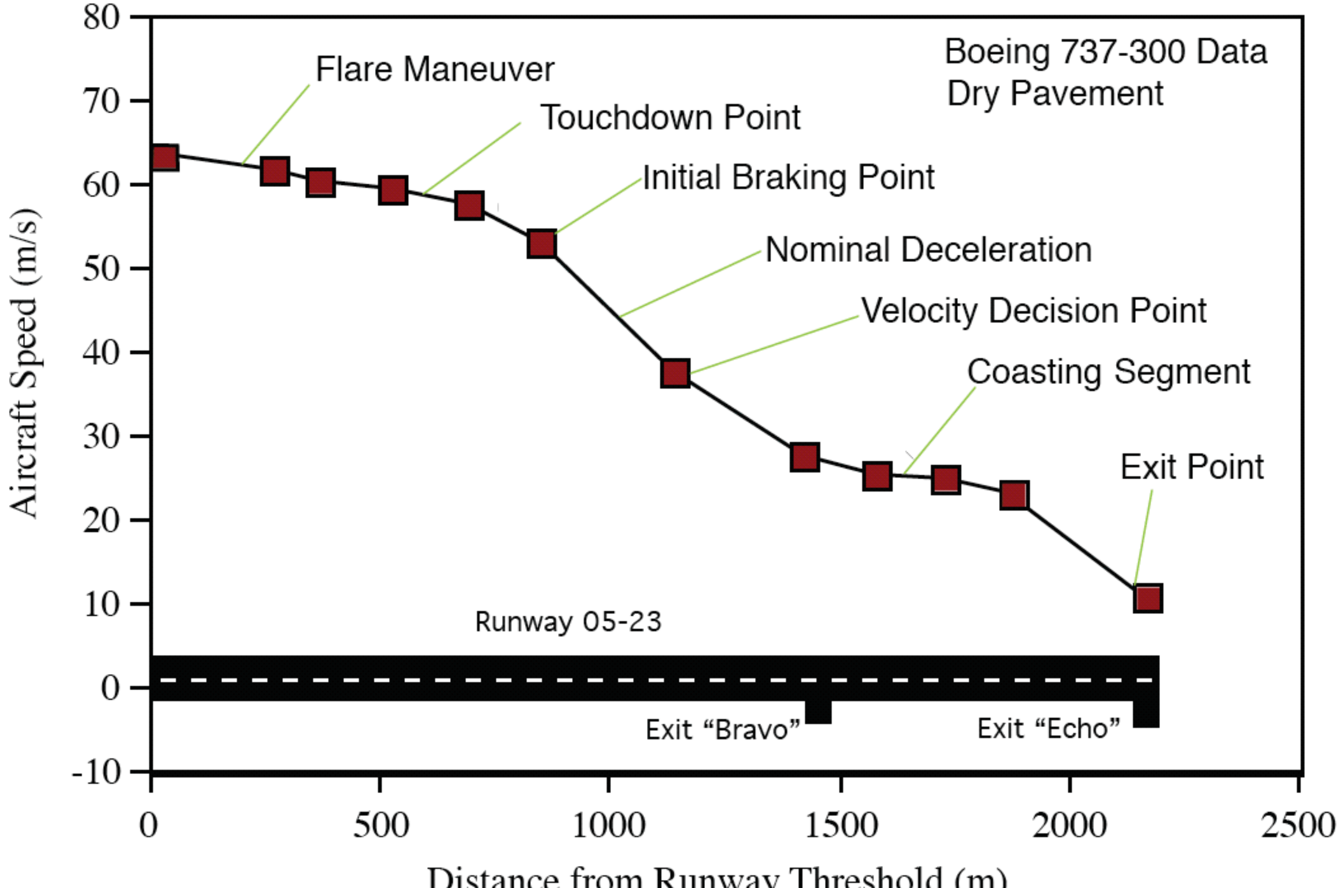
Aircraft Landing Behavior Affects ROT Time Performance



For hand calculation analysis of runway exit placement, we can model the landing roll into three segments: air segment, free roll segment, and deceleration segment

Aircraft Landing Roll Profile

- Sample data collected at Charlotte-Douglas International Airport (CLT) Runway 05-23 (Trani et al., 1996)



Typical Landing Milestones

Air phase starts
Crosses the runway threshold
Reference speed over threshold (Vref)

Air phase ends
Main gear touchdown
Typically 95% of threshold crossing speed

Deceleration phase starts
Nose gear touchdown
Engine thrusts reversers deployed
Wing spoilers deployed
Wheel braking on

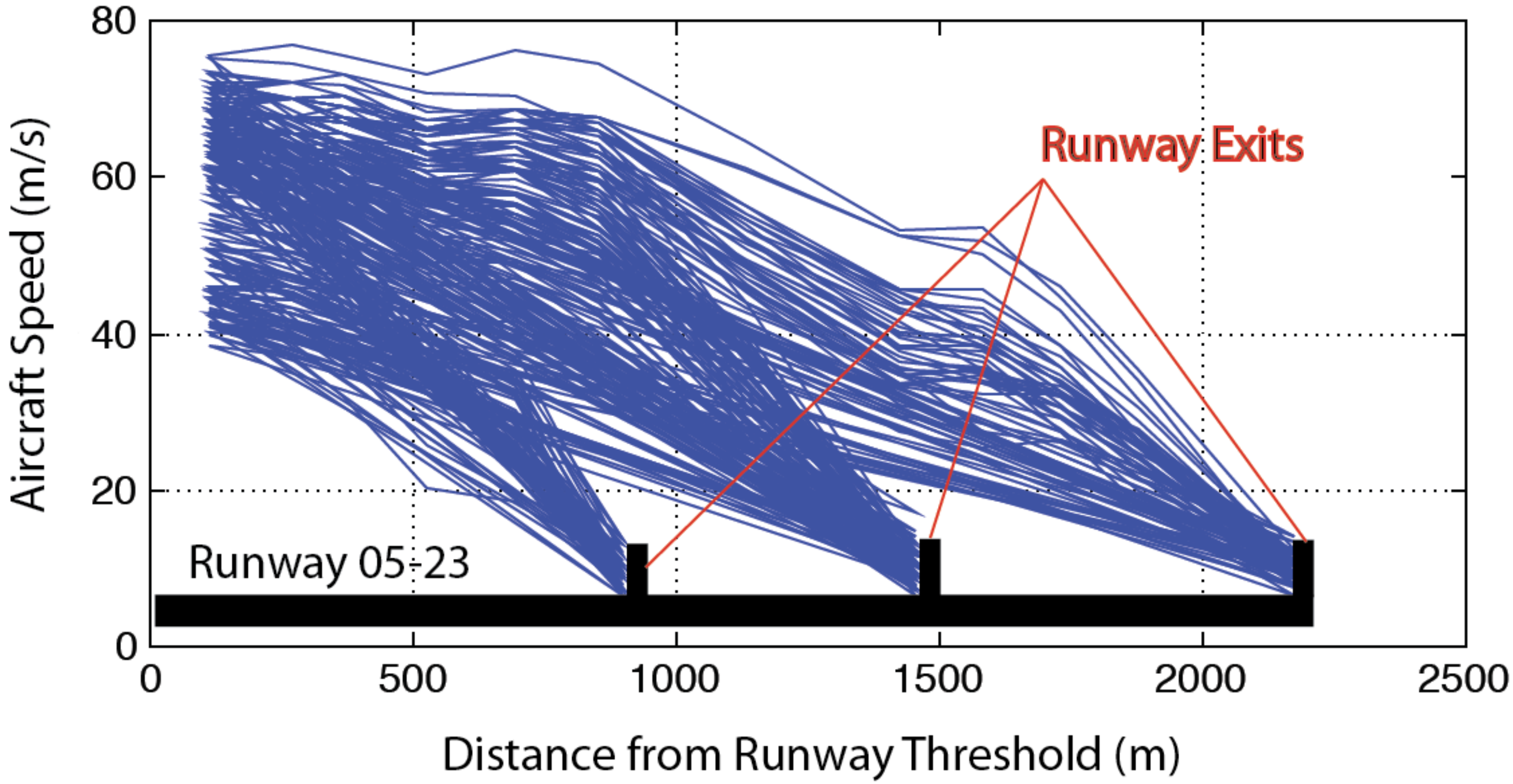
Typical Landing Milestones (2)

Landing deceleration segment
Engine thrusts reversers deployed
Wing spoilers deployed
Wheel braking on

Turnoff maneuver
Engine thrusts reversers stowed
Wing spoilers retracted
No wheel braking

Most jet powered aircraft manufacturers recommend thrust reversers to be stowed at 60 knots to avoid engine foreign object ingestion

Variability Across Many Aircraft (CLT Runway 05-23 Data)



Effects of ROT on Runway Capacity

- Modest gains in runway saturation capacity are possible with reductions in ROT because in today's environment, inter-arrival separations dominate over runway capacity
- ROT nevertheless is important in runways used with mixed operations (i.e., arrivals and departures) in both IMC and VMC conditions
  - Reduced weighted average ROT values reduce the gap needed to launch departures between successive arrivals
  - The same effect is true if reductions in the standard deviation of ROT are possible
- ROT is more important under VMC operations because inter-arrival times (IAT) are smaller compared to those observed during IMC conditions
- Standard deviation of ROT is very important
- Some small gains under IMC conditions (mixed operations in a single runway)

Runway Exits

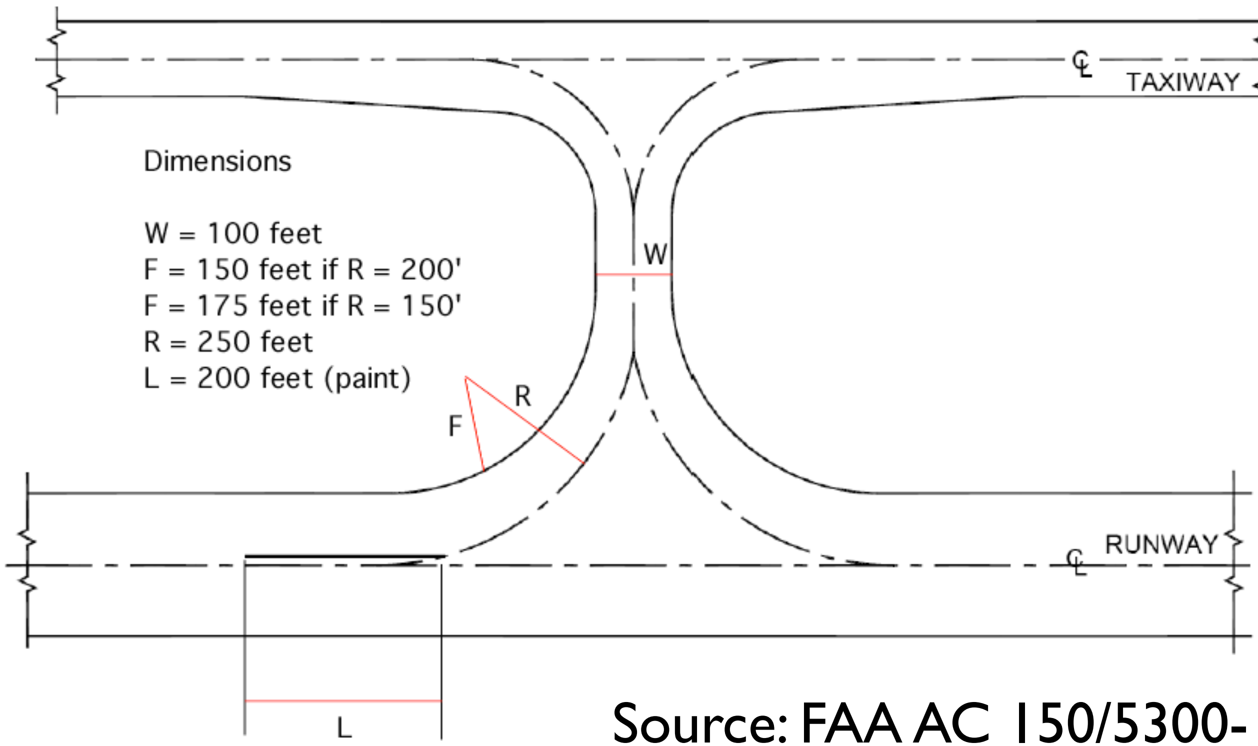
- The purpose of runway exists is to improve service
- times of airport runways
- The number of runway exists varies from airport to
- airport and within runways at the same airport
- Several types of runway exits can be

Types of Runway Exits

Runway Exit Type	Characteristics and Use	Remarks and Exit Speeds
Right-angle (90 degree)	Low volume of traffic Ends of a runway	Low speed (5-8 m/s)
45 degree General Aviation	Old design (not recommended)	Medium speeds (8-15 m/s)
30-degree Constant Radius Design	Two versions Use when > 30 operations/hr	High-speed 15-23 m/s
30-degree Spiral Design	Adopted in the mid 80s Use when > 30 operations/hr	Transition spiral 15-23 m/s

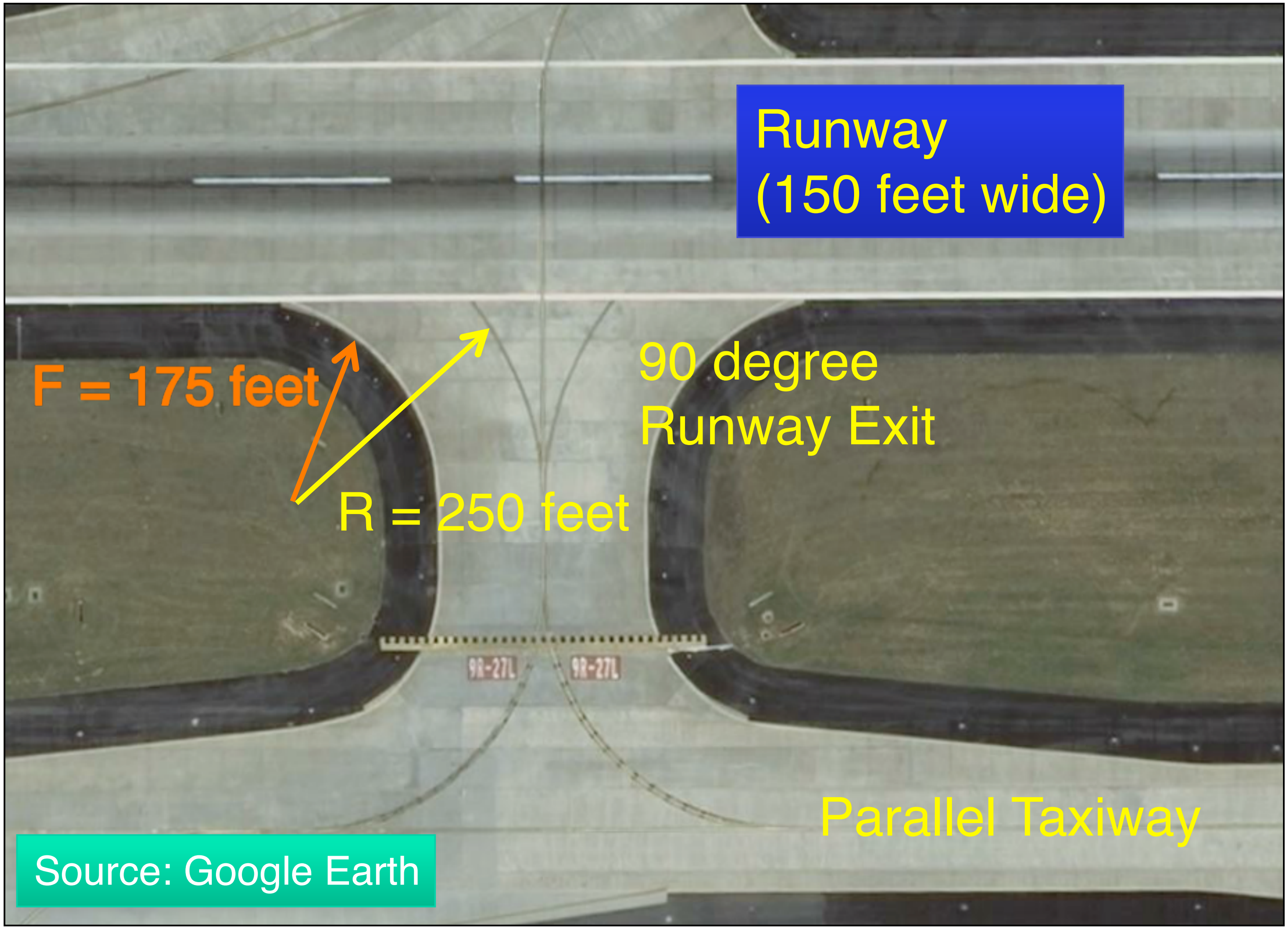
Right-Angle Exits

- **Old (legacy) design -** baseline centerline radius was 250 feet
- Pavement edge radius varies according to runway width
- Legacy design has been replaced by new design practice

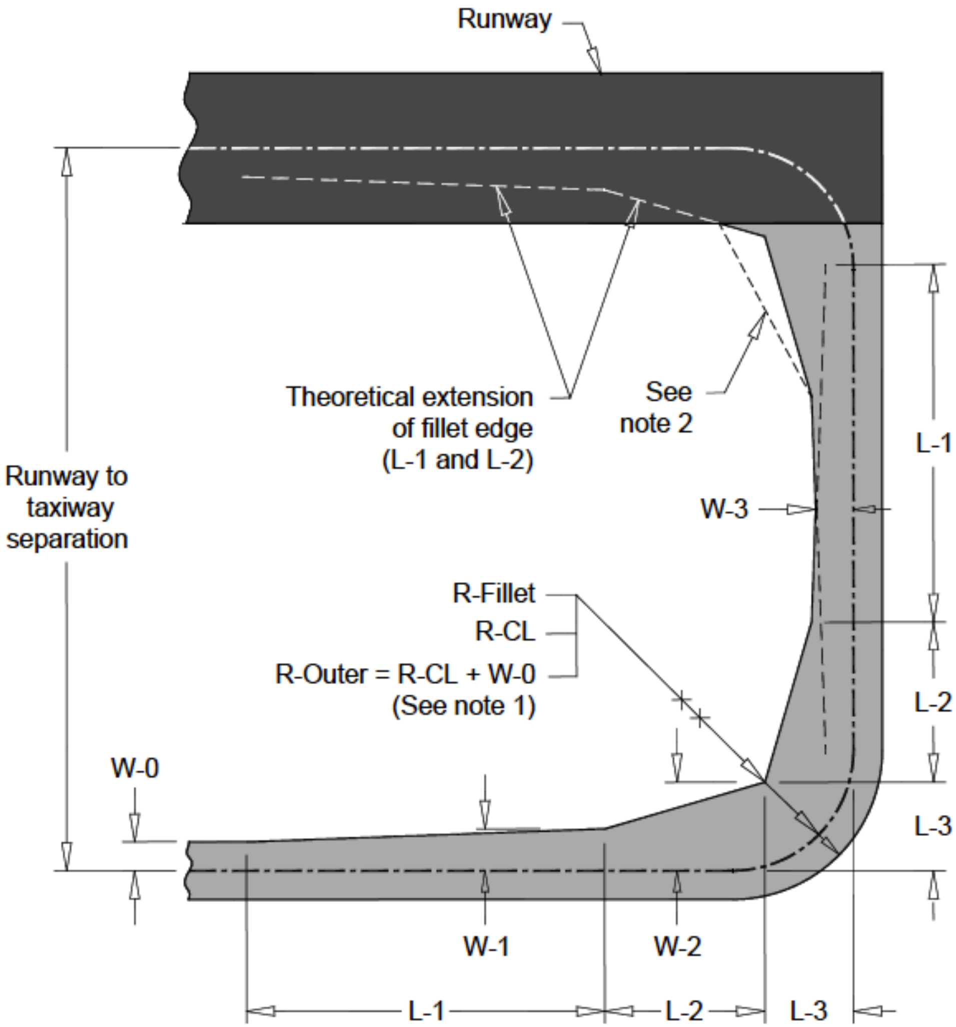


Source: FAA AC 150/5300-13 (1990s)

Sample Implementation (ATL)



Right-Angle Runway Entrance Taxiways (see Figure 4-15 in 150/5300-13B)



1. Design a runway entrance taxiway as two standard 90-degree turns
2. Each end of the runway has one entrance taxiway
3. Avoid direct entrance runway entrance taxiways to apron areas
4. Provide designs with steering angles limited to 50 degrees

Right-Angle Runway Entrance Taxiway Dimensions when steering angles > 50

Dimension	TDG														
(see Figure 4-15)	3			4					5			6			
Runway Centerline to Taxiway Centerline Distance (ft)	300	350	400	300	350	400	450	500	400	450	500	400	450	500	550
W-0 (ft)	25	25	25	25	25	25	25	25	37.5	37.5	37.5	37.5	37.5	37.5	37.5
W-1 (ft)	33	33	33	37	37	36	36	36	49	48	48	51	51	51	50
W-2 (ft)	55	54	54	80	77	75	74	74	84	83	83	102	100	98	97
W-3 (ft)	31	29	28	49	42	38	35	33	50	47	45	63	57	53	50
L-1 (ft)	173	172	172	315	310	307	305	305	301	299	298	408	405	403	401
L-2 (ft)	82	83	83	140	140	140	140	140	137	136	138	180	180	180	180
L-3 (ft)	55	54	54	80	77	75	74	74	84	83	83	102	100	98	97
R-Fillet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R-CL (ft)	62	61	60	110	102	98	95	94	98	95	94	133	126	122	120
R-Outer	87	86	85	135	127	123	120	119	135.5	132.5	131.5	170.5	163.5	159.5	157.5

1. Increase the centerline radius
2. Increase the fillet dimensions
3. use Tables 4-3 and 4-4 (labeled as Dimensions for Runway Entrance/Exit Taxiways with Two 90-Degree Turns are Nonstandard)

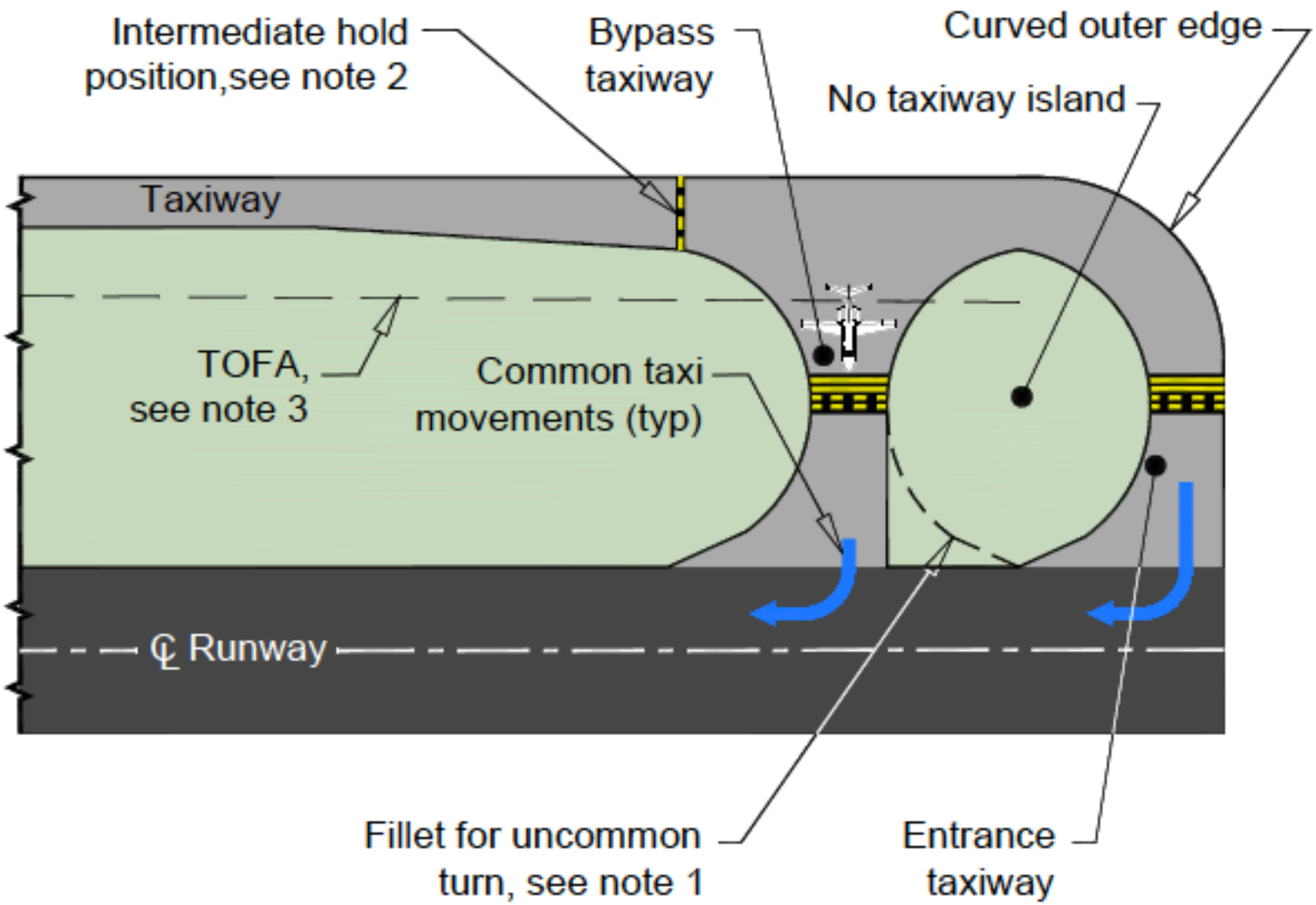
Runway Entrance Taxiways (TDG Groups 3-6)

Dimension	TDG														
(see Figure 4-15)	3			4					5			6			
Runway Centerline to Taxiway Centerline Distance (ft)	300	350	400	300	350	400	450	500	400	450	500	400	450	500	550
W-0 (ft)	25	25	25	25	25	25	25	25	37.5	37.5	37.5	37.5	37.5	37.5	37.5
W-1 (ft)	33	33	33	37	37	36	36	36	49	48	48	51	51	51	50
W-2 (ft)	55	54	54	80	77	75	74	74	84	83	83	102	100	98	97
W-3 (ft)	31	29	28	49	42	38	35	33	50	47	45	63	57	53	50
L-1 (ft)	173	172	172	315	310	307	305	305	301	299	298	408	405	403	401
L-2 (ft)	82	83	83	140	140	140	140	140	137	136	138	180	180	180	180
L-3 (ft)	55	54	54	80	77	75	74	74	84	83	83	102	100	98	97
R-Fillet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R-CL (ft)	62	61	60	110	102	98	95	94	98	95	94	133	126	122	120
R-Outer	87	86	85	135	127	123	120	119	135.5	132.5	131.5	170.5	163.5	159.5	157.5

Note: Use two standard 90-degree turns for combinations of TDG and common runway to taxiway separation, not shown in this table.

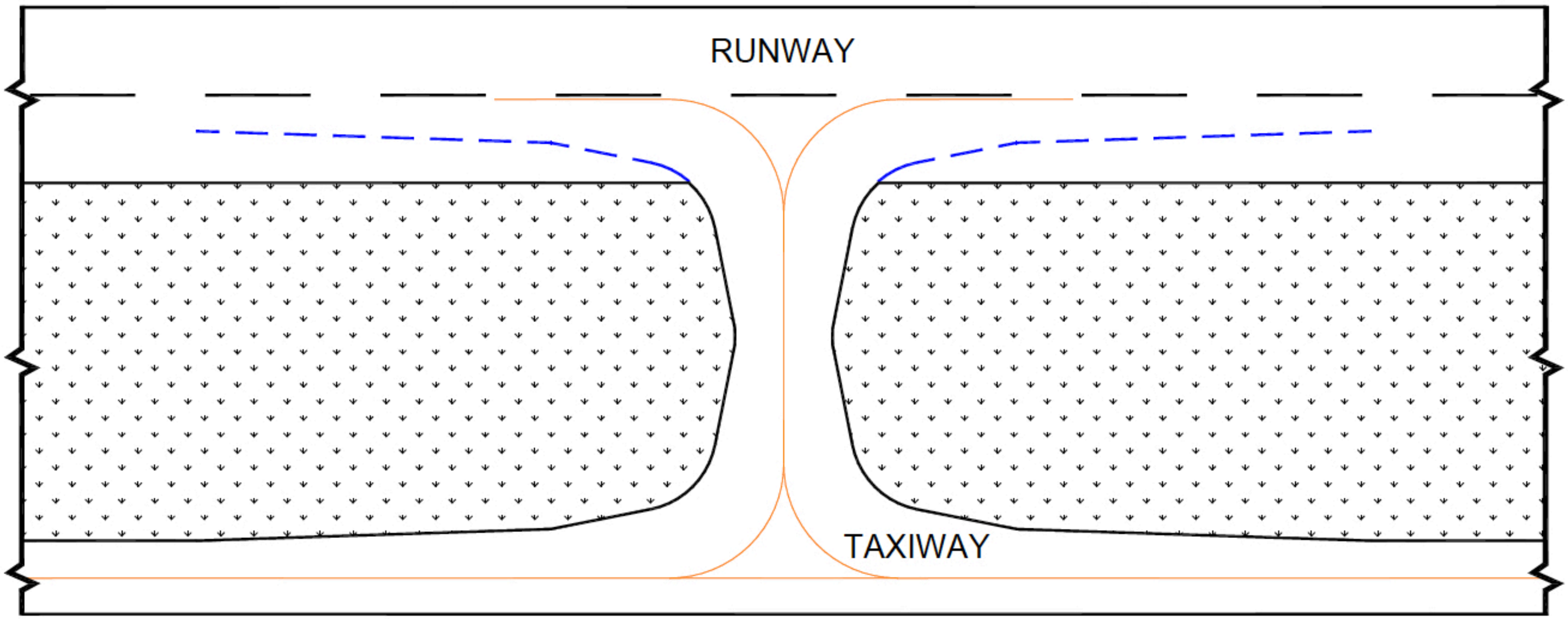
Source: FAA AC 150/5300-13B Table 4-4

Runway Ends - Bypass Entrance Configuration



Source: FAA AC 150/5300-13B Figure 4-16

Right Angle Runway Exit (see Figure 4-19)



New standard for right angle exits
Build the exit as a projection of two runway entrance exits

Example Problem

- Design a new right-angle runway exit for a 8,000 foot runway (150 foot wide)
- Critical aircraft design is the Airbus A340-600
- For this airport the runway to taxiway centerline is 500 feet

Procedure

Step 1 - Identify the Airbus A340-600 as **TDG-6**

CMG = 121.6 feet MGW = 41.37 feet

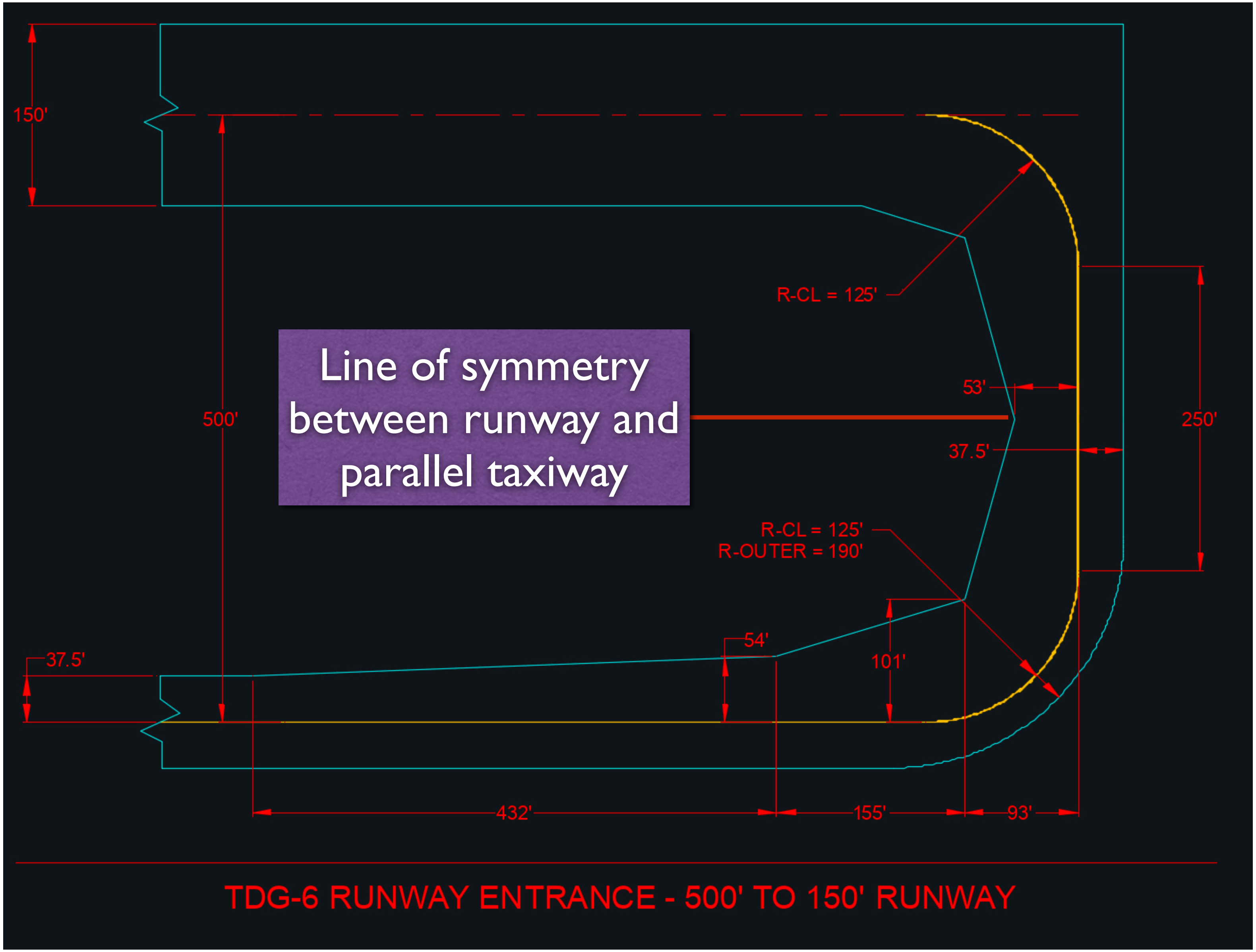
Step 2

- Use the FAA Taxiway Fillet Design Tool or tables in Appendix J of the Faa AC 150/5300-13B
- If the steering angle estimated by the fillet design tool exceeds 50 degrees, increase R-Cl and fillet dimensions according to Table 4-4

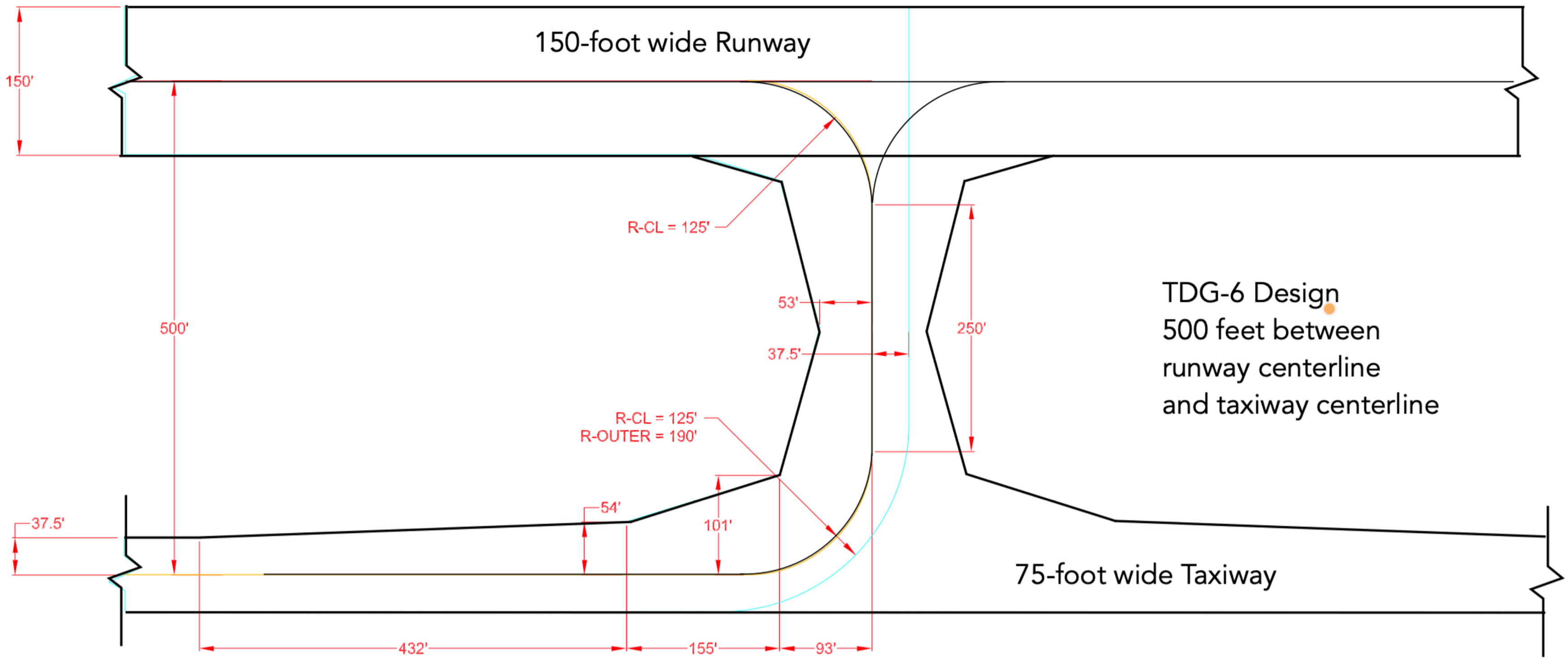
Step 3

- Draw the solution using CAD software

TDG-6 Runway Entrance Taxiways



Right Angle Runway Exit (TDG-6 Group) Solution

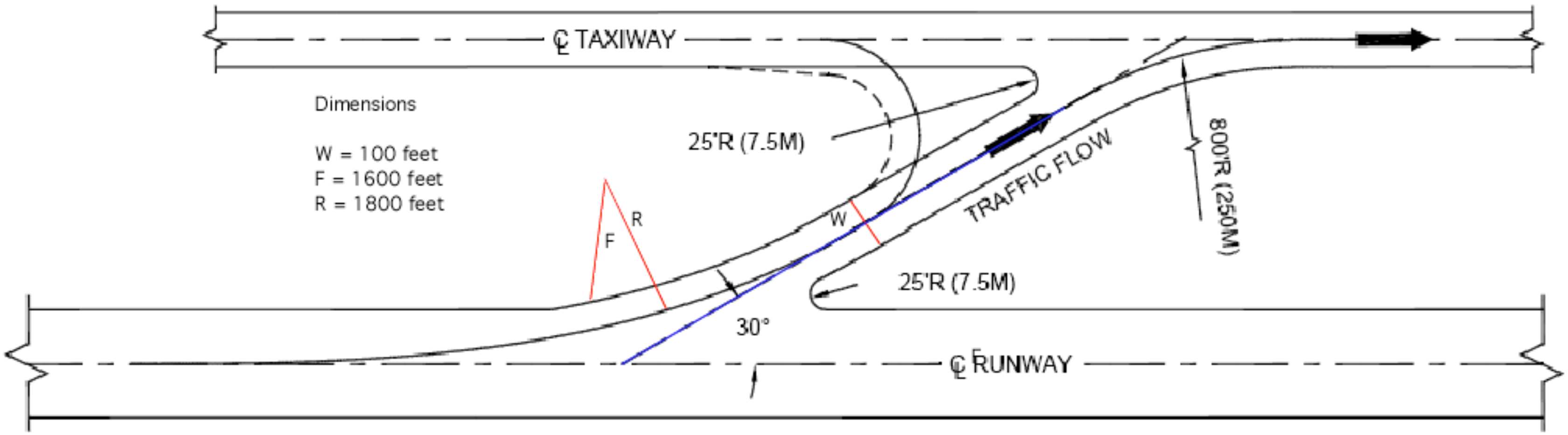


Build the runway exit as a projection of a runway entrance exit with two sides

Sample Implementation of a Right Angle Runway Exit (Bradley Intl. Airport)

Acute Angle Runway Exits
Also Called High Speed Runway Exits

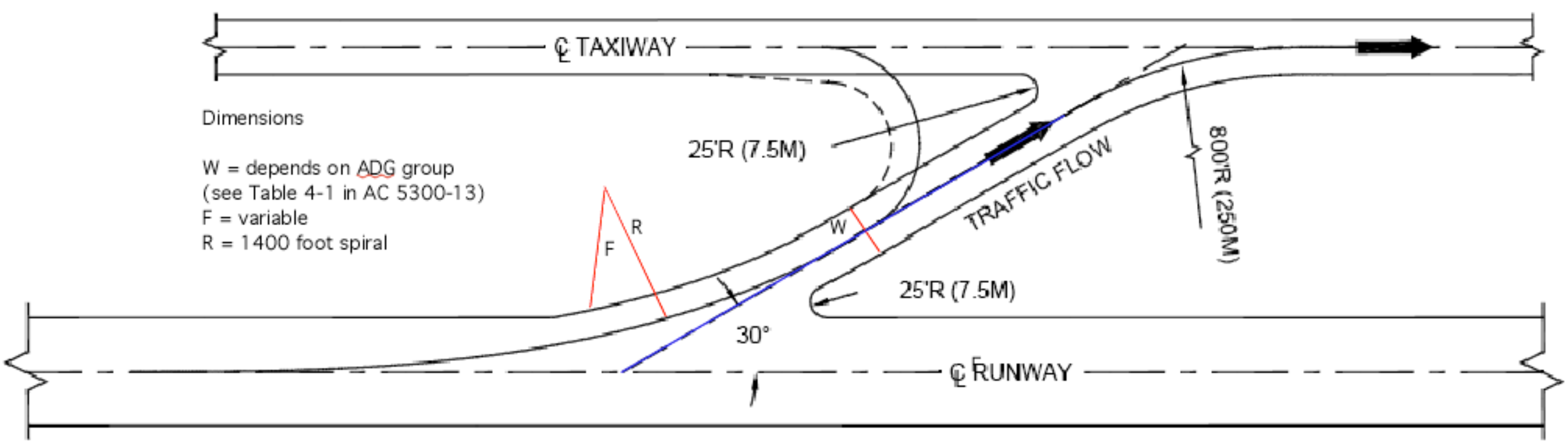
Acute Angle or High-Speed Runway Exit 30 Degree - Constant Radius (**Old Standard** with 1800 foot centerline radius)



Research done in 1960s by Horonjeff demonstrated that a 1,800 foot radius would allow aircraft to exit at 60 knots.

Acute Angle or High-Speed Runway Exit 30 Degree - Spiral Design (Another Legacy High-Speed Runway Exit Design)

- **Nominal 1400 feet centerline spiral**
- FAA computer program AD42.exe application for design (companion computer program to AC 5300-13)



Current Design Standards

- Available in ready made DXF files at: https://www.faa.gov/airports/engineering/airport_design

Airport Design Tools, Videos and Drawings for Advisory Circular 150/5300-13

Additional Design Technical Videos, Tools, and Drawings

Advisory Circular

- AC 150/5300-13 - Airport Design
- Runway Design Matrix Tool

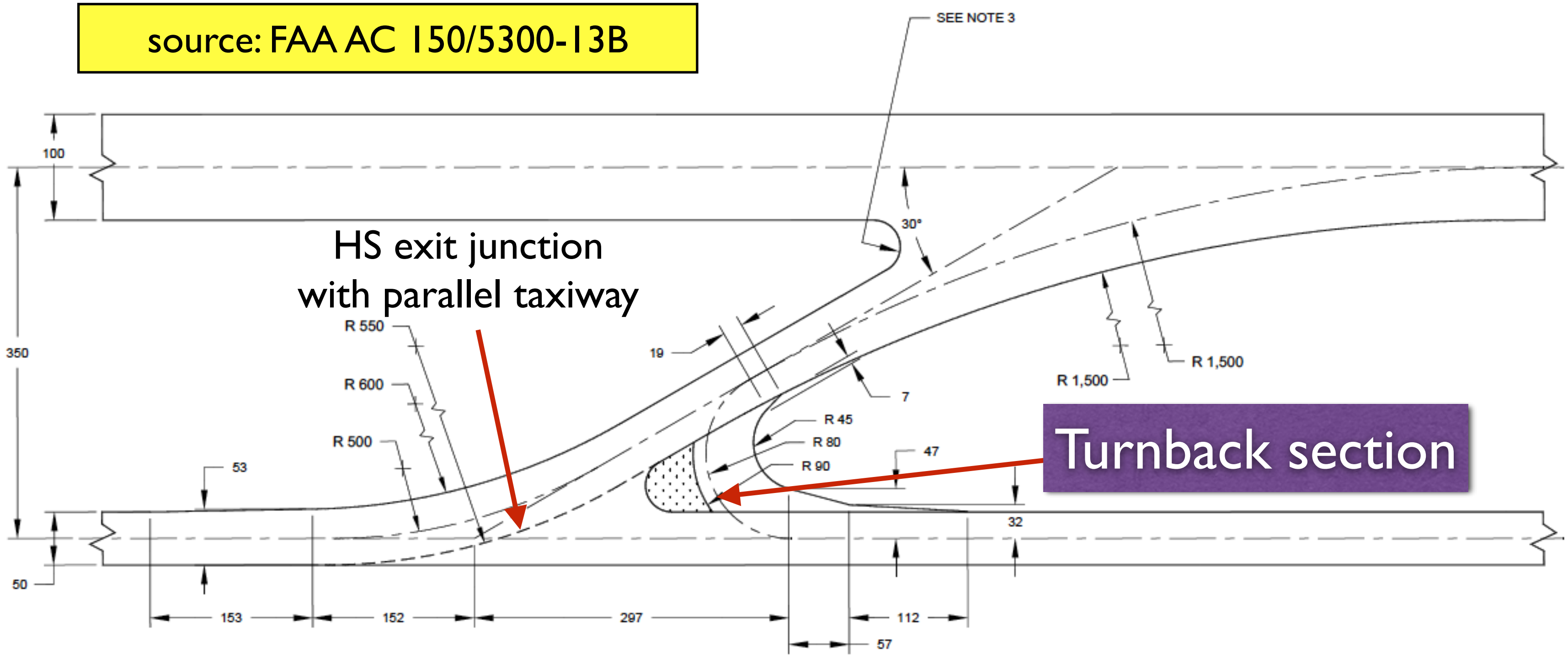
EXPAND ALL COLLAPSE ALL

Airport Design Tools

Drawings by Taxiway Design Group (TDG)

Acute Angle or High-Speed Runway Exit 30 Degree for ADG V, TDG 3 (**Current Design - 1500 ft. Centerline Radius**)

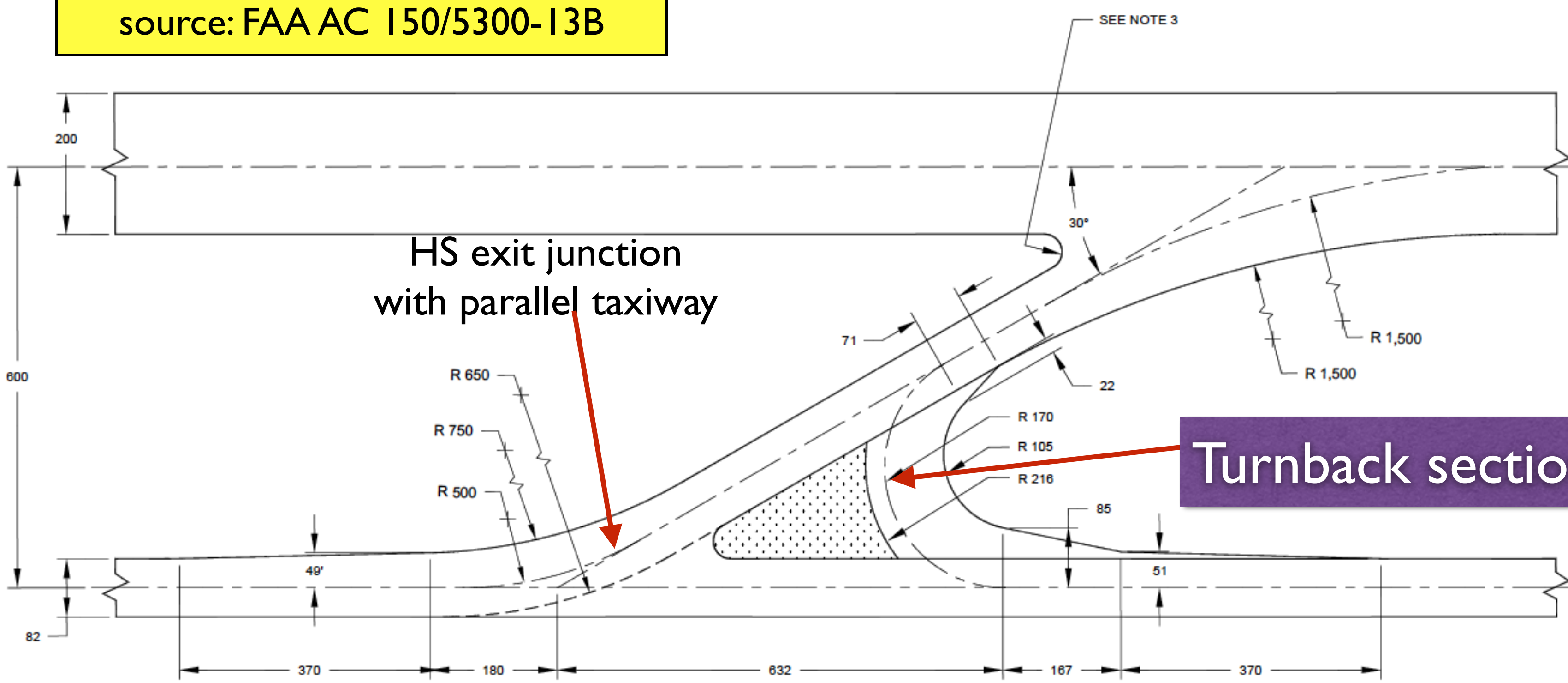
source: FAA AC 150/5300-13B



Note: 350 foot separation between runway centerline and parallel taxiway centerline

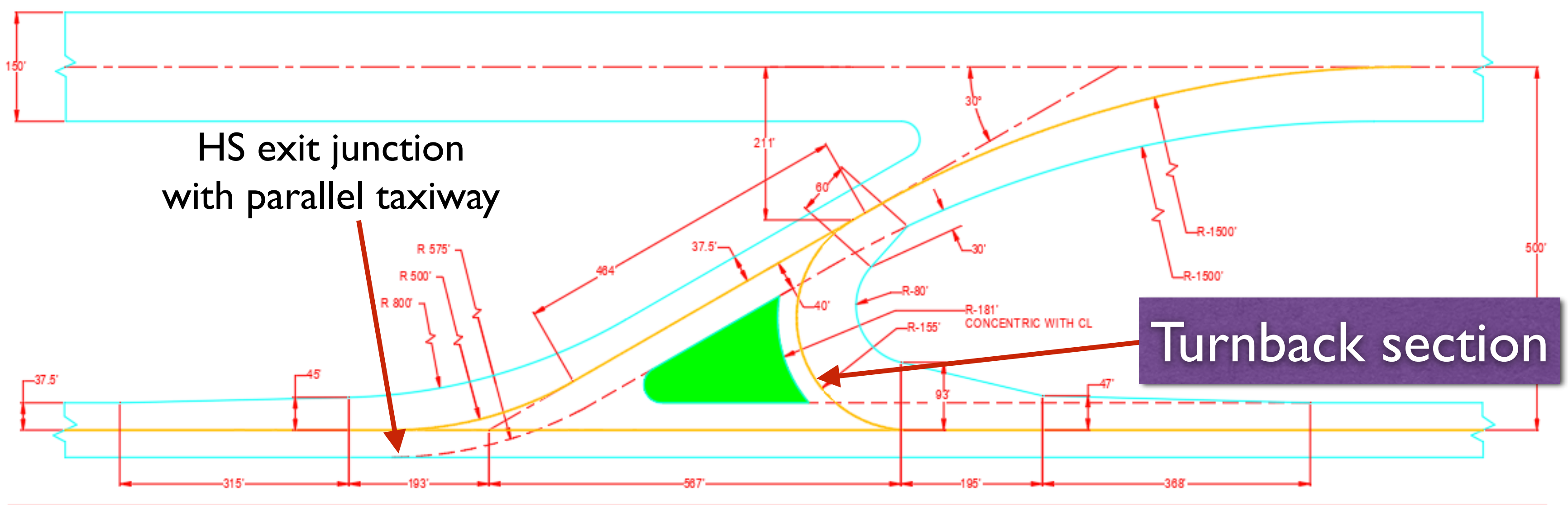
Acute Angle or High-Speed Runway Exit 30 Degree for ADG V, TDG 6 (**current design**)

source: FAA AC 150/5300-13B



Note: 600 foot separation between runway centerline and parallel taxiway centerline

Acute Angle or High-Speed Runway Exit for TDG 6 (FAA DXF file)



HIGH-SPEED EXIT FOR TDG-6 - 500' TO 150' RUNWAY

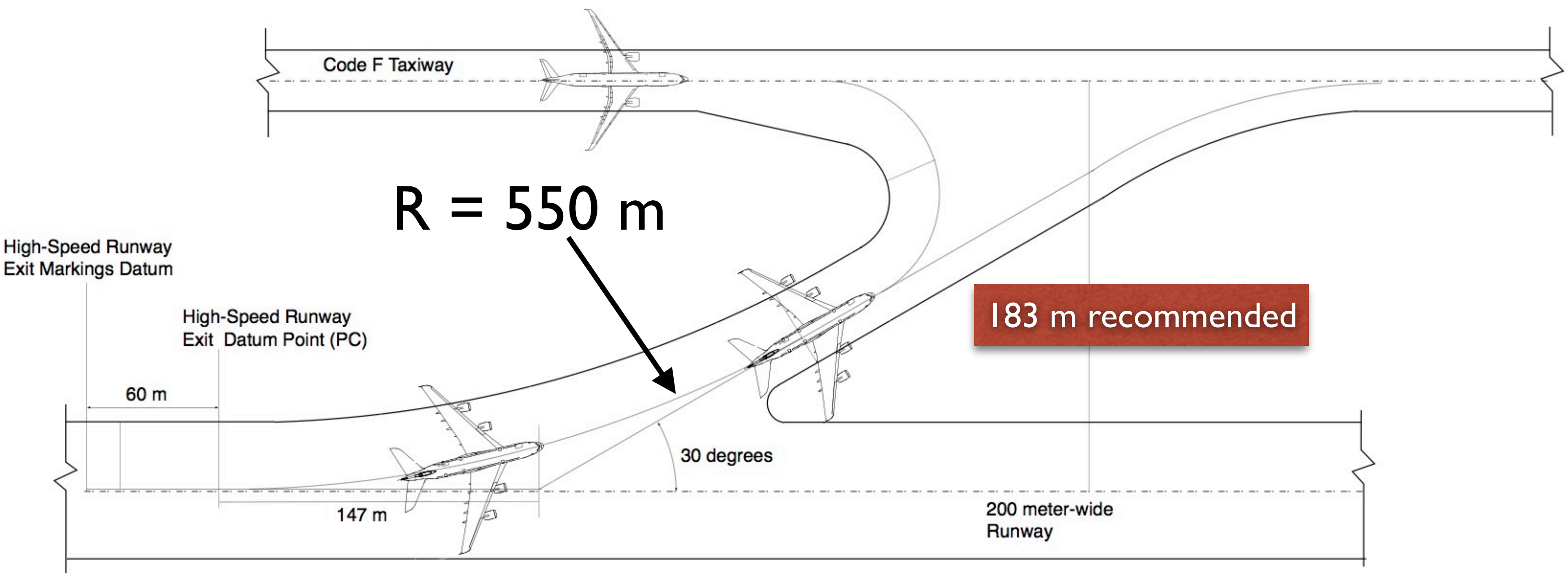
Drawings available at: https://www.faa.gov/airports/engineering/airport_design

Comparison Between HS Exit Designs

- The old 30-degree acute angle exit standard was originally proposed by Horonjeff et al. with a constant centerline radius of 1800 feet
- In the early 1990s, a 1400 foot spiral transition was introduced as the 30 degree (acute angle) design
- In 2013, the FAA went back to a constant radius design (1500 feet at centerline)
- Note that in the current designs suggested by FAA, the transition centerline radii dimensions change at the junction with the parallel taxiway for various TDG groups

ICAO Rapid Exit Taxiways

- ICAO uses a constant radius 550 meter curve
- The ICAO standard is similar to the old FAA standard (first developed by Horonjeff in 1961)



Design and Operational Considerations

- Virginia Tech observations suggest that most HS exits are used 10-20 knots below their design speed (60 knots)
- Perhaps this could be one reason for the FAA to change course
- However, Virginia Tech research suggest that pilots do not like abrupt transitions from a 150 foot runway width to a narrow 75 foot HS runway exit (as is the case for the current FAA design)
- Always be generous with the transition form a wide runway to a narrow runway exit
- HS runway exits are more effective when the separation between the runway and the parallel taxiway is at least 600 feet

To be Effective High-Speed Runway Exits require Good Separation Between Runway and Parallel Taxiway

Table 4-5. Runway to Taxiway Separation for Reverse Turns from a High-Speed Exit Based on TDG

Runway Centerline to Taxiway/ Taxilane Centerline	TDG			
	3	4	5	6
Recommended separation	350 ft (107 m)	450 ft (137 m)	450 ft (137 m)	600 ft (183 m)
Radius for 150-degree turn after 30-degree exit	79 ft (24.1 m)	121 ft (37 m)	121 ft (37 m)	152 ft (46 m)
Minimum separation [1]	348 ft (106 m)	427 ft (130 m)	427 ft (130 m)	485 ft (148 m)

Note 1: Minimum separation distance based on the standard 30-degree high speed exit and maximum 50-degree steering angle for the reverse turn.

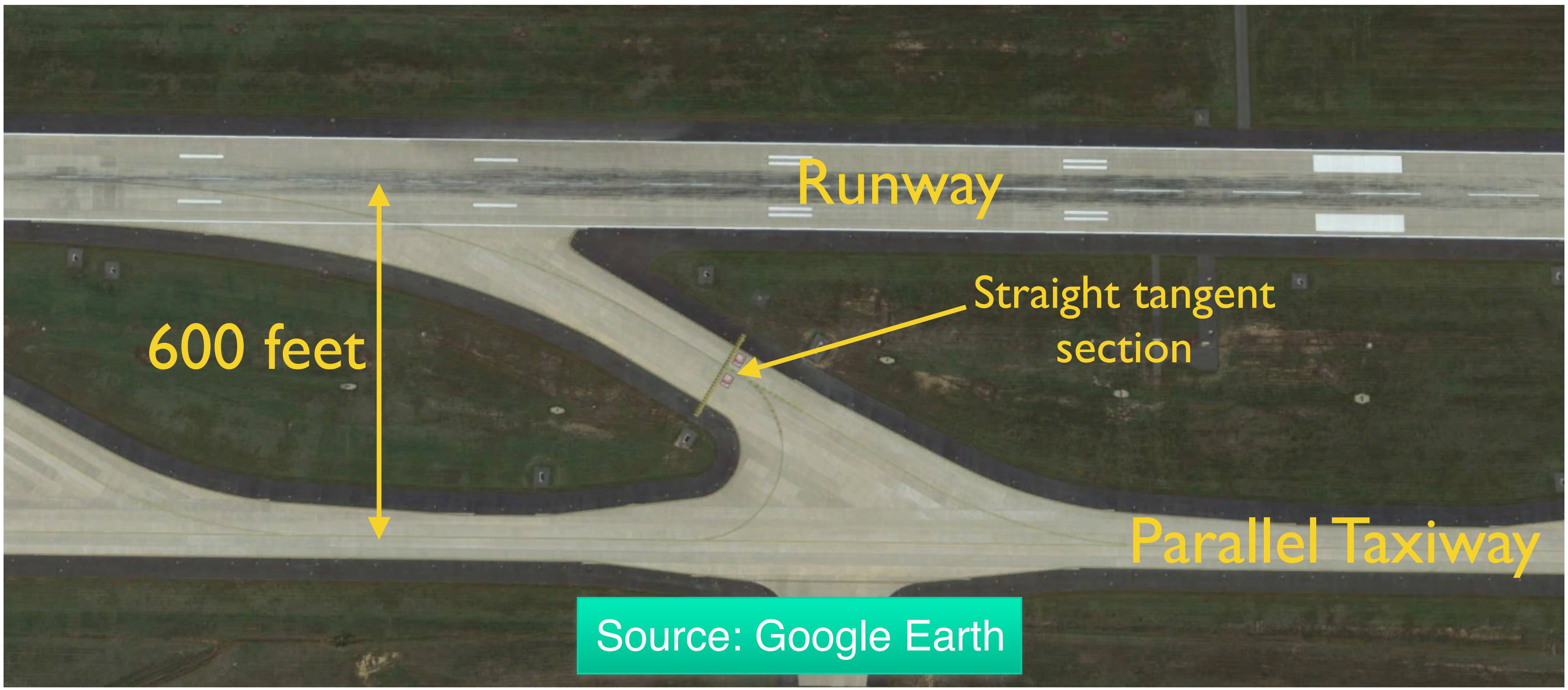
Source: Table 4-5 FAA AC 150/5300-13B

Example of a HS Runway Exit with 400 feet Separation (not recommended)

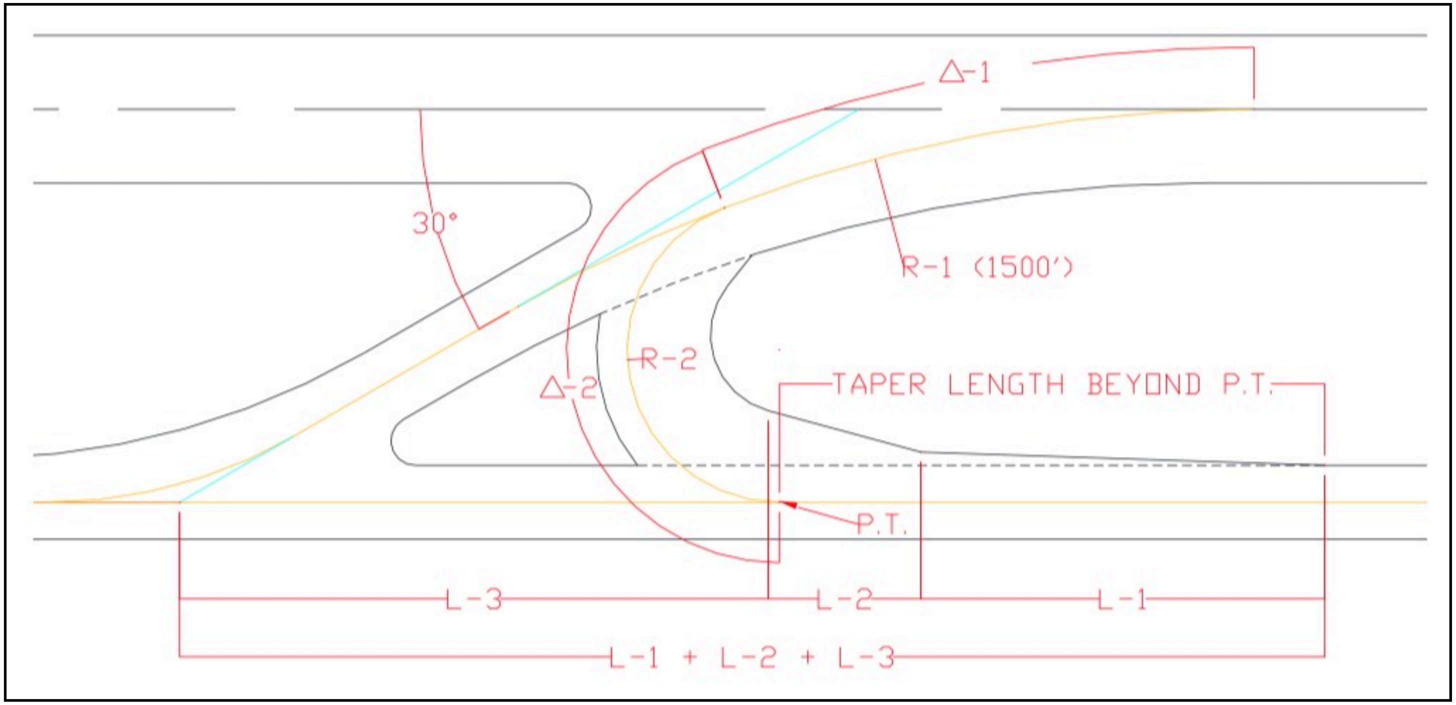
- Little tangent section on the HS exit for deceleration
- Taxiway is too close to the runway (pilots will exit at lower speeds)

Example of a HS Runway Exit with 600 feet Separation (good practice)

- A generous tangent section on the HS exit for deceleration
- Pilots will exit at higher speeds in such design

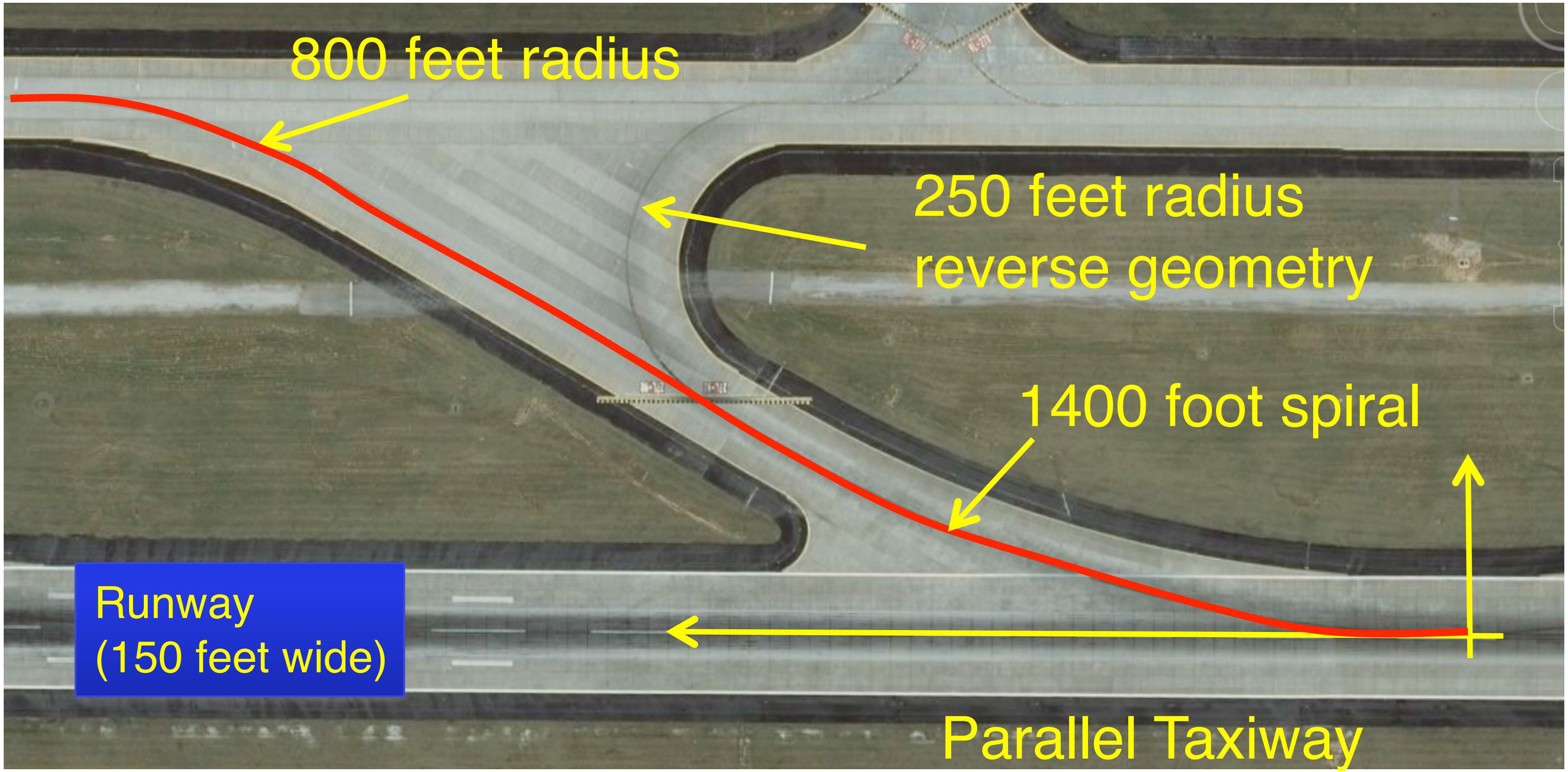


FAA Spreadsheet Calculator for Runway Exit Design



- https://www.faa.gov/airports/engineering/airport_design/

Example Implementation (ATL)
30 Degree Angle Runway Exit



Source: Google Earth

High-Speed Speed Exits (IAD)
(Standard 30 degree angle)

No longer recommended
Large pavement overlap can confuse pilots

Issues with 30 Degree Runway Exits

- The FAA recommends a minimum runway-taxiway **separation of 600 feet** for High-Speed runway exits
- Some airport have used 30 degree runway exits with only 400 feet between runway and taxiway centerlines (**avoid - this is bad practice**)
  - The result is low exits speeds and possible issues with busting hold lines
- Be careful and try to provide the minimum 600 foot recommended distance
- **Consider limited pilot visibility while crossing active runways**

FAA Airport Design Website

- Available at: https://www.faa.gov/airports/engineering/airport_design/

Available tools:

FAA Microsoft Excel Spreadsheet Programs

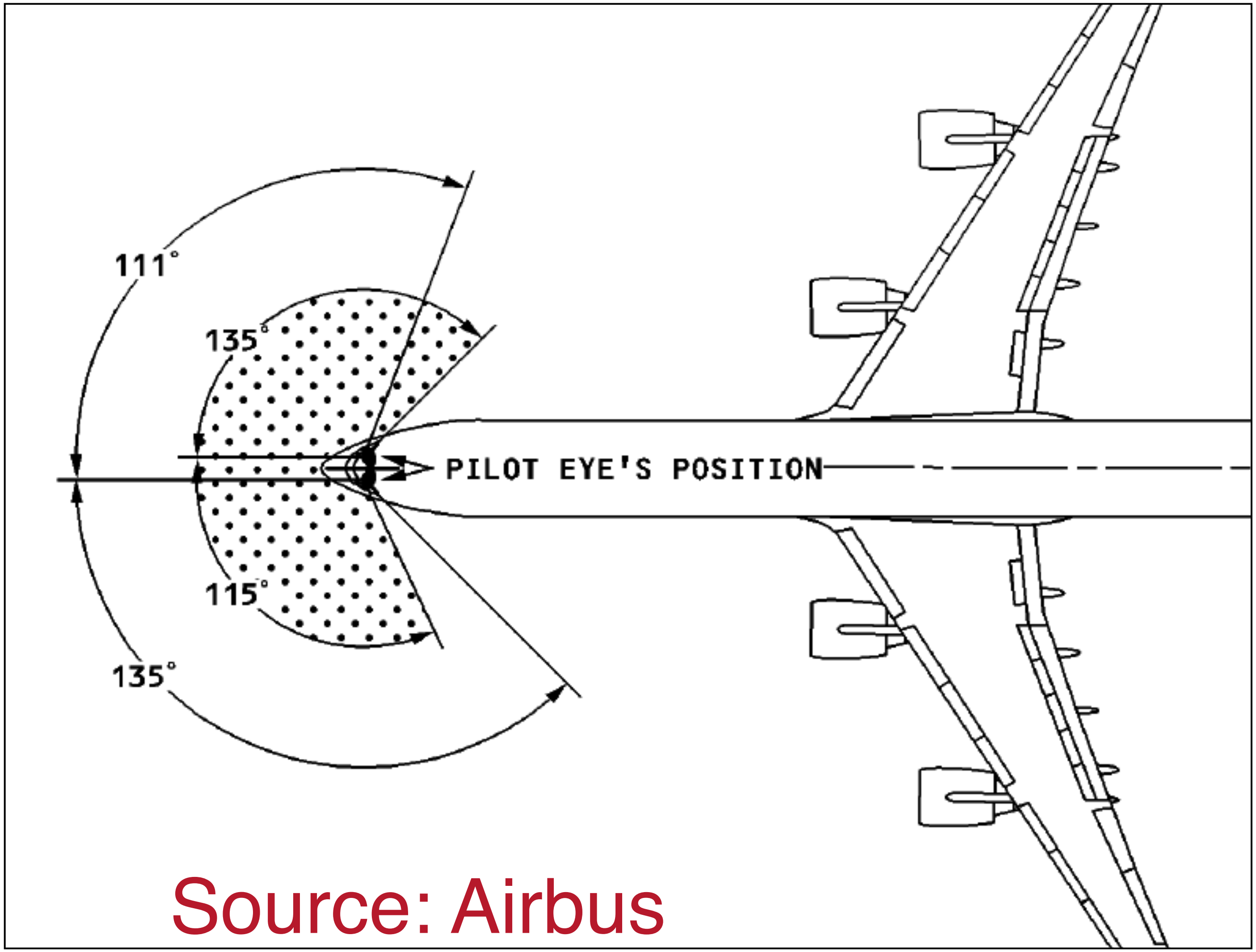
- Taxiway Design Tool for High Speed Exits (MS Excel)
  - Instructions for how to design High Speed Exits (PDF)

- Taxiway Fillet Design Tool (MS Excel) (added 6/6/2018)
  - Taxiway Fillet Design Tool User's Guide (PDF)

Tool developed at Virginia Tech

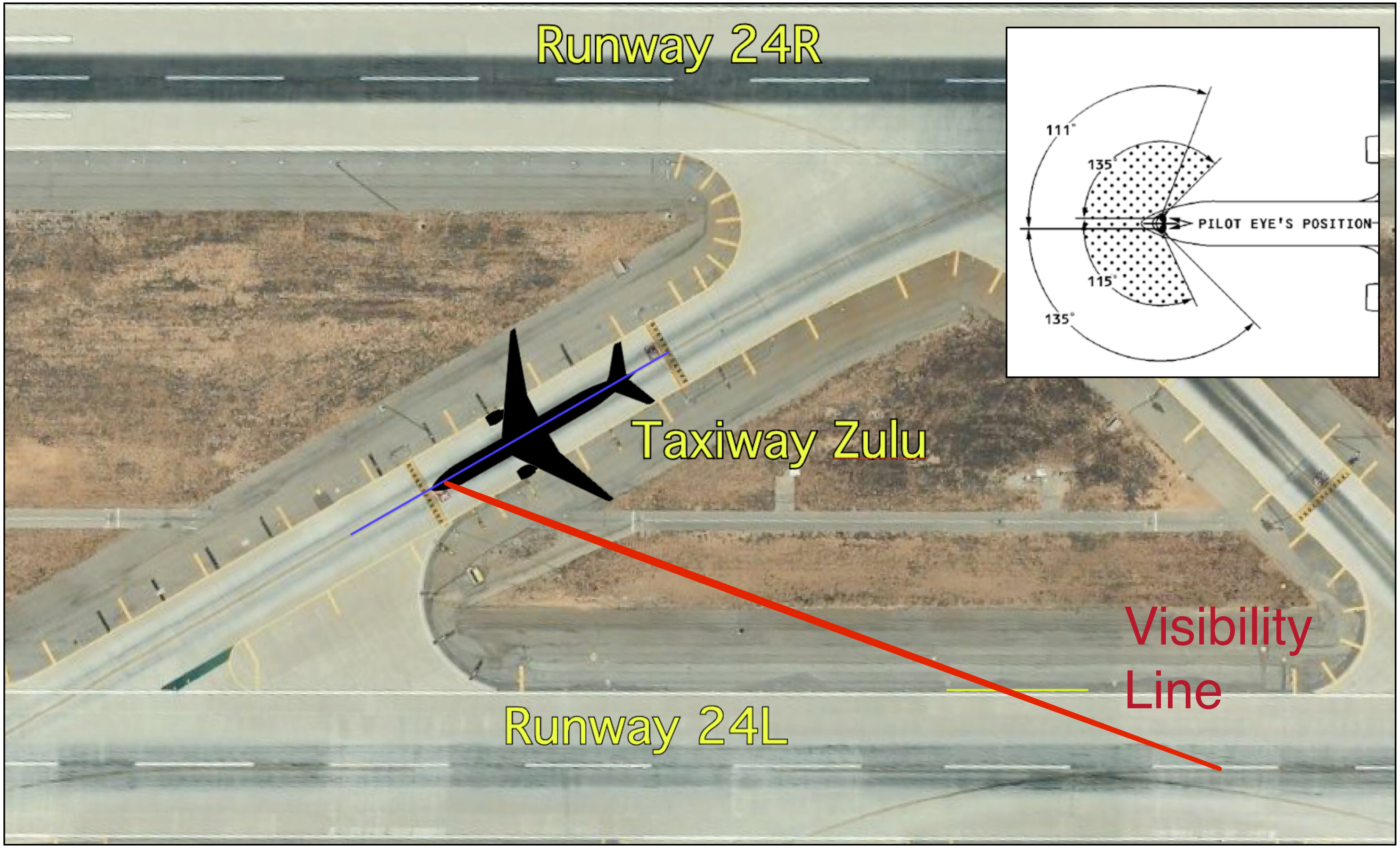
- Runway Exit Design Interactive Model (REDIM) **(added 5/6/2020)**
  REDIM is a computer model developed to locate and design high-speed runway and right angle exits at airports. The model uses kinematic equations to characterize the aircraft landing dynamics

Airbus A340-600 Visibility from Cockpit



Source: Airbus

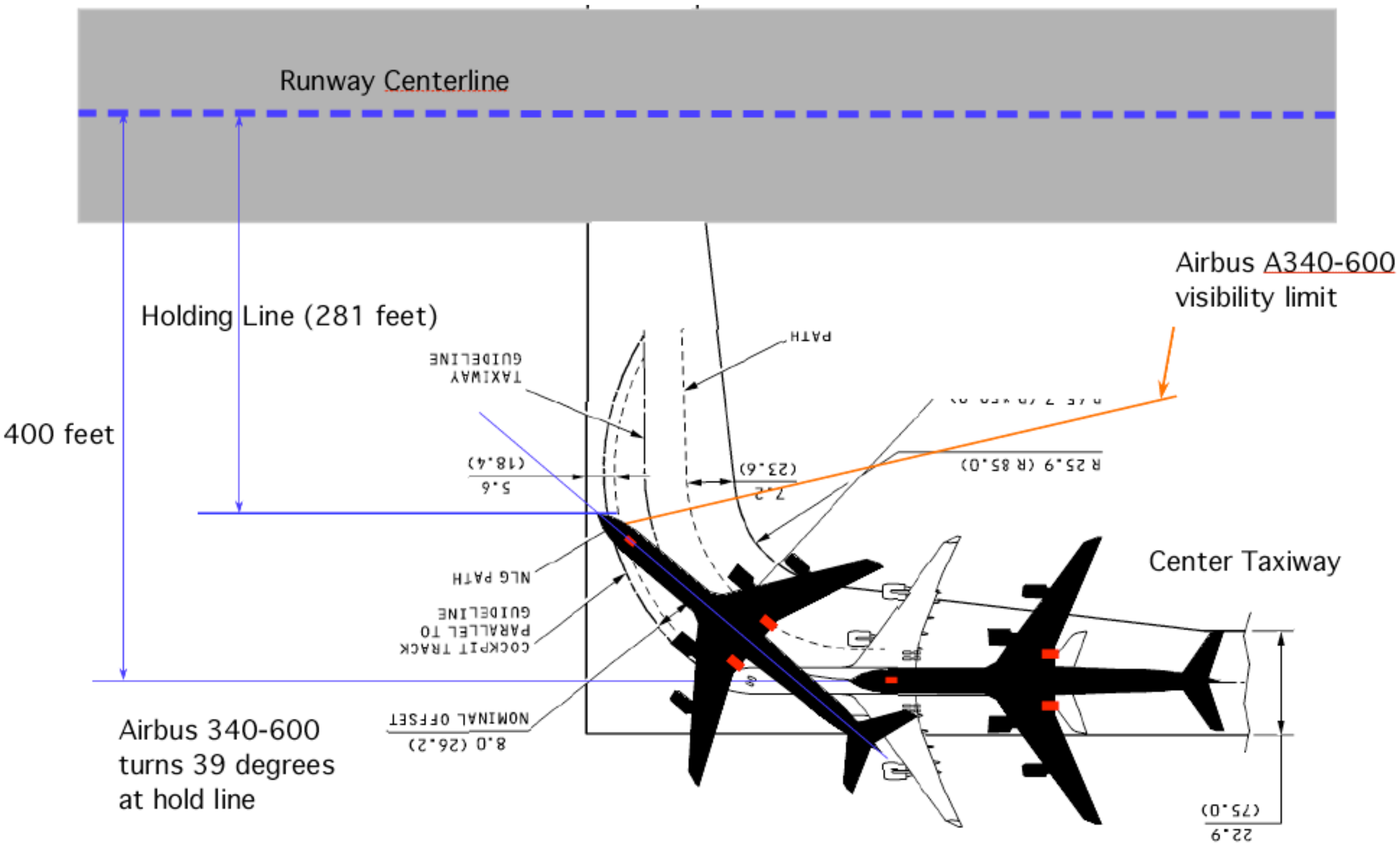
Sample Limited Visibility due to High-Speed Runway Exits (LAX Airport)



Final turning angle at hold line = 30 degrees

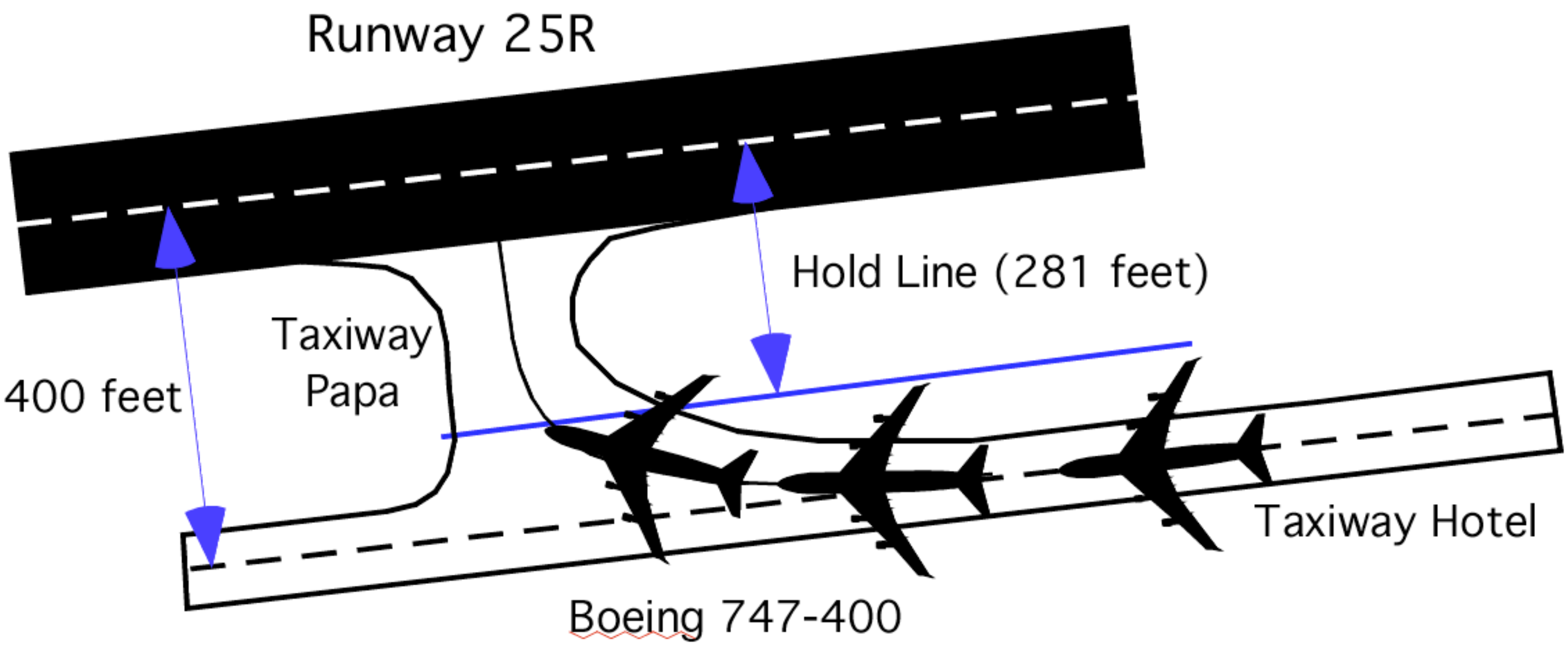
VirginiaTech
Invent the Future

Example of Limited Visibility due to Short Runway-Taxiway Distance



Example of Limited Visibility from Aircraft Cockpit Driven by Hold Line Location

- Before the aircraft nose reaches the hold line, the aircraft wingtip violates the hold line distance



Runway Exit Placement

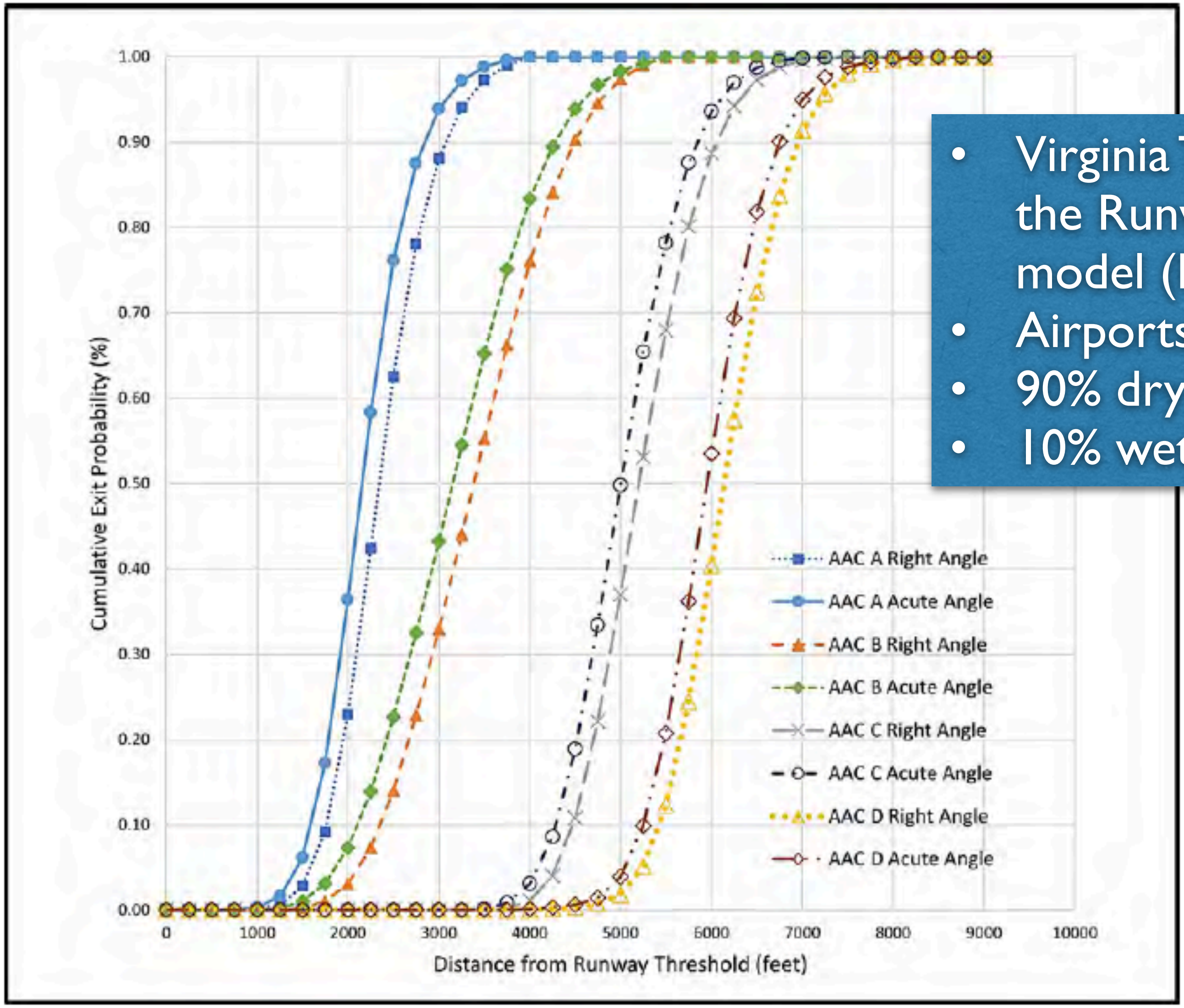
Procedures to Locate Runway Exits

- Factors that affect the runway exit locations:
  - Fleet mix
  - Operations/hr
  - Environmental conditions (wet vs. dry pavement)
  - Terminal or gate locations
  - Type and number of runway exits
- Manual tables developed by ICAO and FAA
- Use computer models like REDIM - Runway Exit Design Interactive Model (Developed at Virginia Tech for the FAA and NASA)

Methods to Locate Runway Exits

- Graphical solution of cumulative exit probability runway exit use charts (see Figure 4-17 in AC 150 5300-13B)
- Three segment method using simple aircraft kinematics
- Use the Runway Exit Design Tool (REDIM version 3) developed by Virginia Tech for the FAA

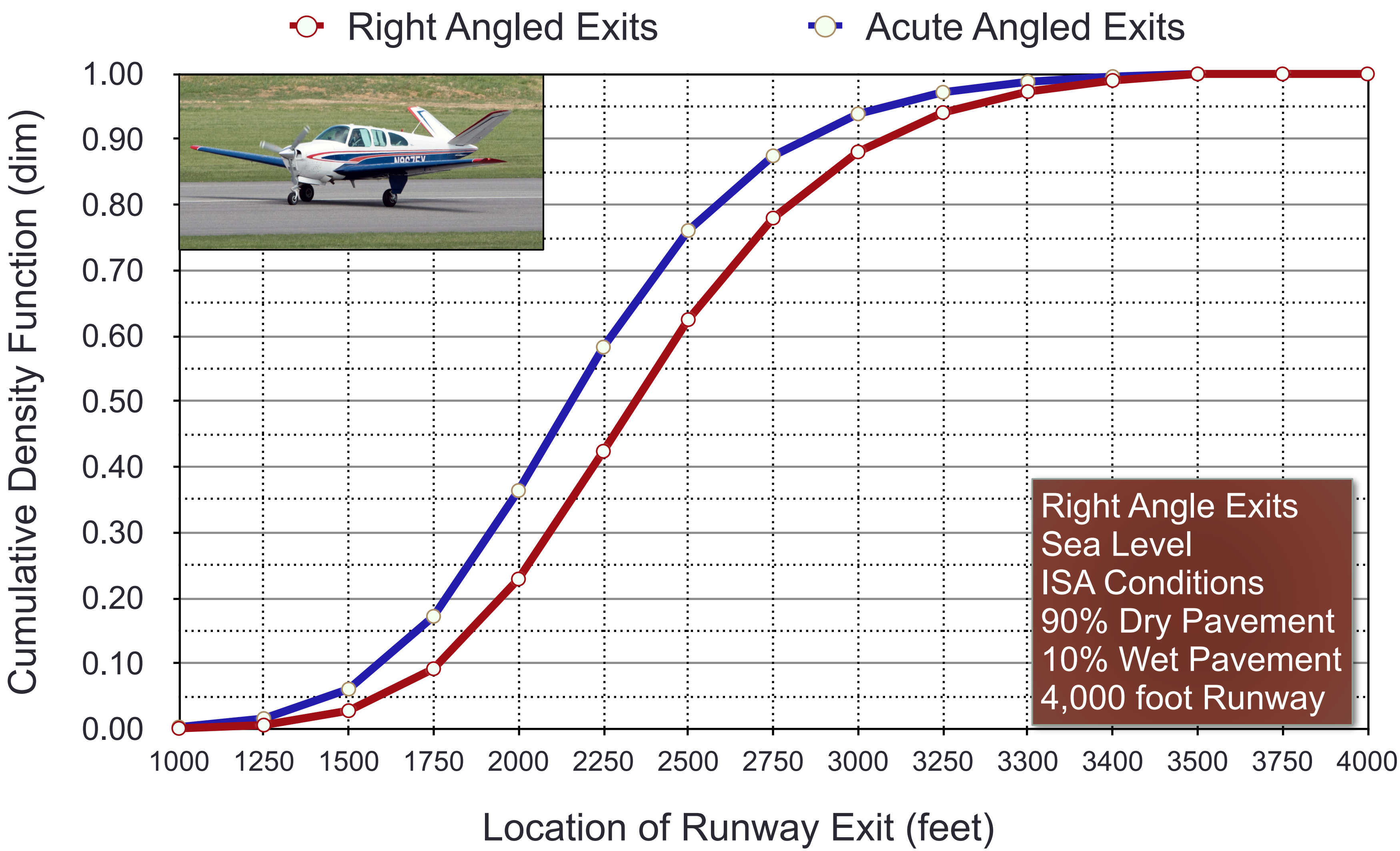
Cumulative Runway Exit Design Curves



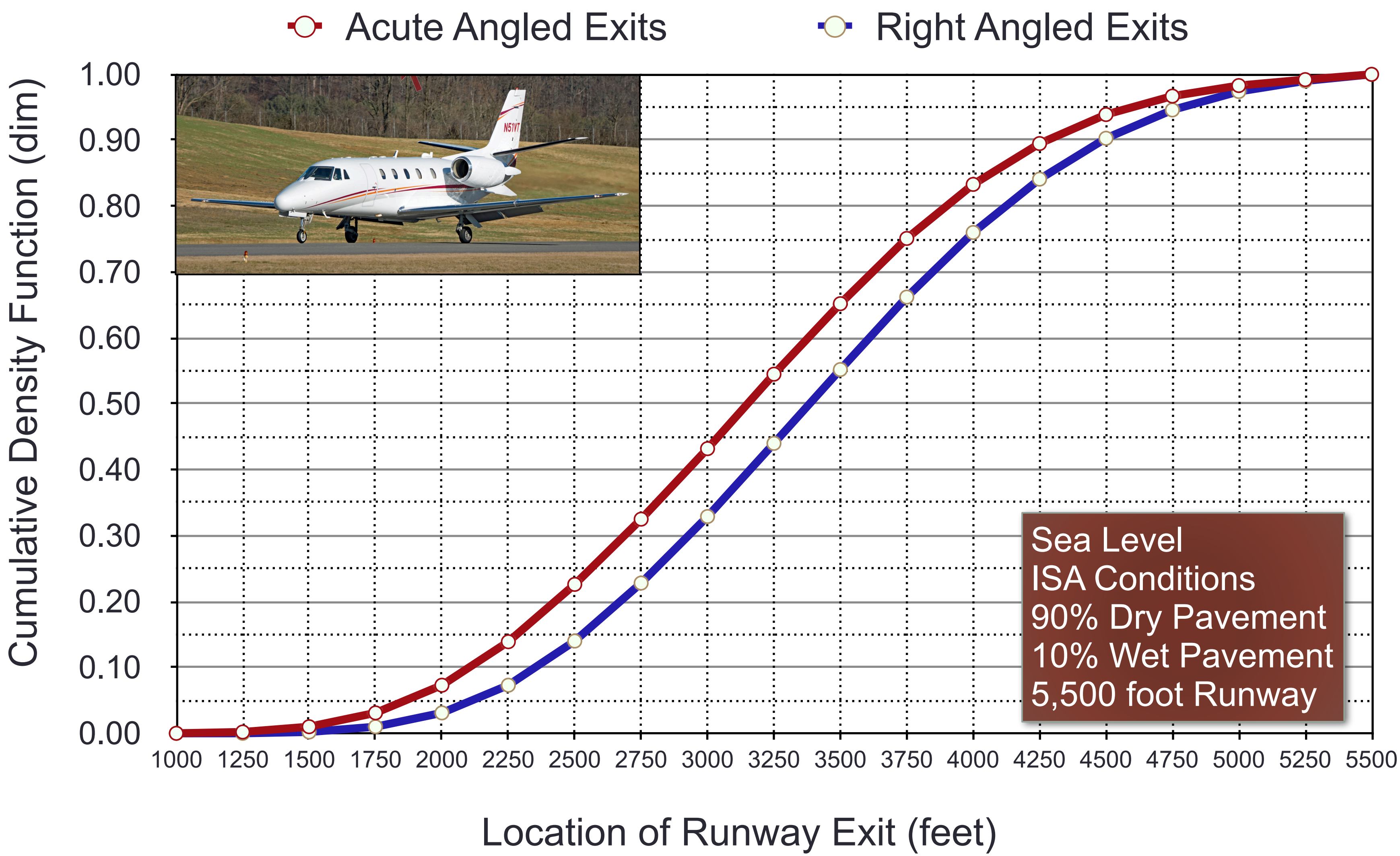
- Virginia Tech analysis using the Runway Exit Tool model (REDIM 3)
- Airports below 2,000 feet
- 90% dry pavement
- 10% wet pavement design

Source: Figure 4-17 in FAA AC 150/5300-13B

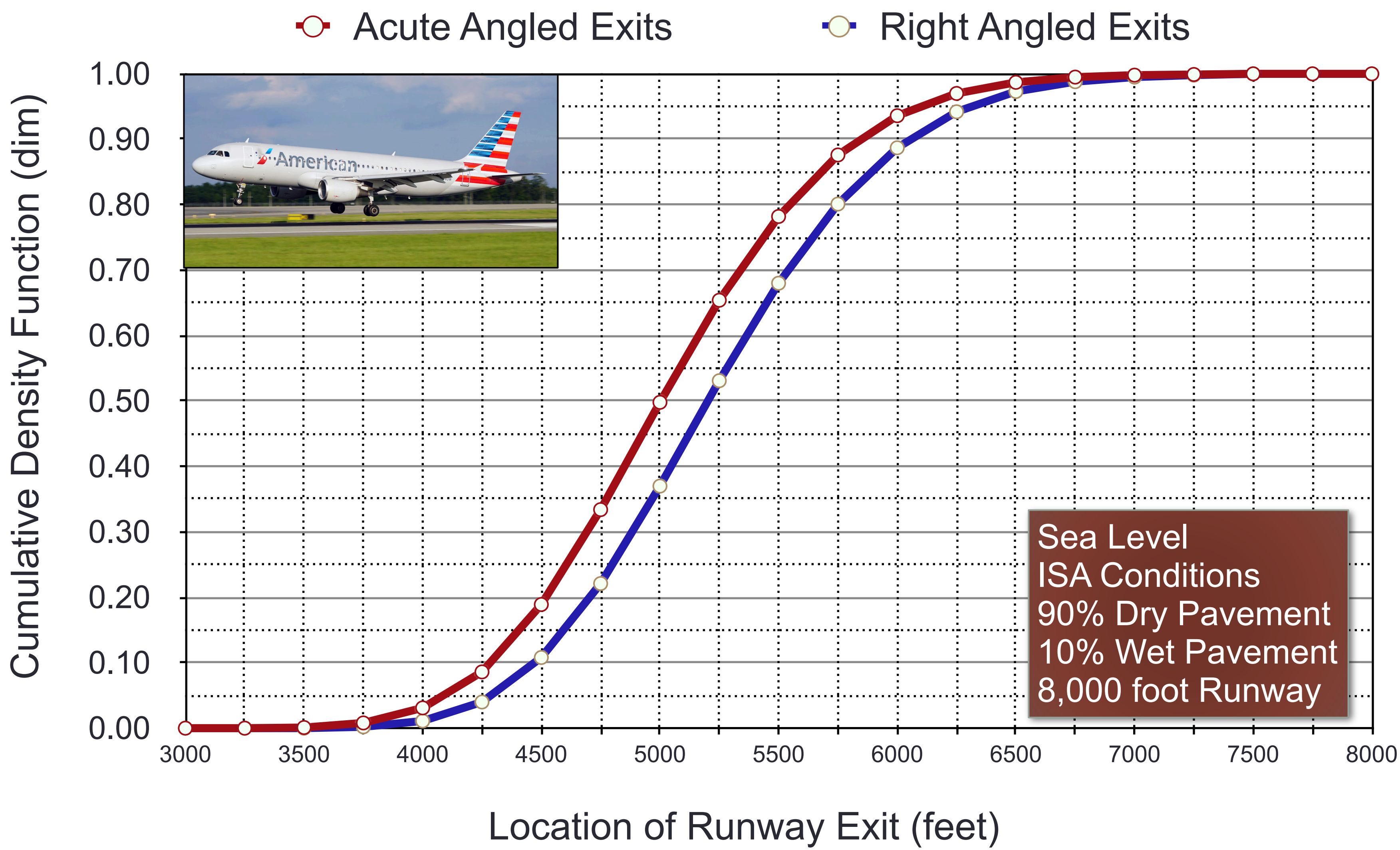
Runway Exit Design for AAC A Class Aircraft



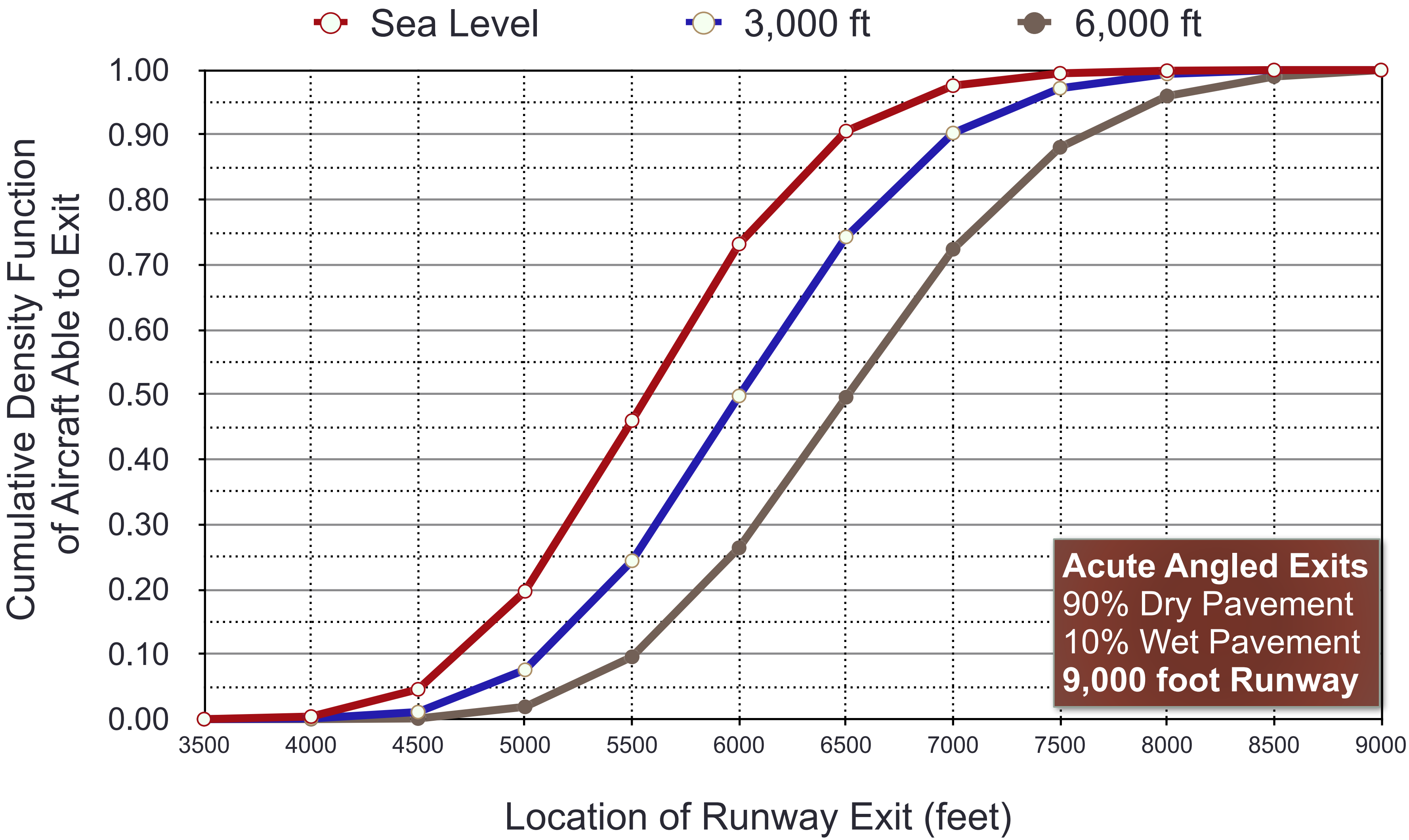
Runway Exit Design for AAC B Class Aircraft



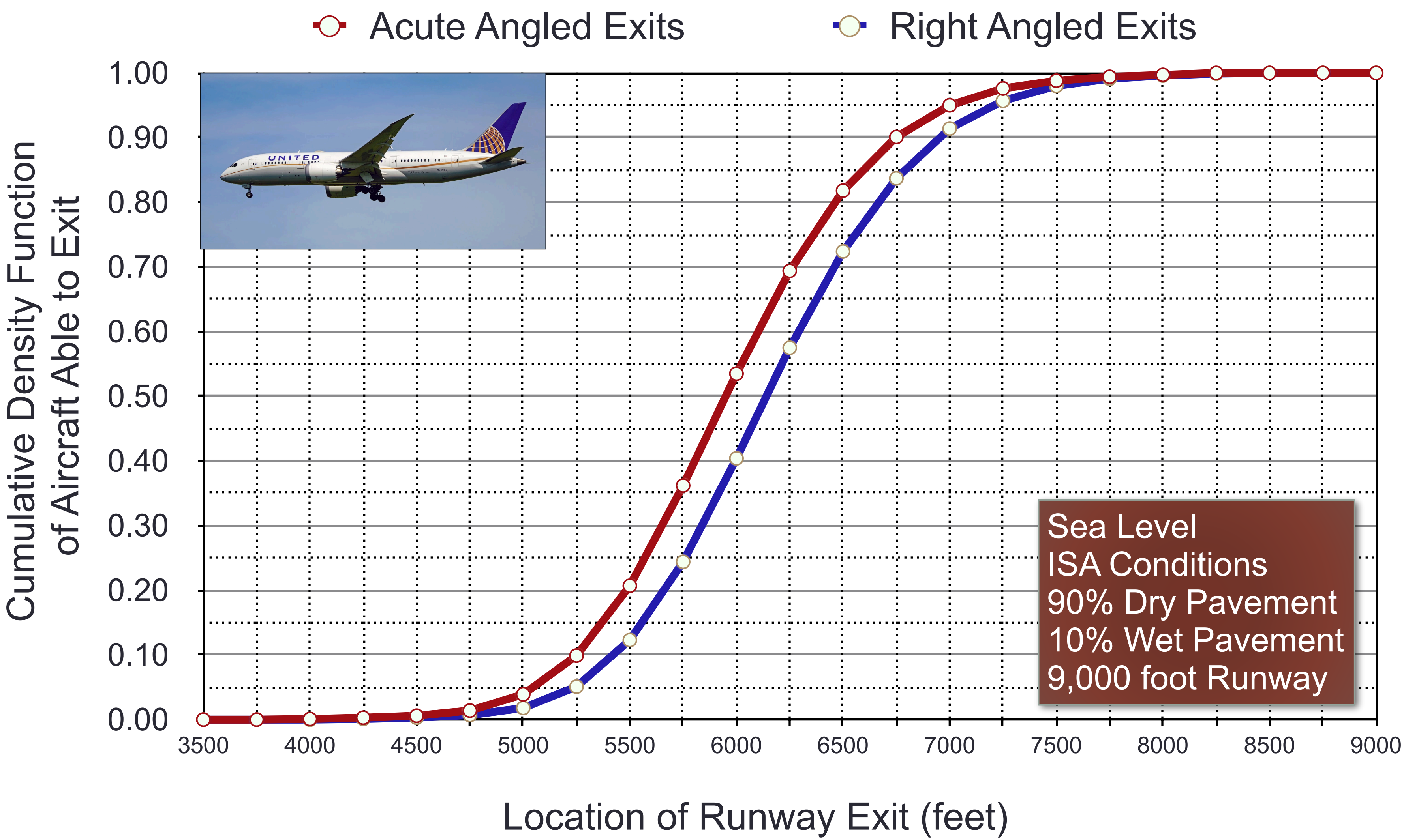
Runway Exit Design for AAC C Class Aircraft



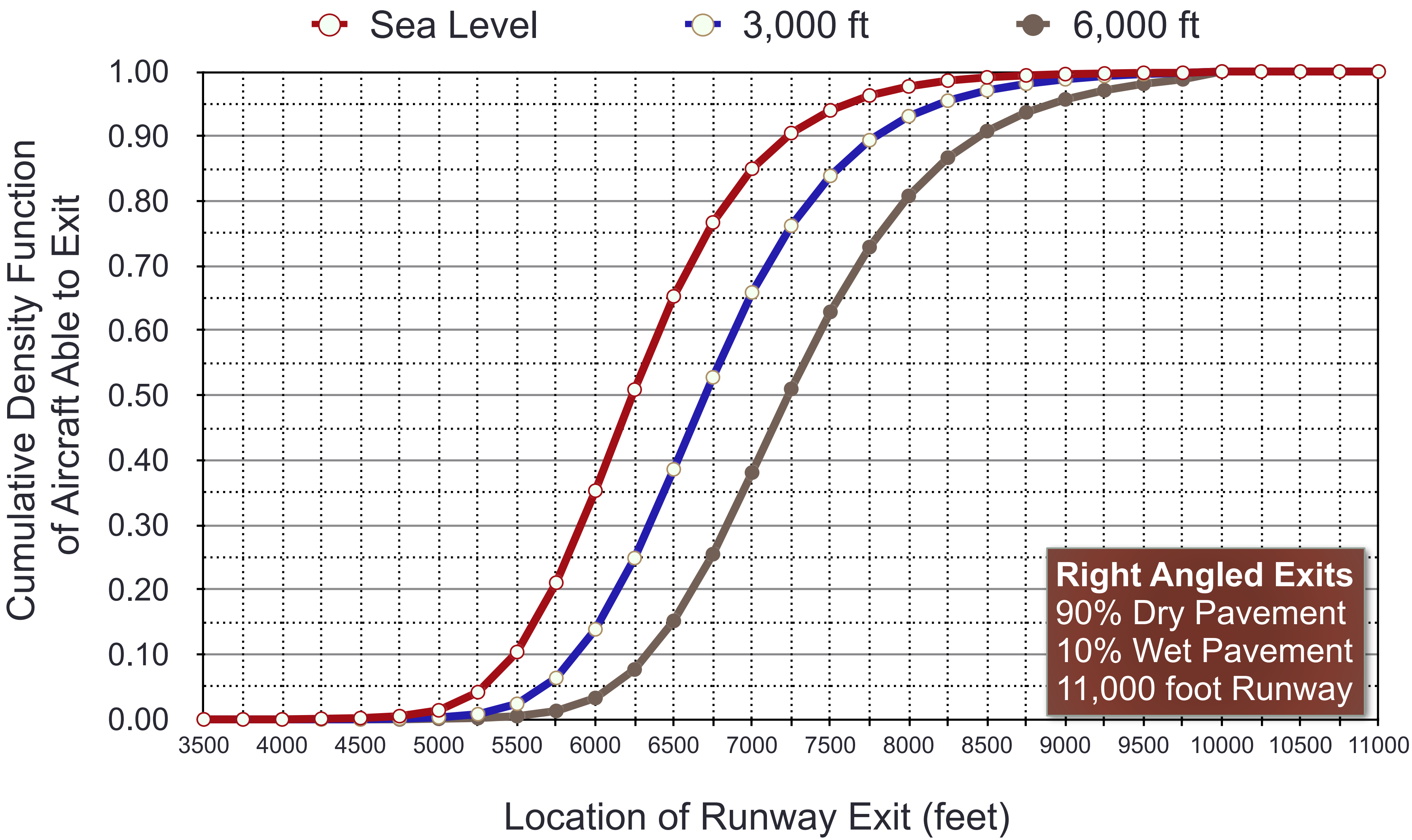
For Typical Acute Angle Exit Locations, Increase Runway Exit Location by 150 feet for Every 1,000 ft Airfield Elevation Change



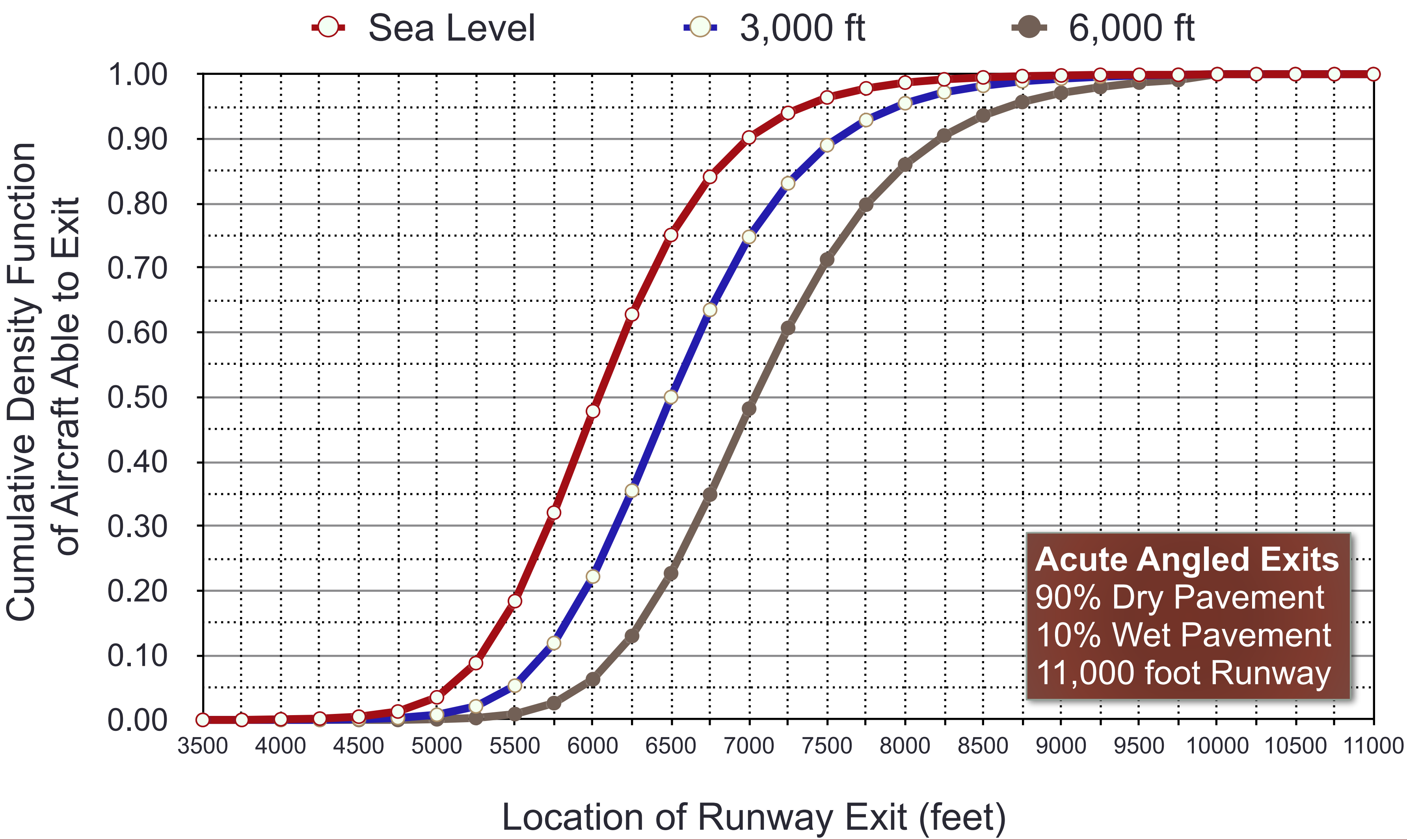
Runway Exit Design for AAC D Class Aircraft



For Typical Acute Angle Exit Locations, Increase Runway Exit Location by 167 feet for Each 1,000 ft Airfield Elevation



For Typical Acute Angle Exit Locations, Increase Runway Exit Location by 185 feet for Each 1,000 ft Airfield Elevation



Runway Exit Location Example Problem Using Cumulative Runway Exit Design Curves

Aircraft and Airport Environment

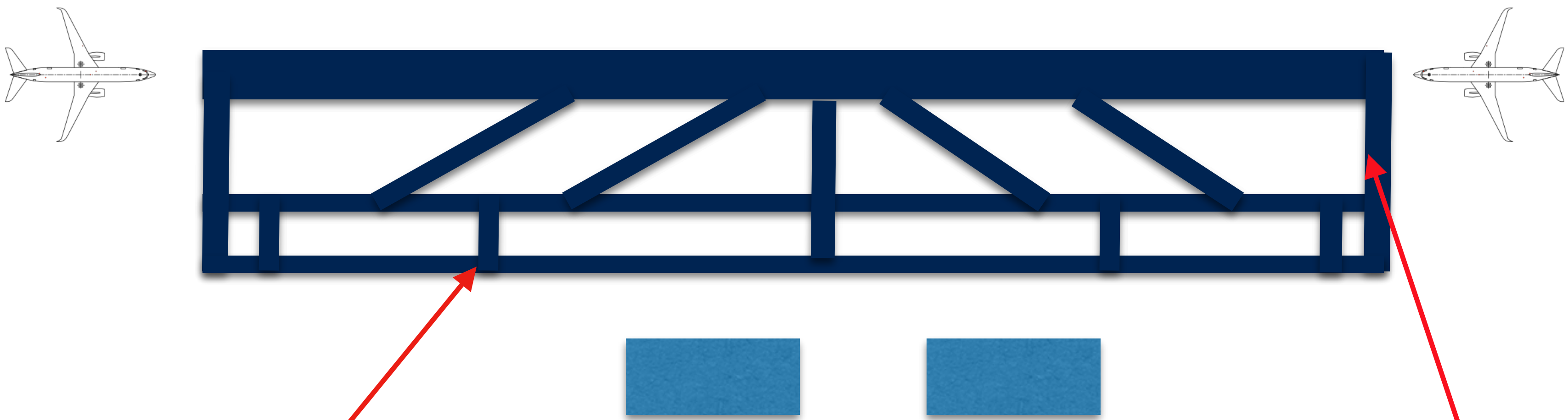
- Airport located at sea level conditions
- 8000-foot runway
- Minimum of 4 runway exits are desired
- AAC groups
  - B - 20% of fleet mix
  - C - 80% of fleet mix
- More than 30 operations per hour in the peak period

Typical Questions and Workflow

- Locate two high-speed (acute angle) runway exits per direction to accommodate 50% and 95% of AAC C class aircraft
- Sketch a runway exit solution
- Measure ROT using the FAA/Virginia Tech Runway Exit Design Model (REDIM)

Sketch the Solution to the Problem

8,000 foot runway

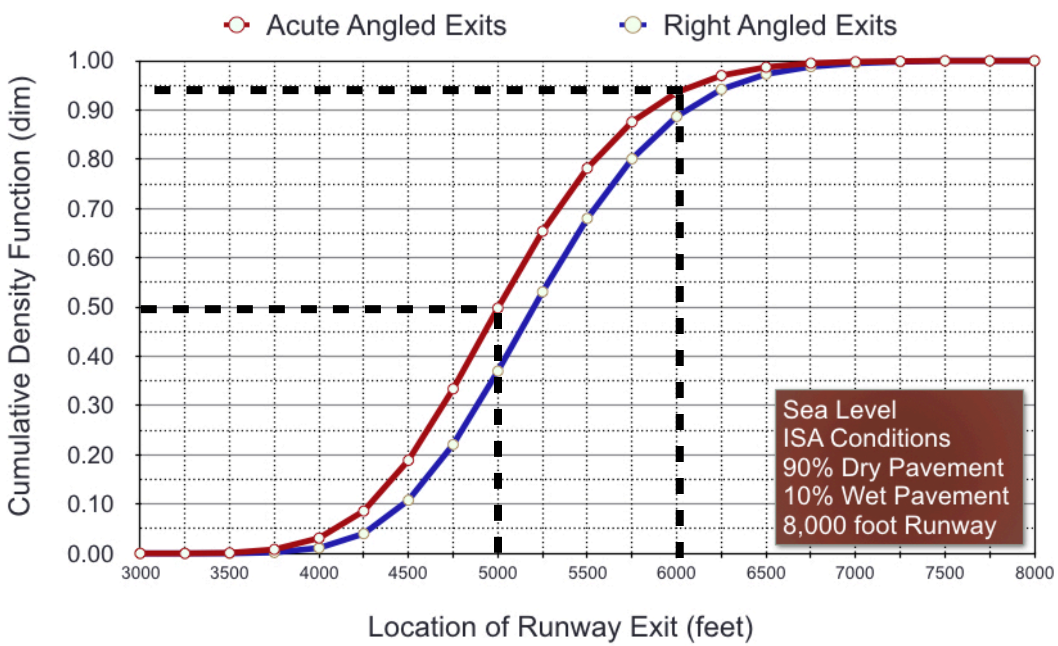


Airport Gate Locations

Note:
taxiway connectors
do not lead from HS exit
to second parallel taxiway
(for safety)

Provide 600 feet from runway
to parallel taxiway allowing
faster exit speeds

Evaluate Runway Exit Usage at Desired Locations Solution to the Problem



AAC C Class Aircraft

Location of Two High-Speed Exits
1st - 5,000 feet (50%)
2nd - 6,000 feet (95%)

Always use 800 feet as the minimum distance between high-speed runway exits

The criteria is satisfied (1,000 feet between two HS exits)

FAA/Virginia Tech Runway Exit Design Tool REDIM Model

Runway Exit Design Tool (REDIM 4 Web Site)

REDIM

Version 4.0.2 - Date: 12/20/2022

Virginia Tech - Air Transportation Systems Lab

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Runway Exit Design Interactive Model V4 (REDIM-V4)

Explore +

Runway Exit Design Interactive Model V4 (REDIM-V4)

Download REDIM 4

- **REDIM 4.0.2** - Windows Installer
- **User Group**
- **User Manual**
- **FAQs**
- **Change Log**

Web site to download the REDIM model

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

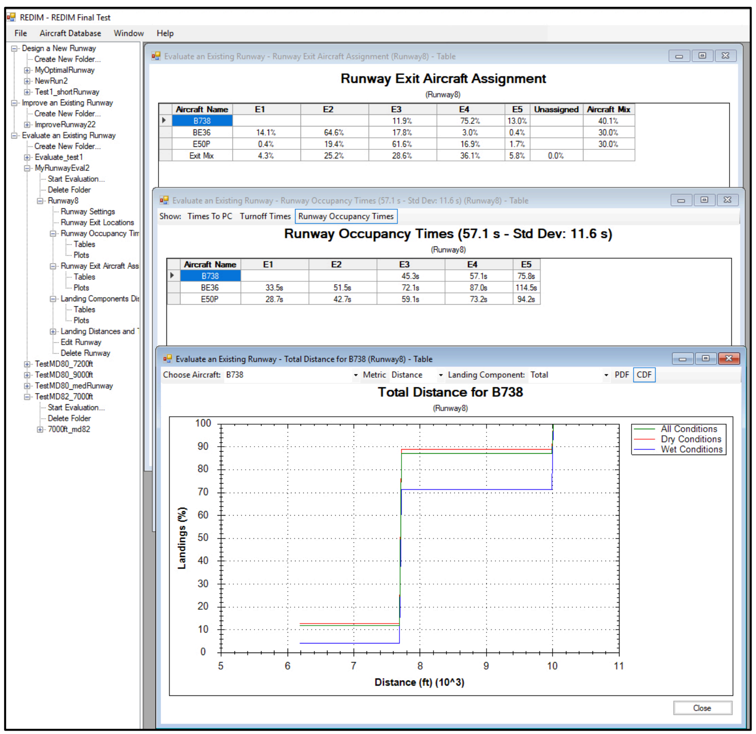
General Information About the Model

- Model has three analysis modules:

  a) Evaluation of an existing runway

  b) Improvements to an existing runway

  c) Design optimal locations for a new runway



Model uses Monte Carlo Simulation to predict aircraft landing roll performance

- Stand-alone Windows application
- Requires ~1.8 Gb of hard disk space
- New runway clustering
- Improvements to landing roll profile calculations

Runway Exit Design Model Workflow

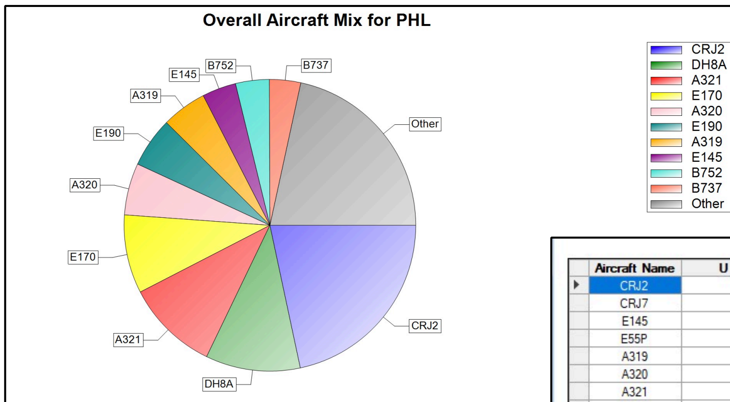
Runway Exit Locations and Geometry

Runway Exit Locations

(PHL27L_HS1_5100)

Exit	Exit Status	Exit Type	Location (ft)
U	Open	90°	2,310
S7	Open	30° (with 1,500 ft circular arc)	3,350
S6	Closed	90°	3,360
Y	Open	90°	4,400
S8	Open	User Defined	4,865
NewHS1	Open	30° (with 1,800 ft circular arc)	5,098
S9	Closed	90°	5,719
S11	Open	30° (with 1,800 ft circular arc)	6,073
Z	Open	90°	7,136
S12	Open	90°	9,409
S13	Open	90°	9,908

Aircraft Fleet Mix



Selected Aircraft

- CRJ2 - Bombardier CRJ 200 - 23.5%
- CRJ7 - Bombardier CRJ 700 - 1.2%
- E145 - Embraer 145 - 4.1%
- E55P - Embraer 55 Phenom 300 - 0.6%
- A319 - Airbus A319 - 5.4%
- A320 - Airbus A320 - 6.2%
- A321 - Airbus A321 - 11.2%
- B737 - Boeing 737-700 - 3.8%
- B738 - Boeing 737-800 - 3.4%
- B739 - Boeing 737-900 - 1%
- CRJ9 - Bombardier CRJ 900 - 1.6%
- DH8C - DeHavilland Canada Dash8-300 - 11.4%
- E170 - Embraer 170 - 9.5%
- E190 - Embraer 190 - 6%
- MD88 - McDonnell Douglas MD-88 - 1.5%

Runway Occupancy Table

(PHL27L_HS1_5100)

Aircraft Name	U	S7	S6	Y	S8	NewHS1	S9	S11	Z
CRJ2		31.2s		36.8s	39.6s	41.3s		47.9s	56.9s
CRJ7		33.9s		37.3s	39.9s	41.5s		48.4s	57.6s
E145		33.6s		37.1s	38.9s	40.7s		47.1s	55.6s
E55P		38.2s		45.0s	47.7s	49.2s		56.1s	65.2s
A319		31.0s		38.1s	41.3s	44.3s		51.3s	58.8s
A320				36.7s	40.3s	42.2s		49.0s	56.4s
A321				35.6s	39.2s	40.7s		47.1s	52.8s
B737				[illegible]	[illegible]	[illegible]		[illegible]	57.1s
B738				[illegible]	[illegible]	[illegible]		[illegible]	53.0s
B739				[illegible]	[illegible]	[illegible]		[illegible]	53.5s
CRJ9		28.0s		[illegible]	[illegible]	[illegible]		[illegible]	55.9s
DH8C		34.6s		[illegible]	[illegible]	[illegible]		[illegible]	60.3s
E170		32.1s		36.7s	40.2s	42.4s		49.1s	56.1s
E190		32.5s		36.1s	37.6s	42.3s		49.3s	55.6s
MD88				35.6s	40.7s	39.9s		46.0s	53.4s
MD90				35.4s	39.0s	39.7s		45.7s	52.7s
B752		35.2s		41.1s	44.5s	45.8s		52.5s	60.8s
B763				39.0s	43.2s	44.2s		50.8s	57.5s
MD11				36.2s	42.3s	43.0s		49.4s	53.9s
A332				40.8s	46.6s	46.9s		53.6s	58.8s
A333					47.2s	46.1s		53.1s	57.1s
B772					46.4s	45.4s		53.7s	58.8s

Runway Exit Design Tool Outputs

Analysis	Purpose	Outputs Produced
Aircraft Mix	Provides an overview of aircraft fleet mix	Percent of aircraft types simulated in the analysis
Runway Occupancy Time	Provides three values of runway occupancy time measured at two locations: 1.Fuselage out 2.At hold bar	1.Average ROT (in seconds) by runway exit and aircraft (table format) 2.Average ROT (in seconds) by runway exit and aircraft (graphical format) 3. Weighted average ROT for the complete aircraft mix using the runway 4. Standard deviation of ROT for the complete fleet mix 5. Individual landing roll times for every aircraft simulated by the model (~50,000 landings per aircraft)
Runway Exit Utilization	Provides information about aircraft assigned to each exit	1. Percent of individual aircraft assigned to each runway exit 2. Individual ROT by aircraft and runway exit
Aircraft Landing Performance	Provides individual landing event information (REDIM uses a Monte Carlo Simulation Process)	1. Landing roll distributions (CDF and PDF) by runway condition (wet or dry) in table format 2. Landing roll distributions (CDF and PDF) by runway condition (wet or dry) in graphical form 3. Landing roll distances and times by aircraft and runway pavement condition (wet or dry) a) Air distance and air time (time to nose gear touchdown) b) Nominal braking distance and time c) Extra roll distance and time d) Turnoff distance and time

Differences with Previous Runway Exit Model

Item	Older Model (REDIM 2.1)	New Model (REDIM 3)
Wind information	Single wind speed and direction Airports have complex wind patterns	Landing observations are effected by local wind conditions Landing events database has wind speed and direction for each landing REDIM 3 designs for average wind conditions included in the landing speed distributions collected at 37 ASDE-X airports
Runway gradient	Ten values of local gradients along the runway Model will calculate the average gradient and apply a very small correction factor	Runways designed for commercial operations have limited gradients by regulation (0.8% in first quarter of runway and a maximum of 1.5%) The correction factor for such runways is very small We plan to investigate this issue in the future
Pavement conditions	50/50 wet dry default condition Wet pavement conditions reduce nominal deceleration	10/90 default condition in new model Rainfall data collected at selected airports provided the basis for the new default Wet pavement conditions reduce nominal deceleration
Safety factor	Turnoff safety factor (user defined)	The new model is based on extensive runway and runway exit data Observed runway exit speeds in the new model make the use of a safety factor in the turning maneuver unnecessary
Aircraft fleet	5 aircraft modeled directly (Douglas DC9-30, McDonnell Douglas MD-80, Boeing 727-200, Boeing 737-300 and Boeing 757-200) 70+ aircraft modeled indirectly based on landing distance parameters adjusted for airport elevation Aircraft performance adjusted for airport elevation and temperature Model assumed all landing roll distributions to be normally distributed truncated to 2.5 sigma	298 aircraft modeled Aircraft performance adjusted for airport elevation and temperature Landing roll distributions use Kernel Density Functions (KDE) for individual aircraft (functions of runway length and runway exit types) Model defaults to Aircraft Approach Group (AAC) category if a Kernel distribution does not exists for the aircraft in question

Runway Exit Model 4 : Aircraft Database

- 330 aircraft modeled (directly or indirectly)
- Improved database consistent with the updated FAA Aircraft Characteristics Database (ACD)
- Includes the latest generation of aircraft (Airbus 220-300, A320neo, Boeing 737-8Max, etc.)

Aircraft Design Group (ADG): III

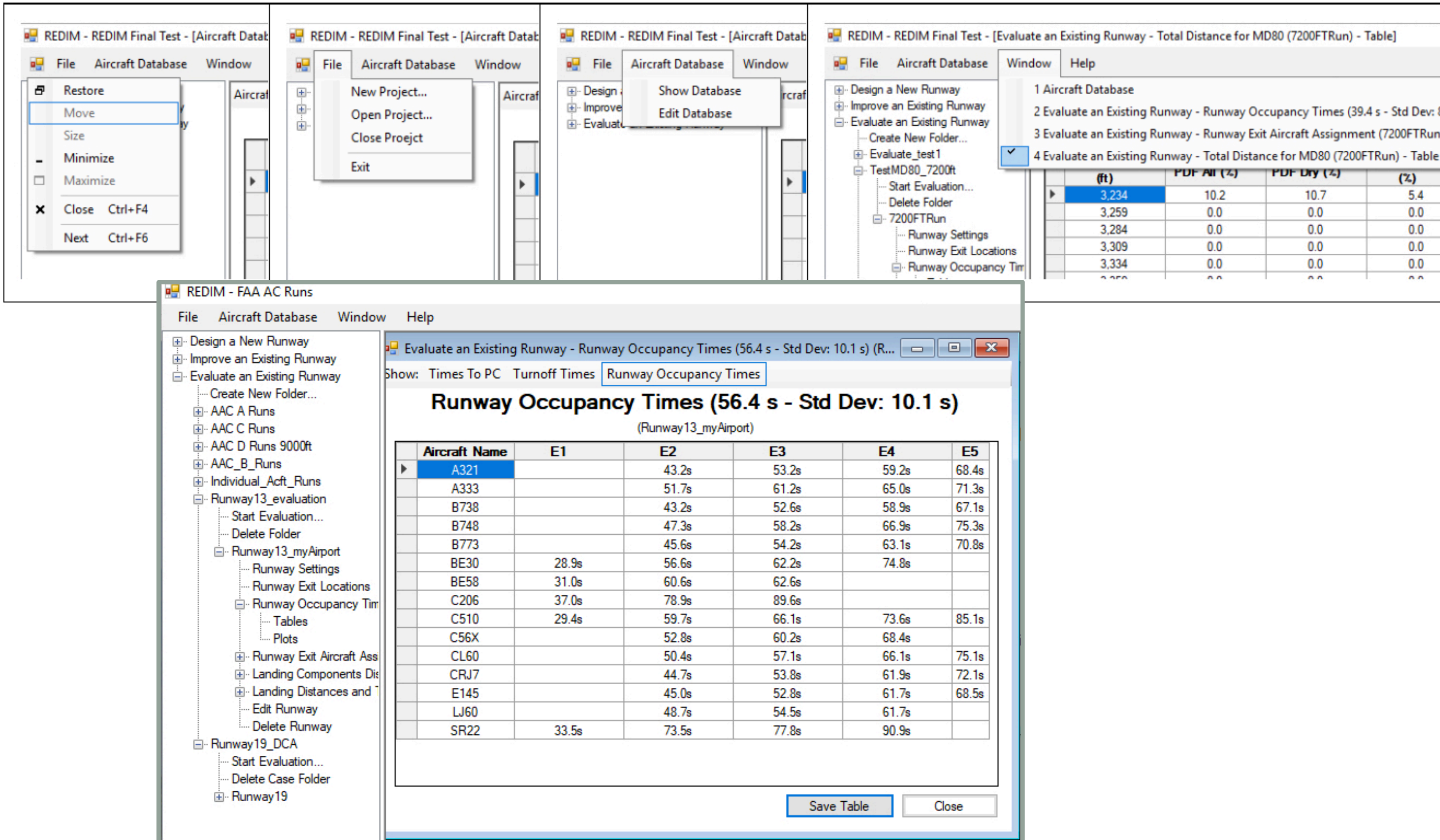
ADG III Aircraft

Aircraft ID	Aircraft Name	Engine Type	Aircraft Design Grou
A19N	Airbus A319 Neo	Jet	III
A20N	Airbus A320 Neo	Jet	III
A21N	Airbus A321 Neo	Jet	III
A318	Airbus A318	Jet	III
A319	Airbus A319	Jet	III
A320	Airbus A320	Jet	III
A321	Airbus A321	Jet	III
AT42	Aeropatiale ATR-42-200	Turboprop	III
AT43	Aeropatiale ATR-42-300	Turboprop	III
AT44	Aeropatiale ATR-42-400	Turboprop	III
AT45	Aeropatiale ATR-42-500	Turboprop	III
AT46	Aeropatiale ATR-42-600	Turboprop	III
AT71	Aeropatiale ATR-72-100	Turboprop	III
AT72	Aeropatiale ATR-72-200	Turboprop	III
AT73	Aeropatiale ATR-72-300	Turboprop	III
AT74	Aeropatiale ATR-72-400	Turboprop	III
AT75	Aeropatiale ATR-72-500	Turboprop	III
AT76	Aeropatiale ATR-72-600	Turboprop	III
B37M	Boeing 737 MAX 7	Jet	III
B38M	Boeing 737 MAX 8	Jet	III
B39M	Boeing 737 MAX 9	Jet	III

Aircraft Design Group (ADG): V

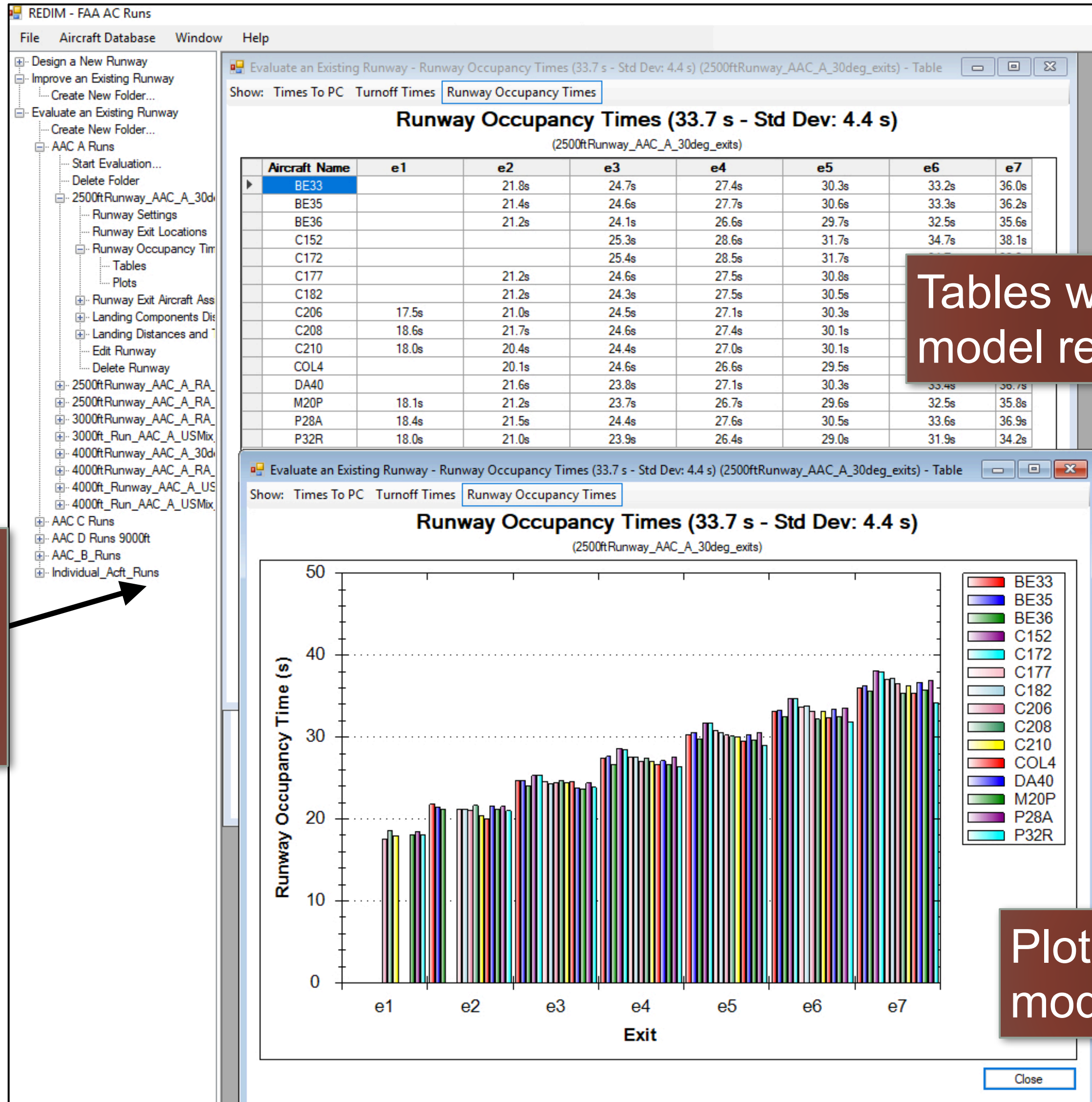
Aircraft ID	Aircraft Name	Engine Type	Aircraft Design Group
A332	Airbus A330-200	Jet	V
A333	Airbus A330-300	Jet	V
A337	Airbus A330-700 - Beluga XL	Jet	V
A338	Airbus A330-800	Jet	V
A339	Airbus A330-900	Jet	V
A342	Airbus A340-200	Jet	V
A343	Airbus A340-300	Jet	V
A346	Airbus A340-600	Jet	V
A359	Airbus A350-900	Jet	V
B742	Boeing 747-200	Jet	V
B744	Boeing 747-400	Jet	V
B772	Boeing 777-200	Jet	V
B773	Boeing 777-300	Jet	V
B77L	Boeing 777-200LR	Jet	V
B77W	Boeing 777-300ER	Jet	V
B788	Boeing 787-8	Jet	V
B789	Boeing 787-9	Jet	V

REDIM 4 Menu Structure



Aircraft Name	E1	E2	E3	E4	E5
A321		43.2s	53.2s	59.2s	68.4s
A333		51.7s	61.2s	65.0s	71.3s
B738		43.2s	52.6s	58.9s	67.1s
B748		47.3s	58.2s	66.9s	75.3s
B773		45.6s	54.2s	63.1s	70.8s
BE30	28.9s	56.6s	62.2s	74.8s	
BE58	31.0s	60.6s	62.6s		
C206	37.0s	78.9s	89.6s		
C510	29.4s	59.7s	66.1s	73.6s	85.1s
C56X		52.8s	60.2s	68.4s	
CL60		50.4s	57.1s	66.1s	75.1s
CRJ7		44.7s	53.8s	61.9s	72.1s
E145		45.0s	52.8s	61.7s	68.5s
LJ60		48.7s	54.5s	61.7s	
SR22	33.5s	73.5s	77.8s	90.9s	

Interface and Panels in the Runway Exit Design Model

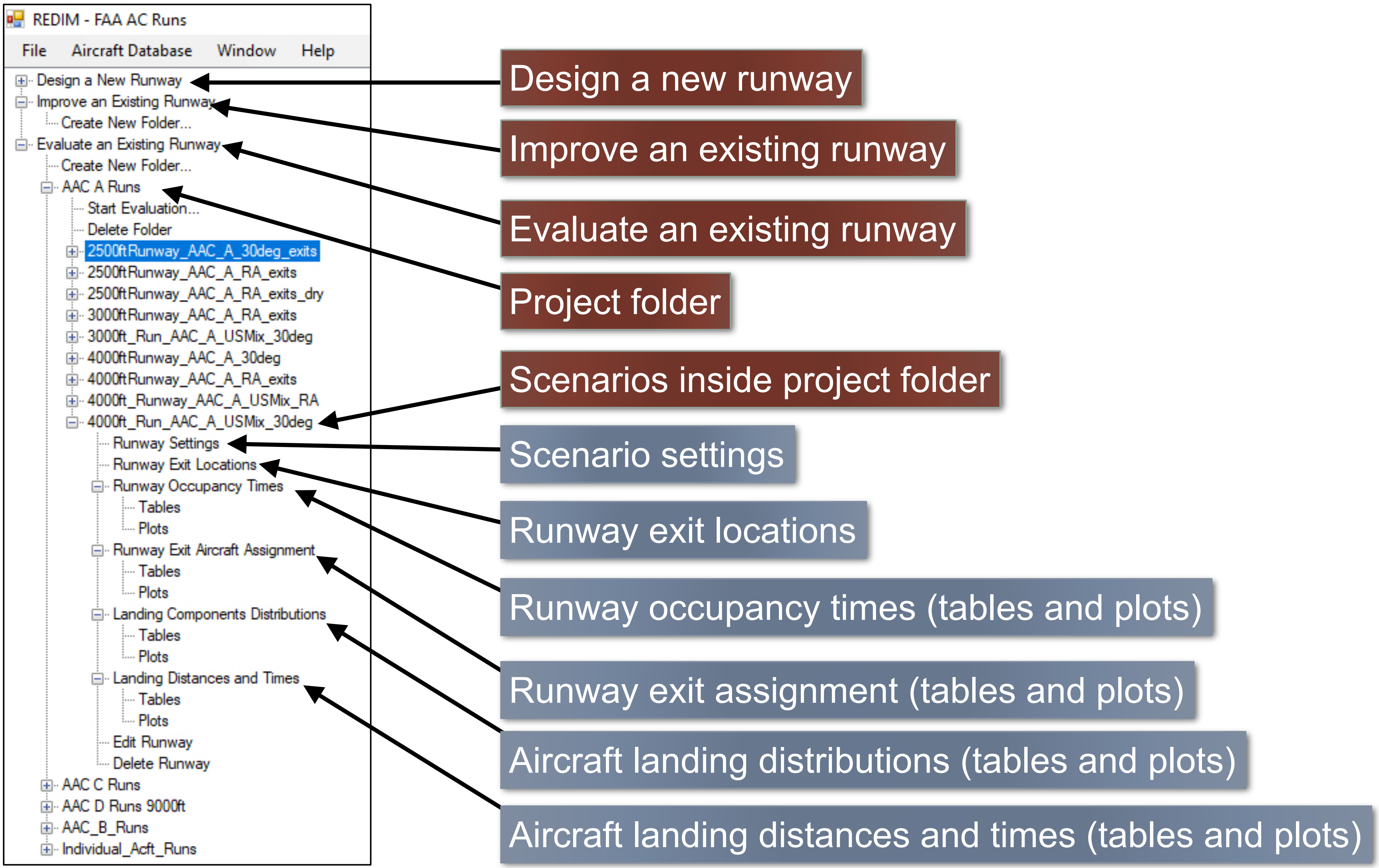


Tables with relevant model results

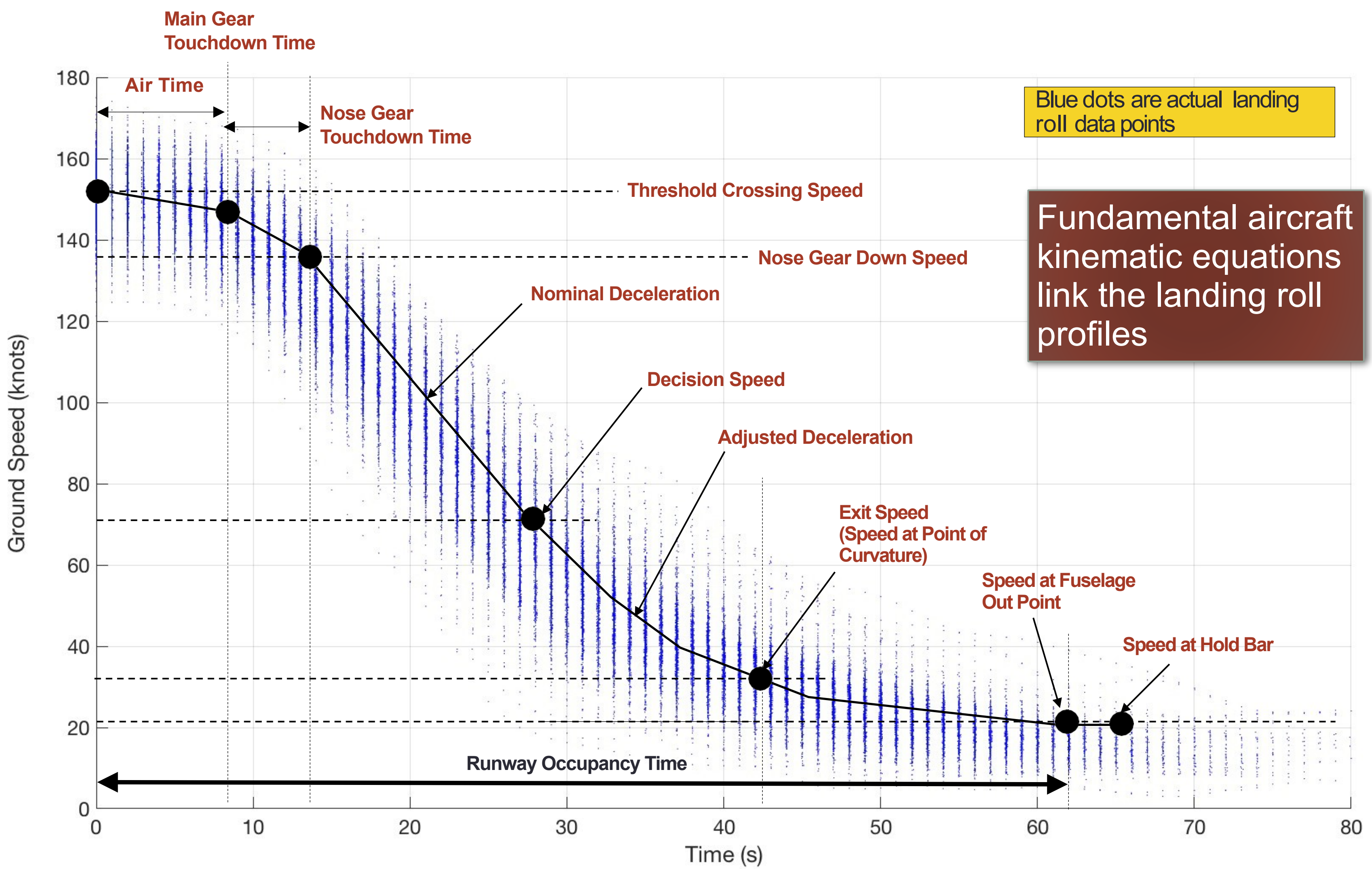
Navigation and project panel with information and results

Plots of relevant model results

Navigation/Project Panel Hierarchy



Runway Exit Model Landing Roll Profile Phases Modeled



Fundamental aircraft kinematic equations link the landing roll profiles

Runway Exit Model 4 Improvements: Runway Exit Data Handling

- REDIM offers default runway exits
- REDIM offers a detailed procedure to define custom runway exits using relative(x-y) or absolute coordinates (latitude-longitude)
- REDIM 4 can store runway exits in a runway exit database file

```
Name,Cartesian Exit Example
Radius_Units,ft
Radius,900
XY_Units,m
X,Y
0,0
26.671,2.015
42.047,3.688
57.997,5.654
72.971,8.734
97.812,15.907
113.304,21.596
125.011,26.633
138.622,33.627
152.282,41.414
164.893,49.682
177.397,59.000
292.216,161.161
```

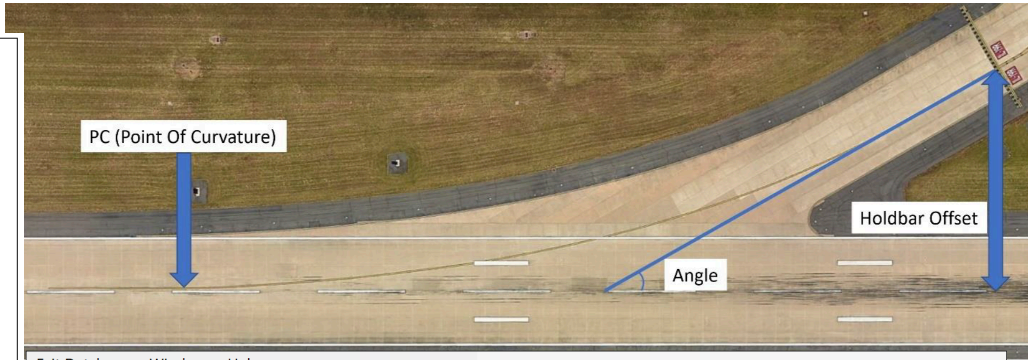
Notes:

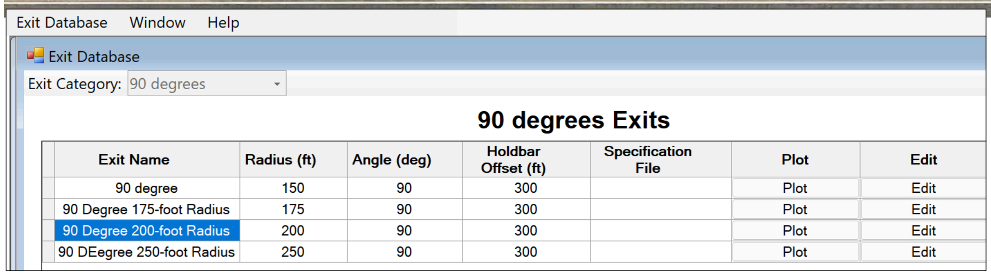
- The Point of Curvature (PC) is located at 0,0
- The orientation of the runway is along the x-axis.
- The direction of landing is from left to right.
- Possible units: m (meters) and ft (feet).

```
Name,LonLat Exit Example
Radius_Units,ft
Radius,900
XY_Units,lonlat
Runway_Azimuth_deg,41.3968450417015
Lon,Lat
-87.8833014762658,41.9669286085378
-87.8831069436841,41.9671207368017
-87.8829994220016,41.9672345446757
-87.8828899817503,41.9673539681213
-87.8827983987043,41.9674734340468
-87.8826651370843,41.9676839077378
-87.8825930378926,41.9678224048937
-87.8825452274012,41.9679314508081
-87.8824999334291,41.9680650192218
-87.8824614291183,41.9682036320656
-87.8824356467823,41.9683380281720
-87.8824202207222,41.9684779508170
-87.8824287593785,41.9698616096226
```

Notes:

- Possible radius units: m (meters) and ft (feet)
- The landing direction must be specified in degrees (Runway_Azimuth_deg).

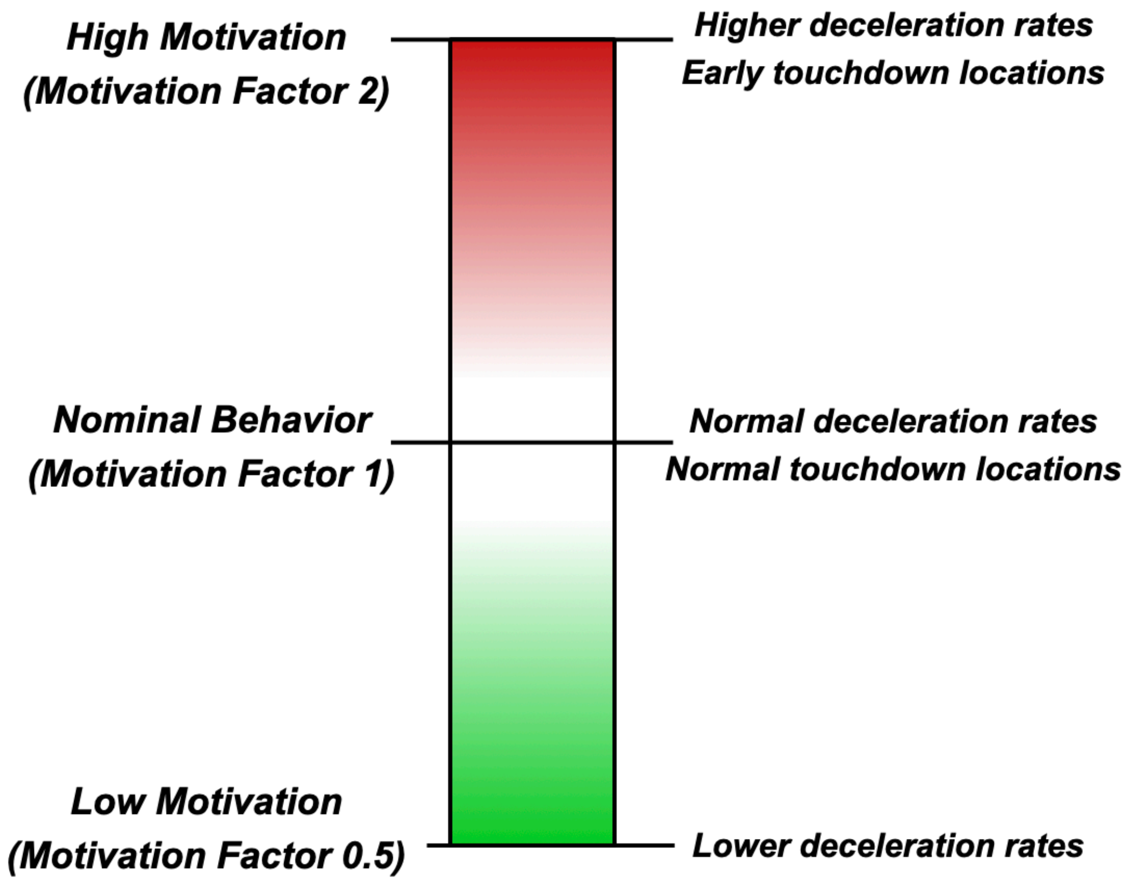




Exit Name	Radius (ft)	Angle (deg)	Holdbar Offset (ft)	Specification File	Plot	Edit
90 degree	150	90	300		Plot	Edit
90 Degree 175-foot Radius	175	90	300		Plot	Edit
90 Degree 200-foot Radius	200	90	300		Plot	Edit
90 DEegree 250-foot Radius	250	90	300		Plot	Edit

Pilot Motivation Factor

- We developed methods to characterize pilot motivation through statistical analyses of individual aircraft data
  - Deceleration rates
  - Touchdown distances
- Briefed a group of pilots invited by the FAA to understand factors that lead to pilot motivation
- All motivation factors provided in the **model are within the kinematic capabilities of each aircraft**



Motivation Factor in the REDIM 4 Model Interface

Evaluate an Existing Runway - Step 2 - Define Aircraft Mix for New Runway

Step 2: Define Aircraft Mix for New Runway

Only provide the aircraft mix for the left or right side of the runway you are modeling.

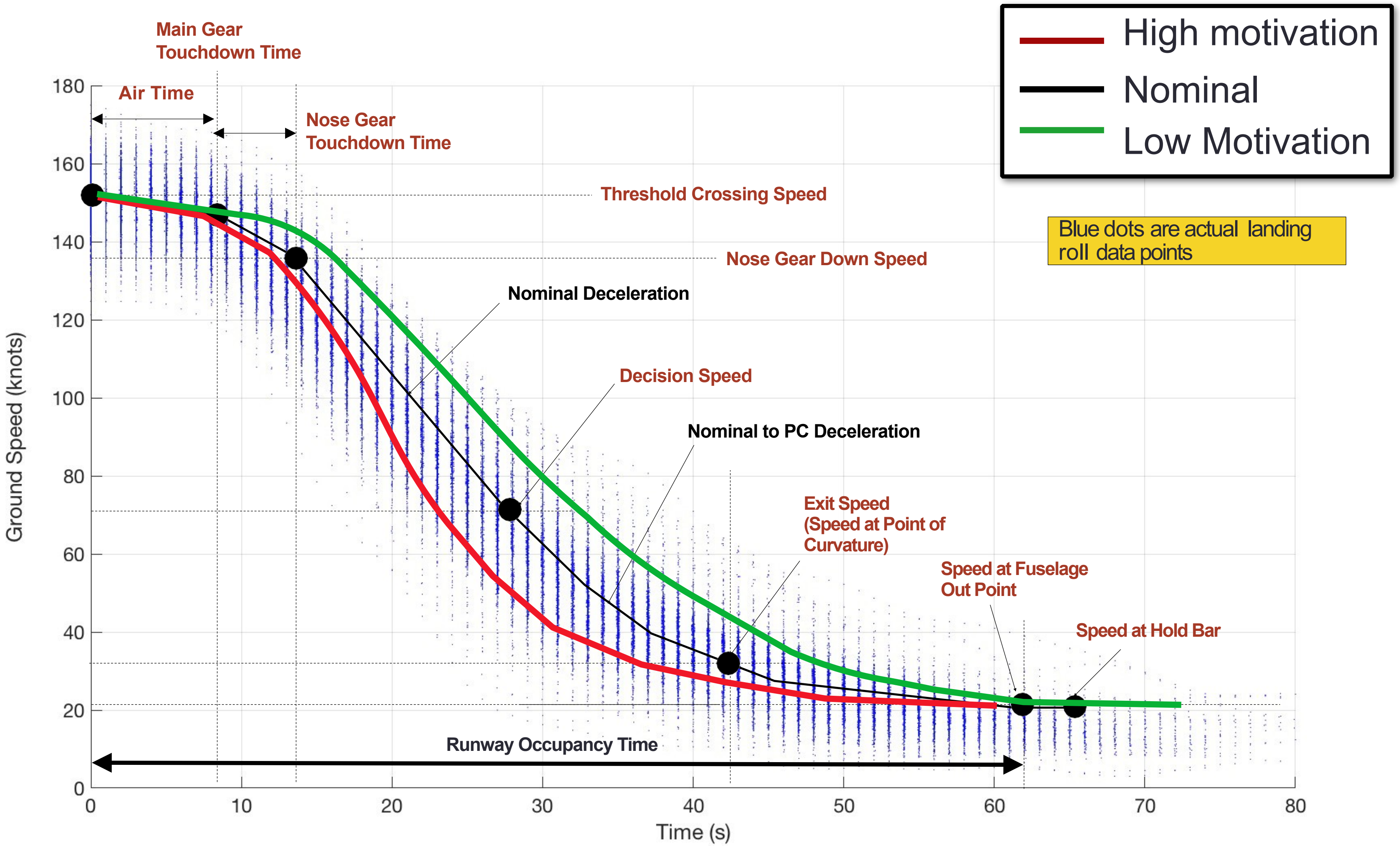
Aircraft ID	Aircraft Name	Aircraft Design Group	Aircraft Approach Category	Aircraft Mix (%)	Motivation Factor
AT76	Aeropatiale ATR-72-600	III	B		1
B37M	Boeing 737 MAX 7	III	C		1
B38M	Boeing 737 MAX 8	III	D	25	2
B39M	Boeing 737 MAX 9	III	D		1
B712	Boeing 717-200	III	C		1
B721	Boeing 727-100	III	C		1
B722	Boeing 727-200	III	C		1
B733	Boeing 737-300	III	C	25	2
B734	Boeing 737-400	III	C		1
B735	Boeing 737-500	III	C		1
B736	Boeing 737-600	III	C		1
B737	Boeing 737-700	III	C	25	2
B738	Boeing 737-800	III	D	25	2
B739	Boeing 737-900	III	D		1
BCS1	Airbus A220-100	III	C		1
C55B	Cessna Citation Bravo	III	B		1
CRJ9	Bombardier CRJ 900	III	C		1
DC91	Douglas DC-9-10	III	C		1
DC93	Douglas DC-9-30	III	C		1
DH8B	DeHavilland Canada Dash8-200	III	B		1
DH8C	DeHavilland Canada Dash8-300	III	B		1

Total aircraft mix allocated: 100%

Load | Save | Cancel | <- Previous | Next ->

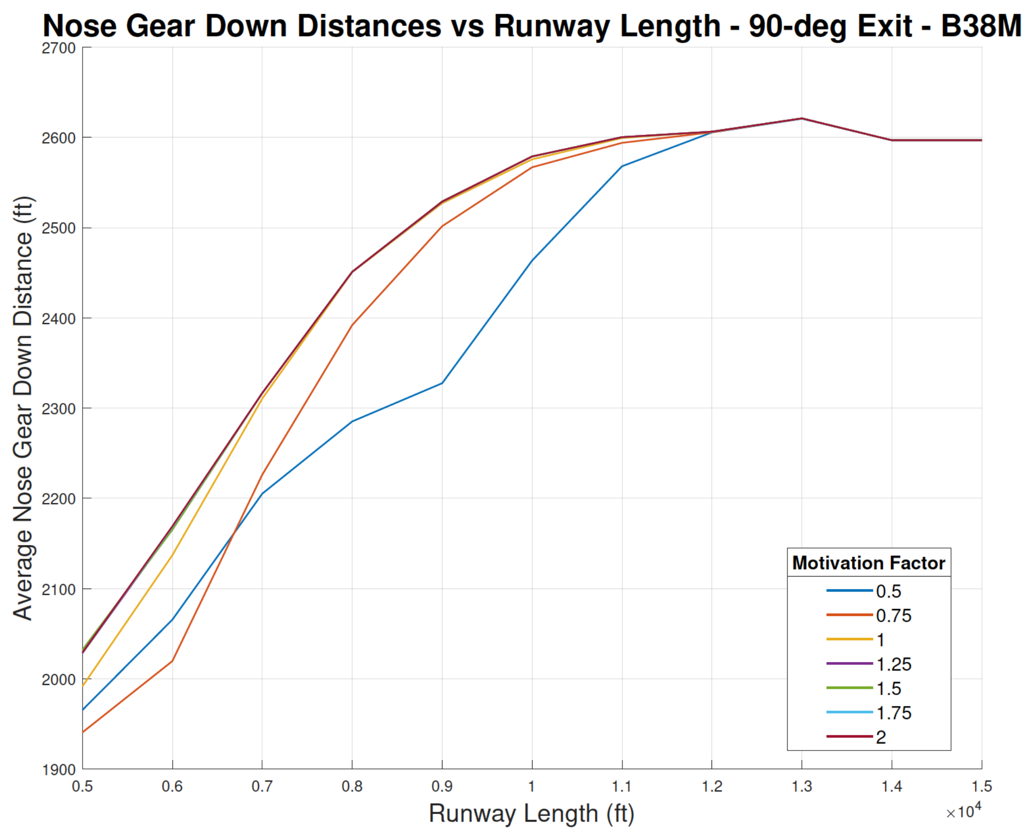
During the landing simulation, Boeing 737-700 will use a motivation factor of 2.0 (high motivation)

Landing Roll Profiles versus Pilot Motivation

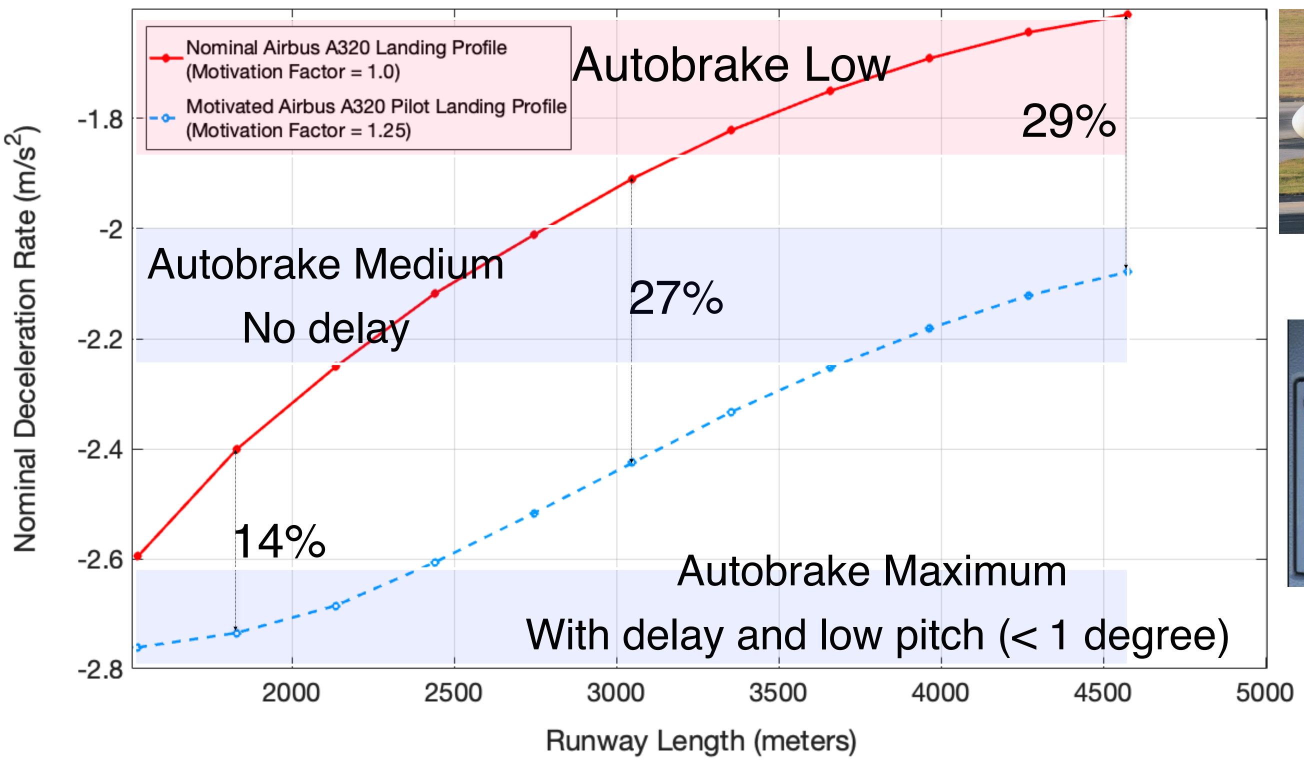


Pilot Motivation in the REDIM 4 Model Starts with Modified Touchdown Locations

- The natural trend of touchdown locations is built into the model based on actual data
  - Short runways produce early touchdown locations
- High motivation factors above 1.5 may reduce the touchdown location by 120-150 feet (~4.8%) on a 8,000-foot runway



Pilot Motivation Factor Effect on Nominal Deceleration Rate Spread Between MF 1 and MF 1.25 Averages 20% for Runways Up to 3,050 meters (10,000 feet)

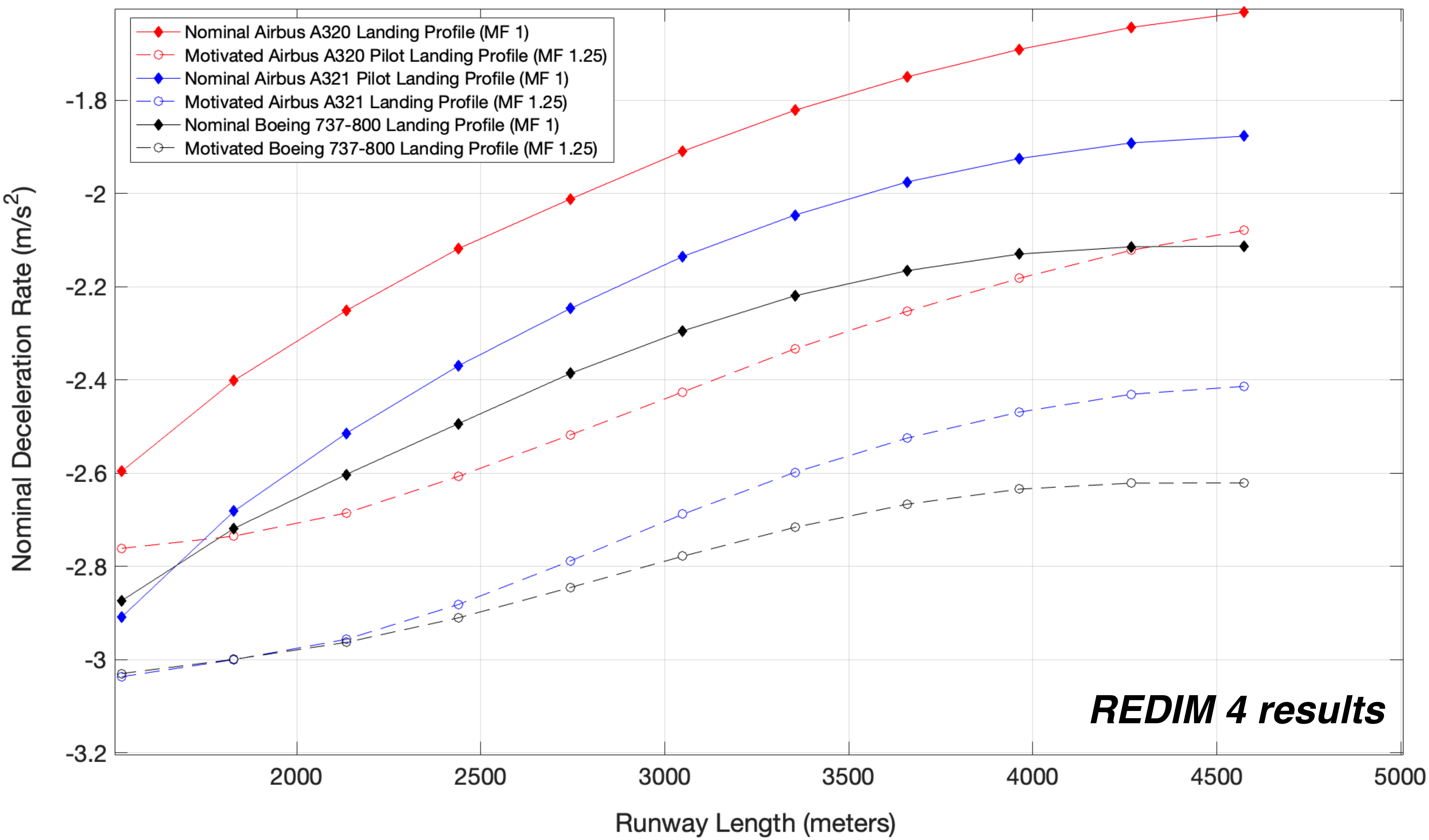


Airbus A320

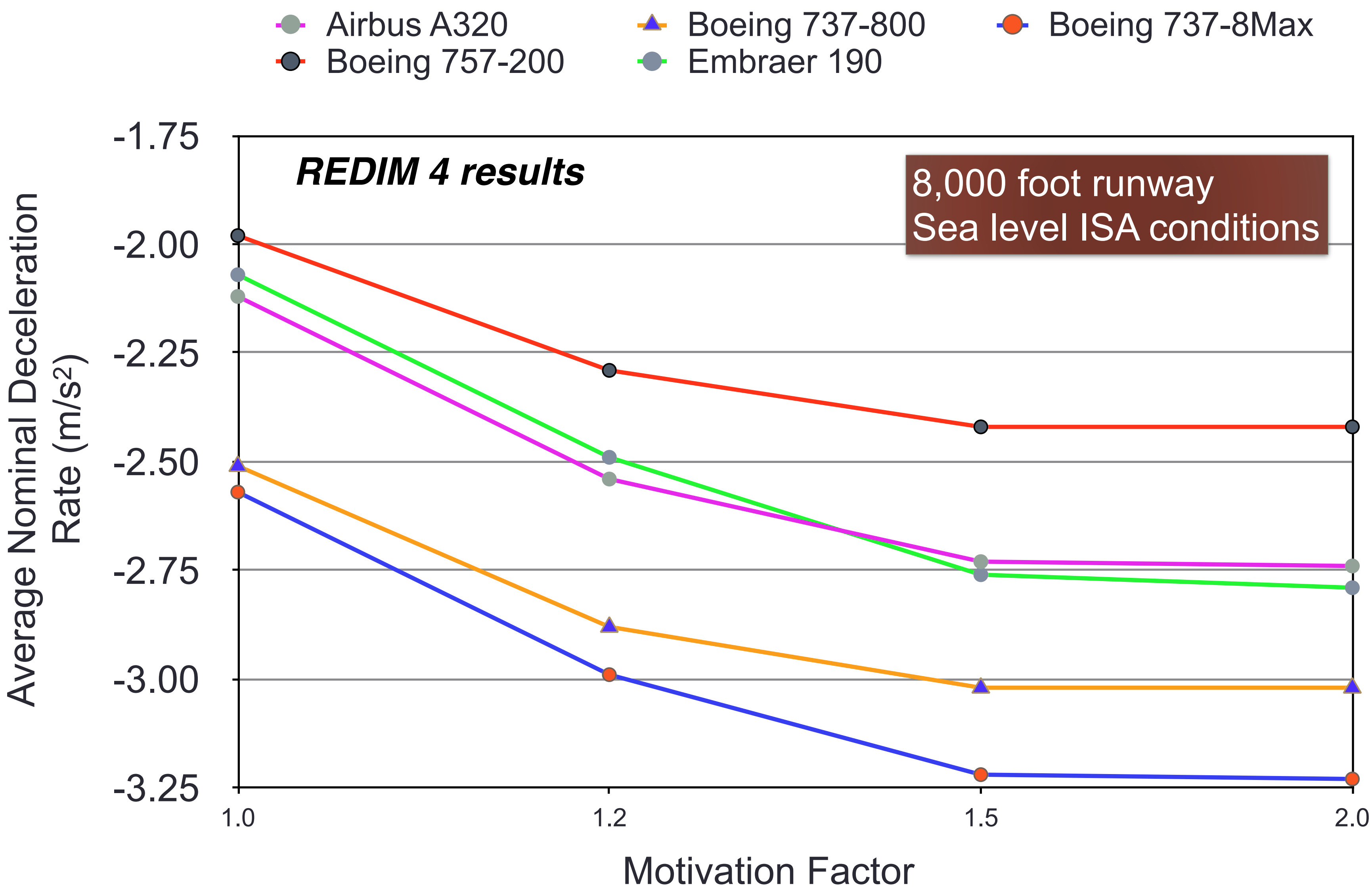
Airbus A320 Autobrake Panel

(https://docs.flybywiresim.com/pilots-corner/a32nx-briefing/flight-deck/front/autobrake-gear/)

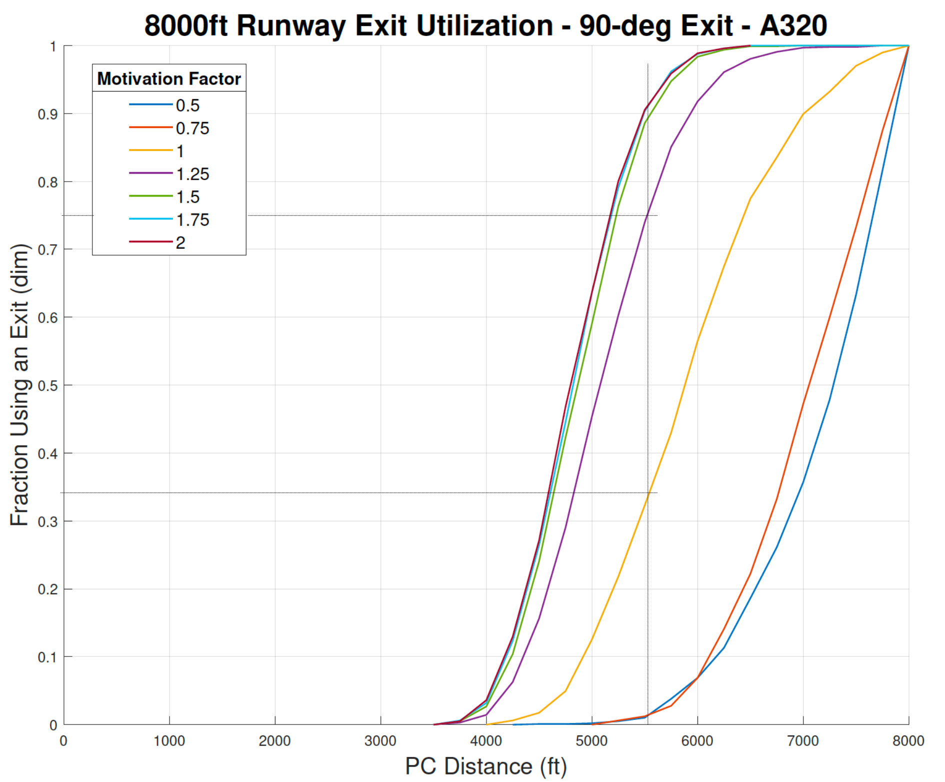
Nominal Deceleration Rate and Pilot Motivation Factor



Nominal Deceleration Rate and Pilot Motivation Factor



Practical Implications of Changing the Pilot Motivation Factor on a 2,440-meter (8,000 feet) Runway



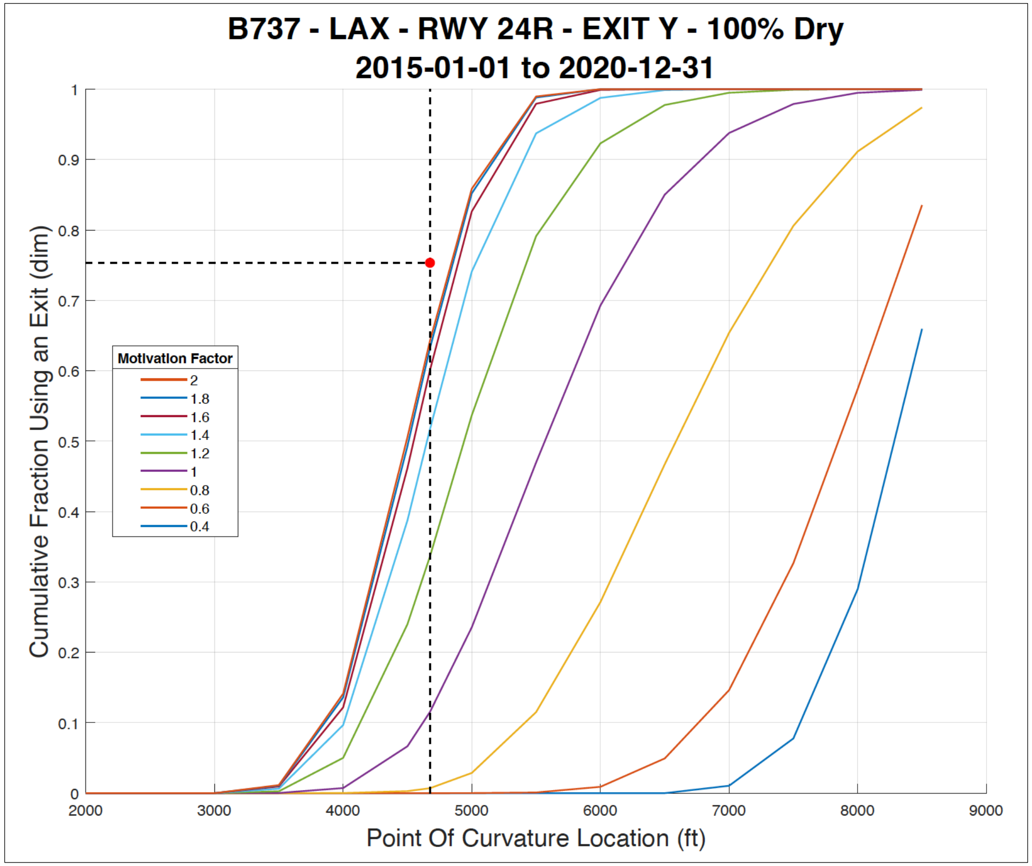
Increasing the pilot motivation factor from 1.0 to 1.25 doubles the cumulative runway exit probability of right-angle exits at a location 5,500 feet along the runway.

Airbus A320

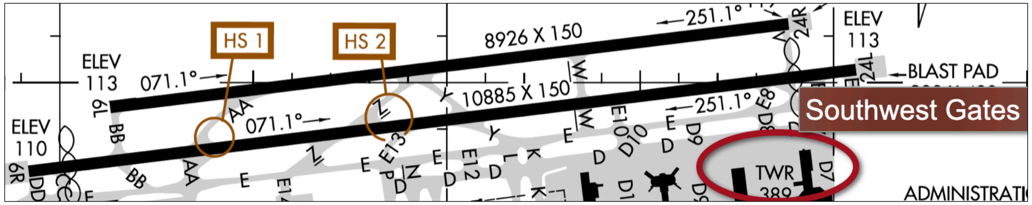
Example Motivation Factors at Selected Airports

- Practical examples of how to translate motivation factor (MF) to real-world landing performance
  - Los Angeles Runway 24R
  - LaGuardia Runway 31
- REDIM model motivation factor guidance for model users

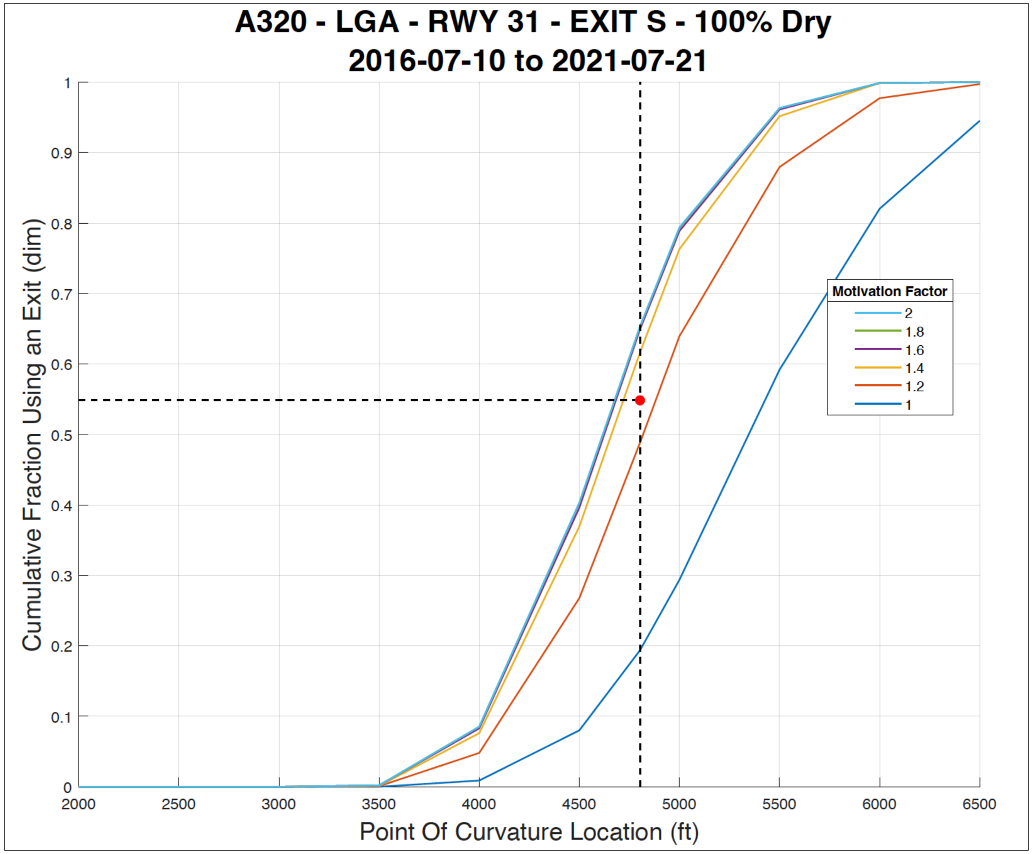
77.5% of Motivated Pilots of Boeing 737-700 Landings Exit at Yankee (Y)



- A case of very high pilot motivation
- Motivation factor slightly higher than 2
- Nominal deceleration rate for a Boeing 737-700 landing on a 9,000 foot runway is 2.05 m/s^2
- Observed deceleration rate of 2.69 m/s^2 on runway 24R by one motivated airline
- Upper bound pilot motivation factor in the REDIM model is 2

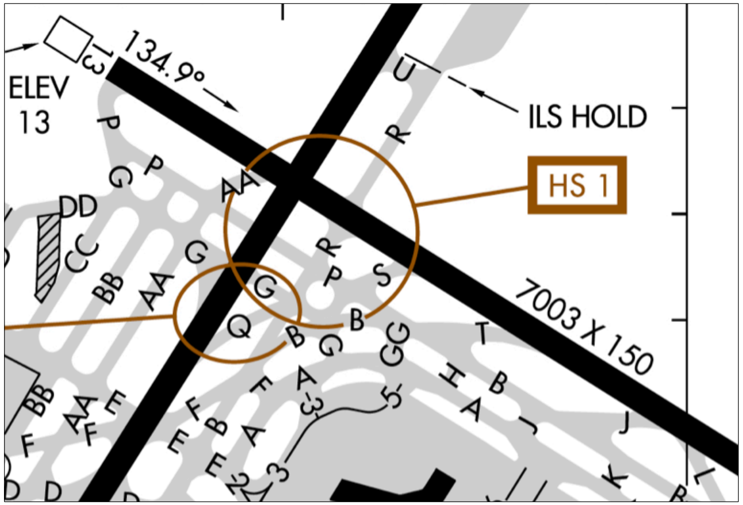


55% of Airbus A320 Landings at LGA Runway 31 Use Exit Sierra (S)



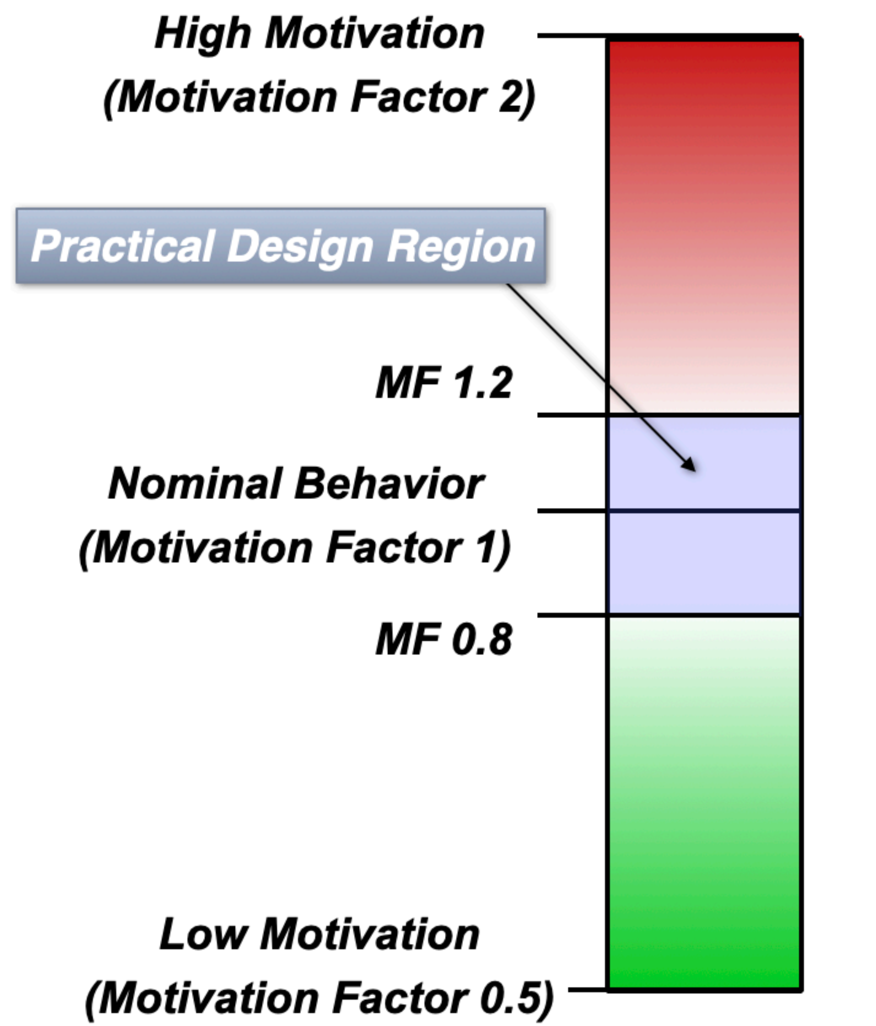
7,003 foot runway
2017-2020 Data

- A case of higher than nominal pilot motivation
- Pilots are motivated is to avoid crossing runway 4/22 while landing on runway 31
- Observed motivation factor is ~1.25



Recommended Guidance for Motivation Factors

- REDIM 4 is designed to predict nominal landing roll behavior on a runway with a motivation factor MF 1.0
- High motivation factors are observed at some U.S. airports (MF 1.25 or higher)
- Practical design guidance should limit the placement of runway exits using MF factors between 0.8 and 1.2 to avoid high deceleration rates that may not be desirable in real-world commercial operations
  - Higher maintenance costs due to heavy braking
  - Passenger comfort
- For narrow-body aircraft, a motivation factor of 1.2 translates into 15-20% increase in deceleration rates compared to the nominal landing conditions



Runway Exit Design Tool (REDIM Model) Resources

Download REDIM 4

- REDIM 4.0.0 - Windows Installer
- User Group
- User Manual
- FAQs
- Change Log

Download Landing Events Database

- Landing Events Database 1.3.7 - Windows Installer
- User Manual

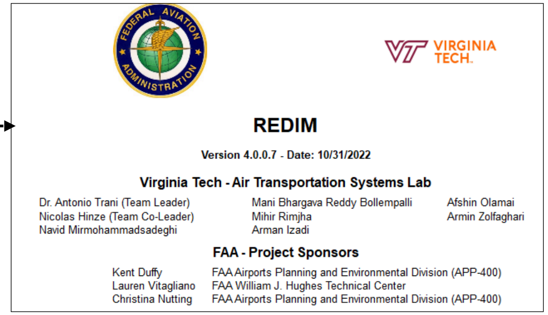
Detailed Documentation for REDIM 4

- Aircraft Database
- Exit Clusters

Webinars

- 3/16/2022: Presentation - Video
- 6/8/2021: Presentation - Video
- 6/18/2020: Presentation - Video

1.9 GB installer

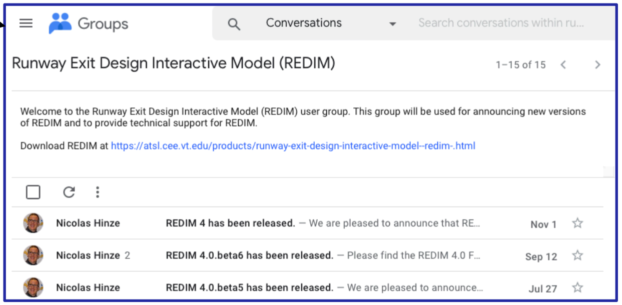


Runway Exit Design Interactive Model (REDIM)

User Guide

Version 4

10/31/2022



Runway Exit Design Model User Group

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

Example Use of the REDIM Model
Runway Evaluation

Runway Evaluation Scenario: Fleet Mix

Aircraft	Fleet Mix (%)	Picture
Cirrus SR22	10	
Cessna Latitude (C680A)	10	
Airbus A320	25	
Boeing 737-800	35	
Boeing 787-8	20	

Runway Evaluation Scenario: Runway Exits

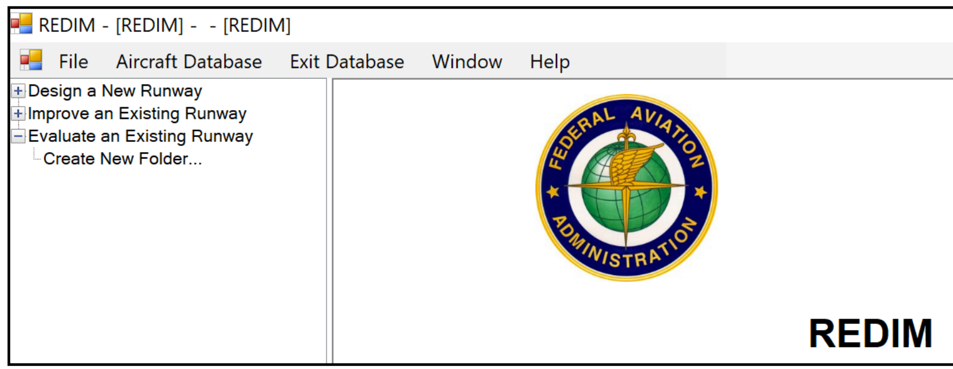
Runway Exit	Location (feet)	Exit Type
Alpha	1500	Right-angle
Bravo	3000	Right-angle
Charlie	5000	Acute-angle (R-CL 1500 feet)
Delta	6200	Acute-angle (R-CL 1500 feet)
Echo	8000	Right-angle
Foxtrot	8900	Right-angle

Runway length = 9000 feet
Airport elevation = 3,200 feet
Design temperature = 80 deg. F.
90% dry pavement, 10% wet pavement

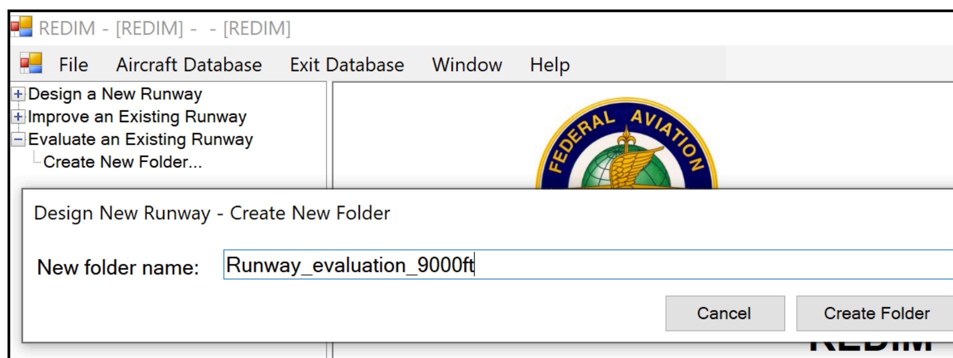
Step by Step Instructions (1)

Step 1: Create a new project

Step 2: Evaluate an Existing Runway

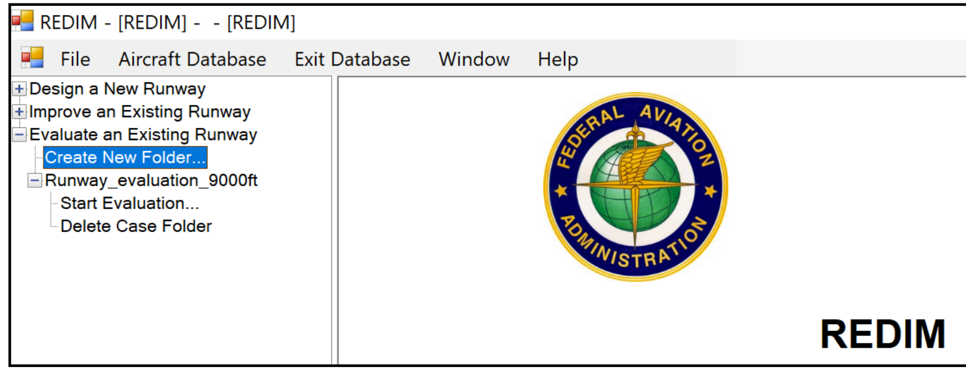


Step 3: Create a new folder name

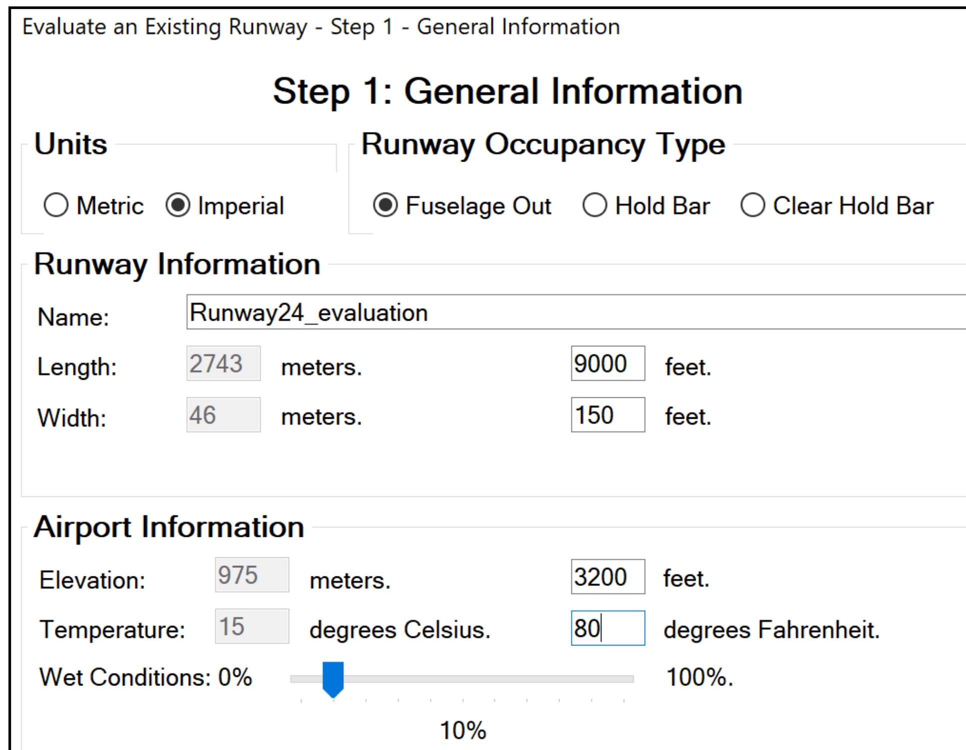


Step by Step Instructions (2)

Step 4: Start the runway evaluation



Step 5: Define airport conditions



Step by Step Instructions (3)

Step 6: Define the fleet mix
Only enter aircraft that are part of the fleet mix

Evaluate an Existing Runway - Step 2 - Define Aircraft Mix for New Runway

Step 2: Define Aircraft Mix for New Runway

Only provide the aircraft mix for the left or right side of the runway you are modeling.

Aircraft ID	Aircraft Name	Aircraft Design Group	Aircraft Approach Category	Aircraft Mix (%)
B737	Boeing 737-700	III	C	
B738	Boeing 737-800	III	D	35
B739	Boeing 737-900	III	D	
B73Q	Boeing 737-200 Quick Conversion	III	C	
BCS1	Airbus A220-100	III	C	

Step 7: Define runway exits

Evaluate an Existing Runway - Step 3 - Exits

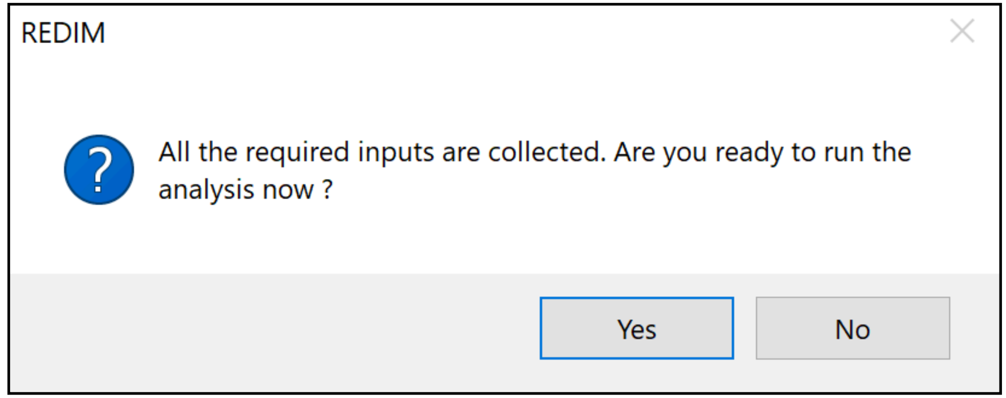
Step 3: Exits

Only specify exits on the left or right side of the runway you are modeling.

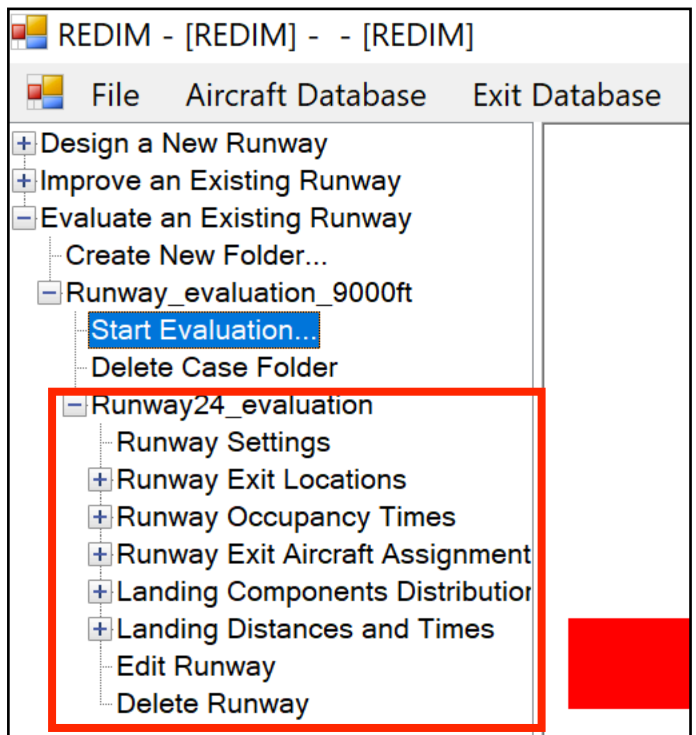
Name	Point Of Curvature Location (ft)	Geometry	Open
Alpha	1500	90 degree	☑
Bravo	3000	90 degree	☑
Charlie	5000	30 degree High Speed	☑
Delta	6200	30 degree High Speed	☑
Echo	8000	90 degree	☑
Foxtrot	8900	90 degree	☑
*			☐

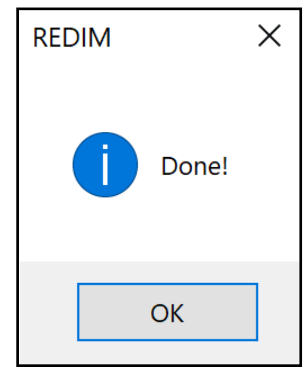
Step by Step Instructions (4)

Step 8: Ready to run the case

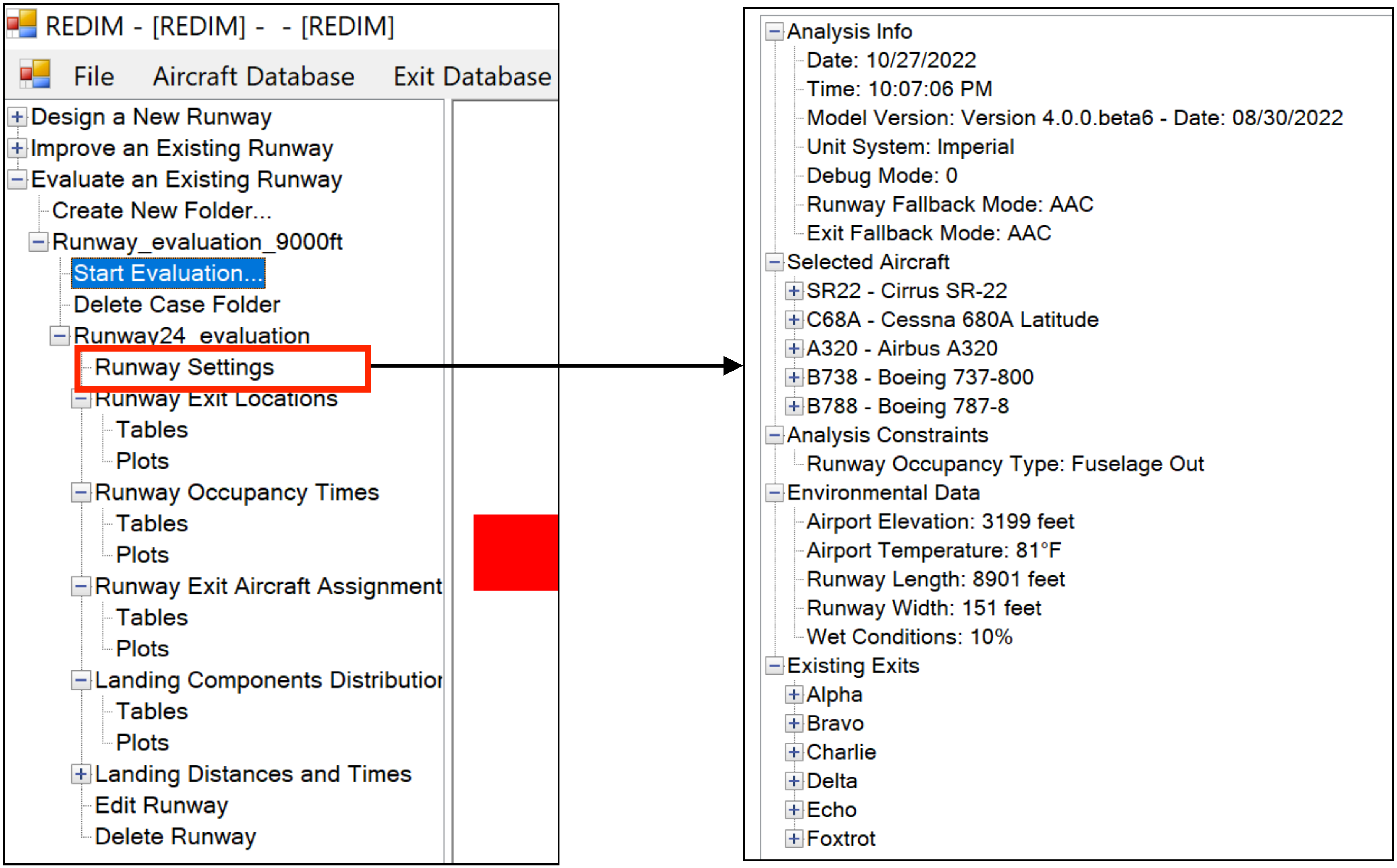


Step 9: Check the outputs

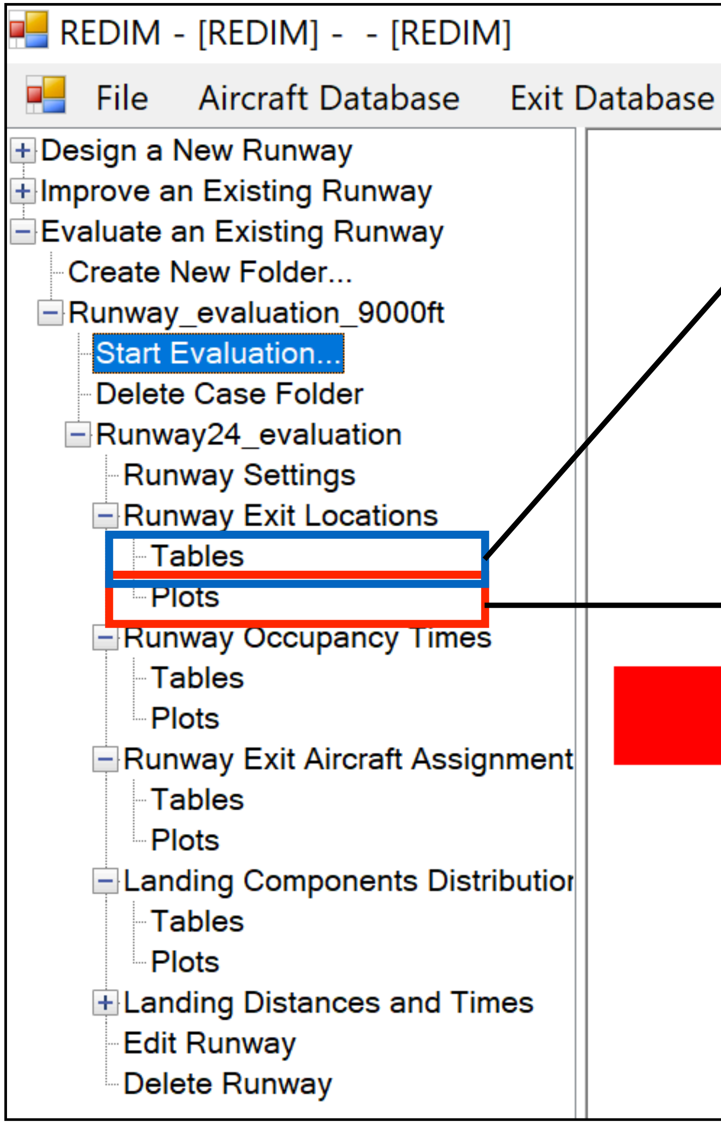




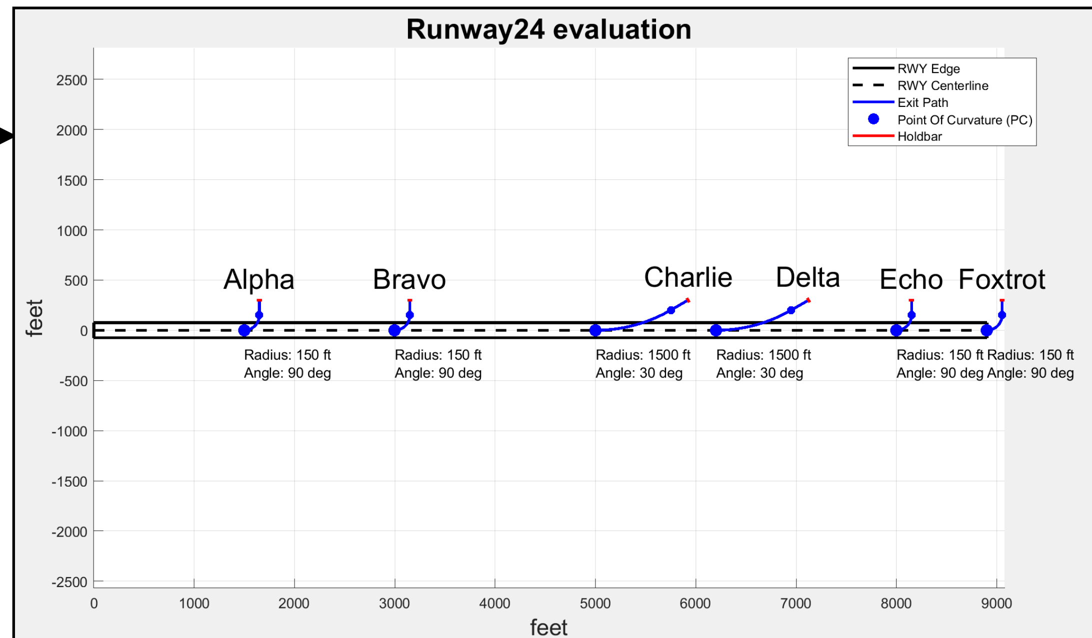
Step by Step Instructions (5)



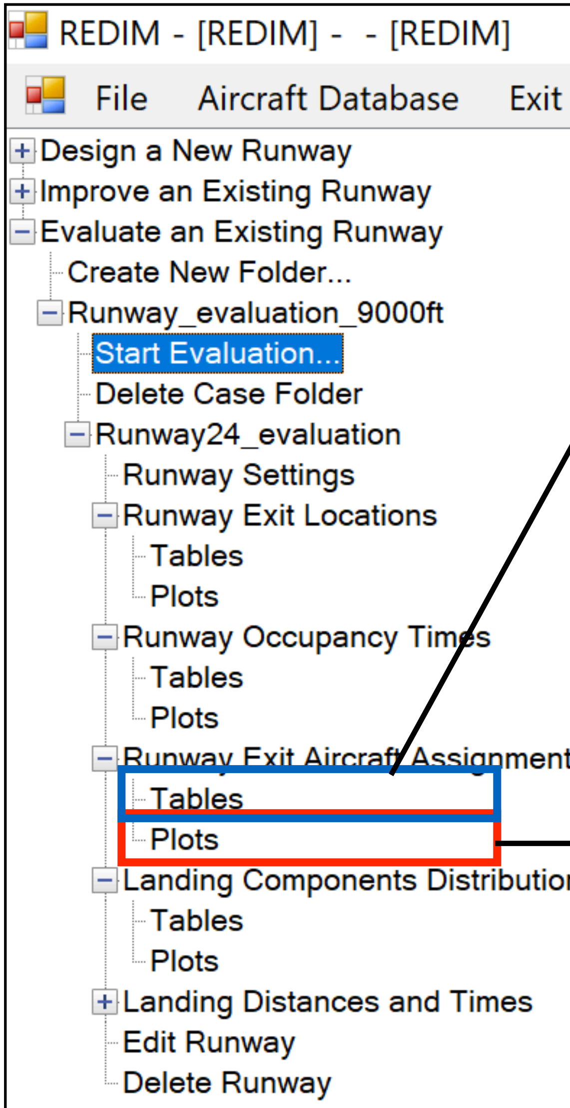
Step by Step Instructions (6)



Exit	Exit Status	Exit Geometry	Point Of Curvature Location (ft)
Alpha	Open	90 degree	1,499
Bravo	Open	90 degree	2,999
Charlie	Open	30 degree High Speed	5,000
Delta	Open	30 degree High Speed	6,201
Echo	Open	90 degree	7,999
Foxtrot	Open	90 degree	8,901



Step by Step Instructions (7)

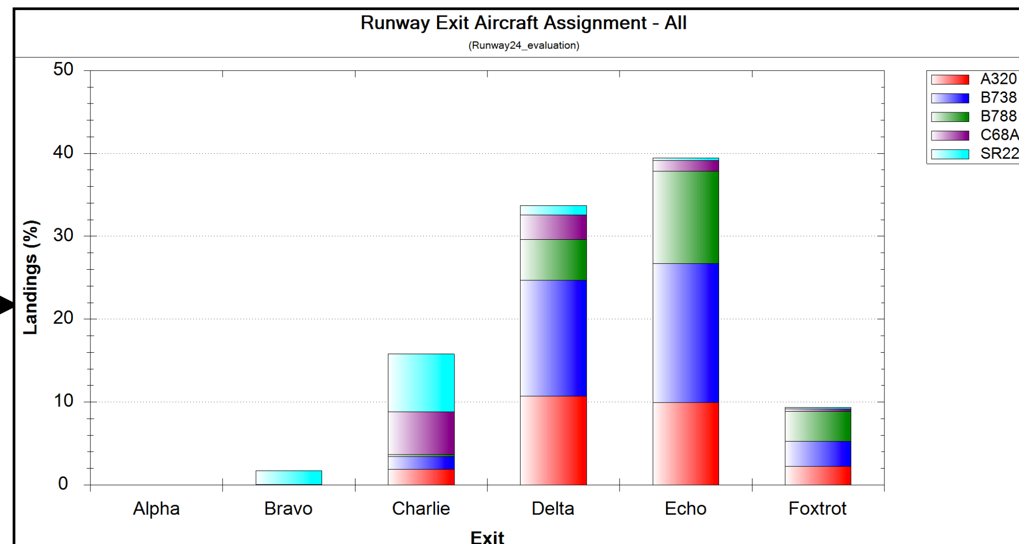


Runway Exit Aircraft Assignment - All

(Runway24_evaluation)

Aircraft Name	Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Aircraft Mix
A320			7.7%	43.2%	40.1%	9.0%	24.8%
B738			4.3%	39.6%	47.5%	8.6%	35.4%
B788			1.2%	24.6%	56.1%	18.1%	19.8%
C68A		0.6%	52.5%	30.3%	13.3%	3.3%	9.9%
SR22	0.1%	16.2%	68.6%	11.2%	2.7%	1.3%	10.1%
Exit Mix	0.0%	1.7%	15.8%	33.7%	39.4%	9.3%	

Example: 43.2% of Airbus A320s use runway exit Delta



VirginiaTech
Invent the Future

Step by Step Instructions (8)

REDIM - [REDIM] - - [REDI...

File Aircraft Database

- + Design a New Runway
- + Improve an Existing Runway
- − Evaluate an Existing Runway
  - Create New Folder...
  - − Runway_evaluation_9000ft
    - Start Evaluation...
    - Delete Case Folder
    - − Runway24_evaluation
      - Runway Settings
      - − Runway Exit Locations
        - Tables
        - Plots
      - − Runway Occupancy Times
        - Tables
        - Plots
      - − Runway Exit Aircraft Assignment
        - Tables
        - Plots
      - − Landing Components Distributior
        - Tables
        - Plots
      - + Landing Distances and Times
      - Edit Runway
      - Delete Runway

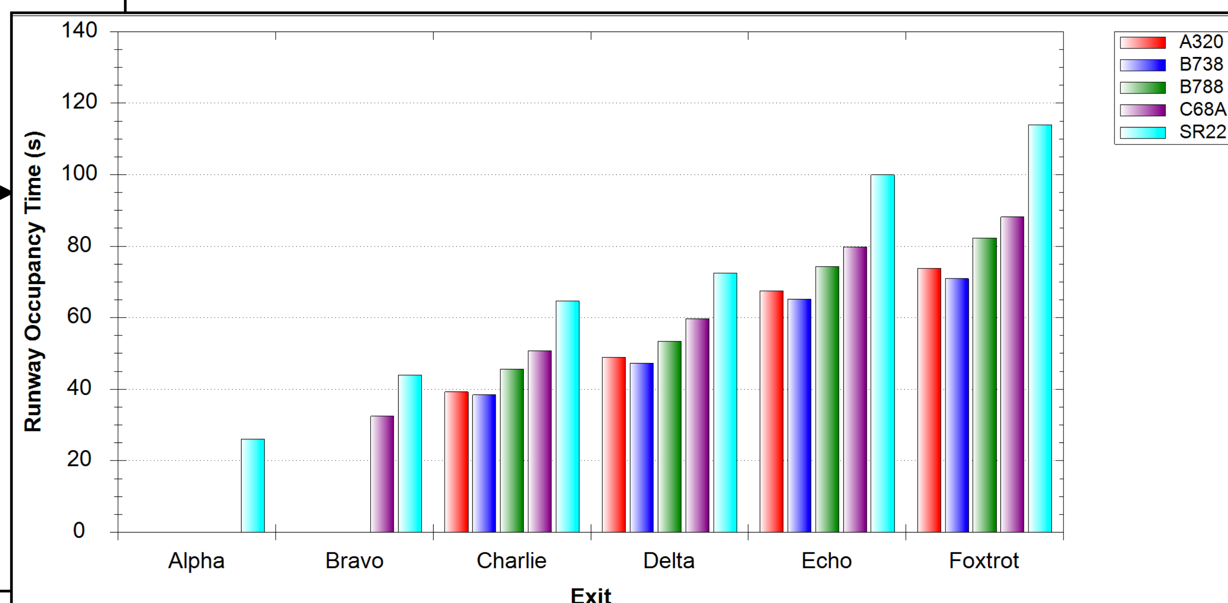
Show: Times To PC Turnoff Times Runway Occupancy Times Surface Condition: All

Runway Occupancy Times (60.8 s - Std Dev: 13.2 s) - All

(Runway24_evaluation)

Aircraft Name	Alpha	Bravo	Charlie	Delta	Echo	Foxtrot
A320			39.3s	48.9s	67.5s	73.8s
B738			38.4s	47.2s	65.2s	70.9s
B788			45.6s	53.3s	74.3s	82.3s
C68A		32.4s	50.8s	59.6s	79.8s	88.2s
SR22	26.1s	44.0s	64.7s	72.5s	100.0s	114.0s

Example: ROT for Boeing 737-800 using runway exit Delta is 47.2 seconds



Conclusions

- Airport is located at medium elevation
  - Higher approach speeds (result in longer landing roll out distance)
- Weighted average runway occupancy time is 60.2 seconds
  - Standard deviation of ROT is 13.2 seconds (high)
- High-speed runway exit “Charlie” is underused (16% of time)
- If this was a design exercise, we could move Charlie to 6,000 feet and Delta to 7,000 feet
  - Both acute angle exits could handle 42% and 33% of the traffic, respectively
  - Reduces ROT by a couple of seconds

Virginia Tech Invent the Future

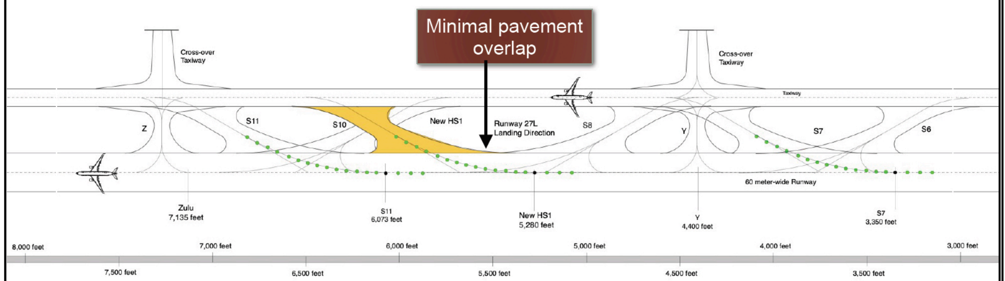
Another Example
Runway Exit Improvements for PHL Airport
Using the REDIM 4.0 Model

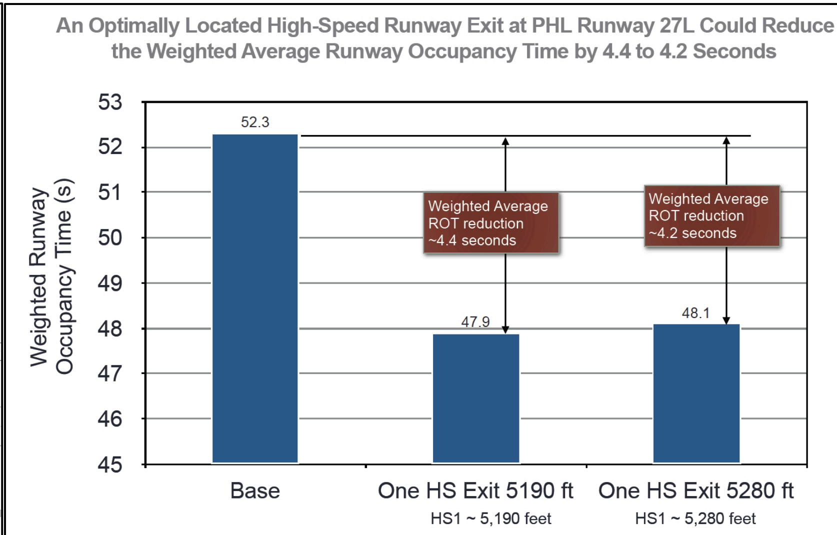
Application of the Runway Exit Design Tool to PHL

Scenario	Location of New Optimal High-Speed Exit (ft)	Wet/Dry Mix (%/%)	Remarks
Baseline	Not applicable	10/90	Open exits: U, S7, Y, S9, S11, S12 and S13
One High-Speed Runway Exit, 10/90	5,190	10/90	Open exits: U, S7, Y, NewHS1, S11, S12 and S13
One High-Speed Runway Exit, 20/80	5,280	20/80	Open exits: U, S7, Y, NewHS1, S11, S12 and S13

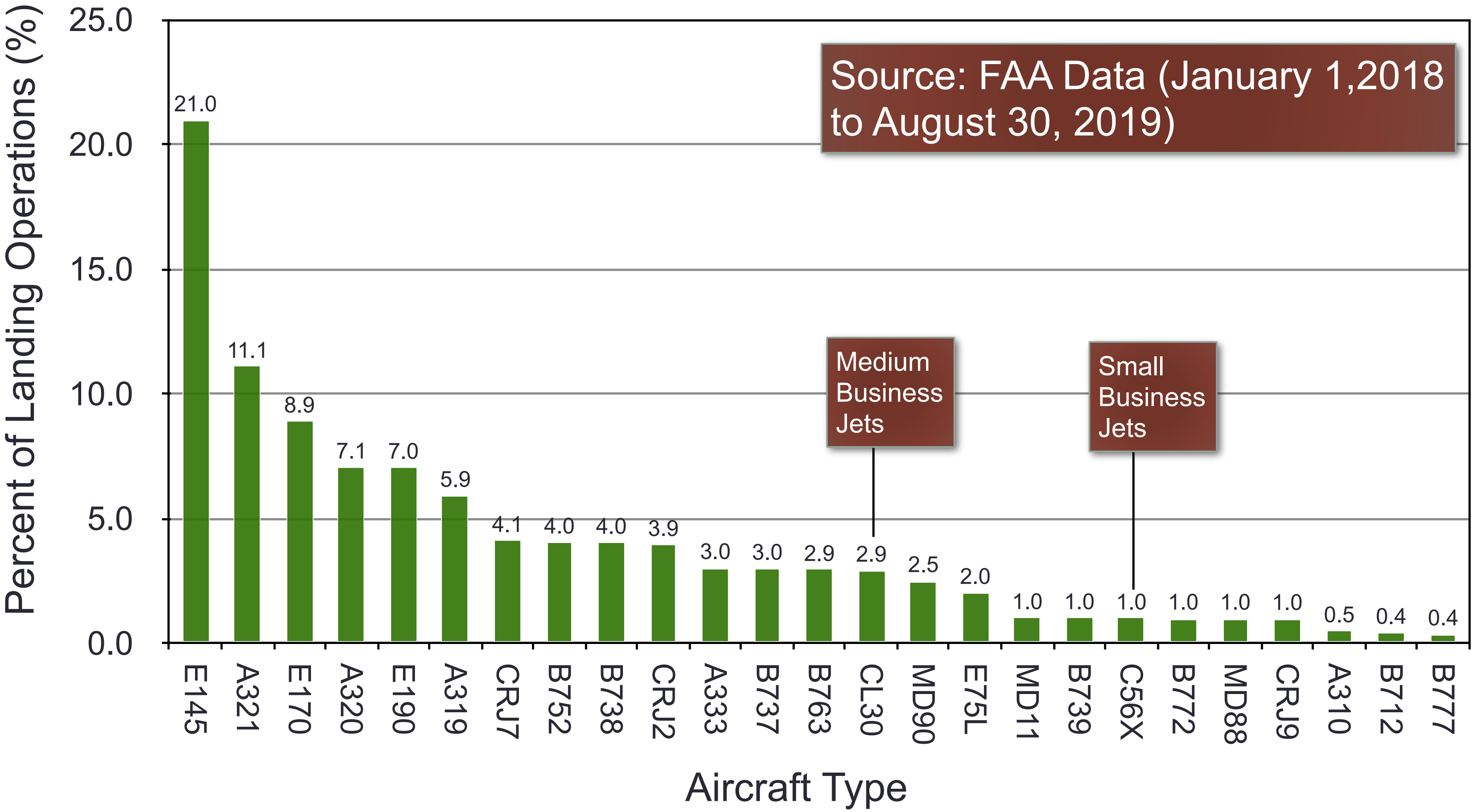
- Optimal location of a **new High-Speed Runway exit** designed for 20/80% wet/dry pavement conditions is **5,280 feet** (point of curvature)
- Runway exit Sierra-9 is eliminated
- **793 feet** - distance between new exit high-speed exit HS2 and Sierra-11

Optimally located runway exit in yellow





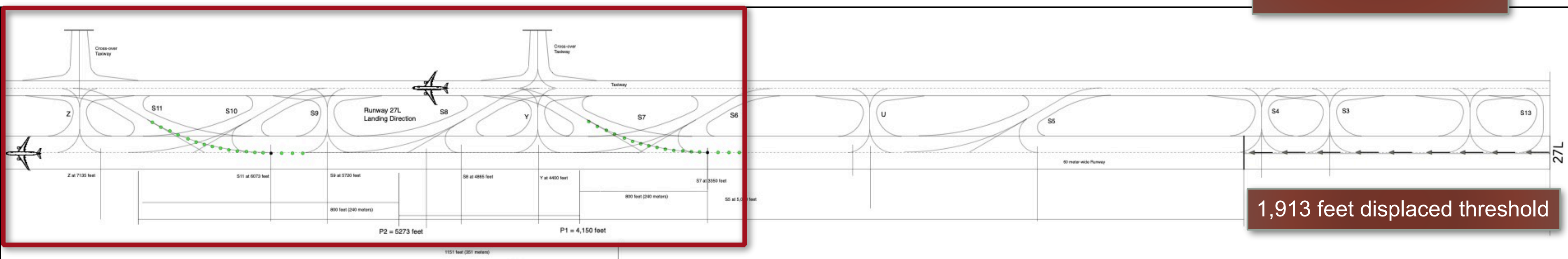
Airport Fleet Mix Used in the Analysis of Runway 27L

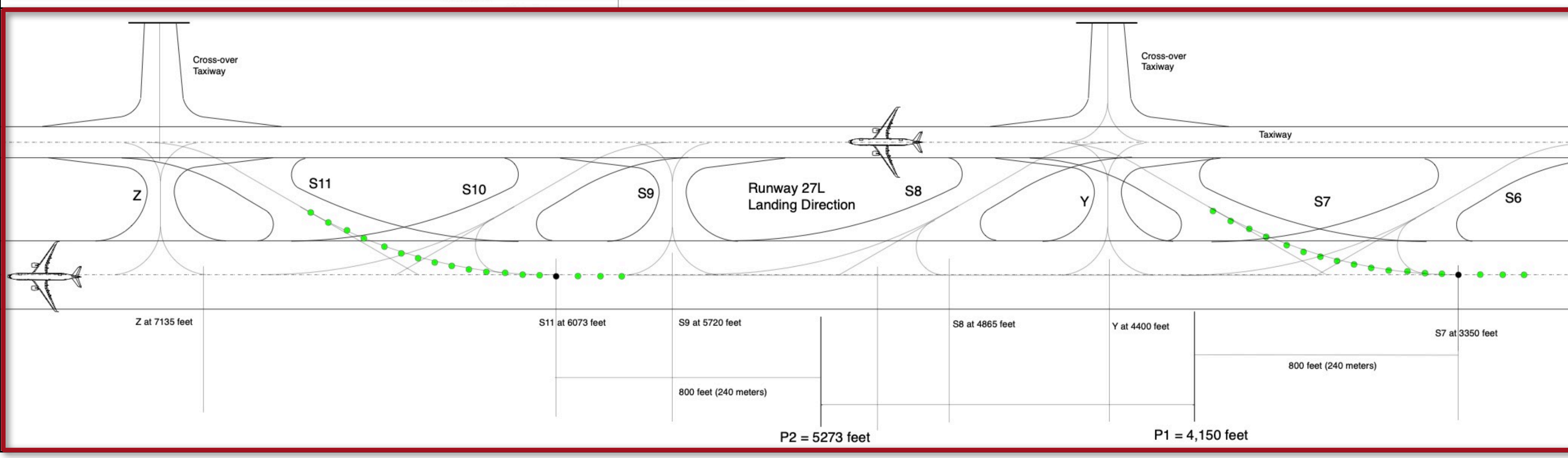


PHL Runway 27L

- S7 located at 3,350 feet from threshold
- S11 located at 6,073 feet from threshold
- Earliest PC of new high-speed runway exit ~ 4150 feet
- Furthest PC of new high-speed runway exit ~ 5273 feet

If 800 feet is the minimum distance to locate two high-speed exits





Scenarios Studied with New PHL Fleet Mix

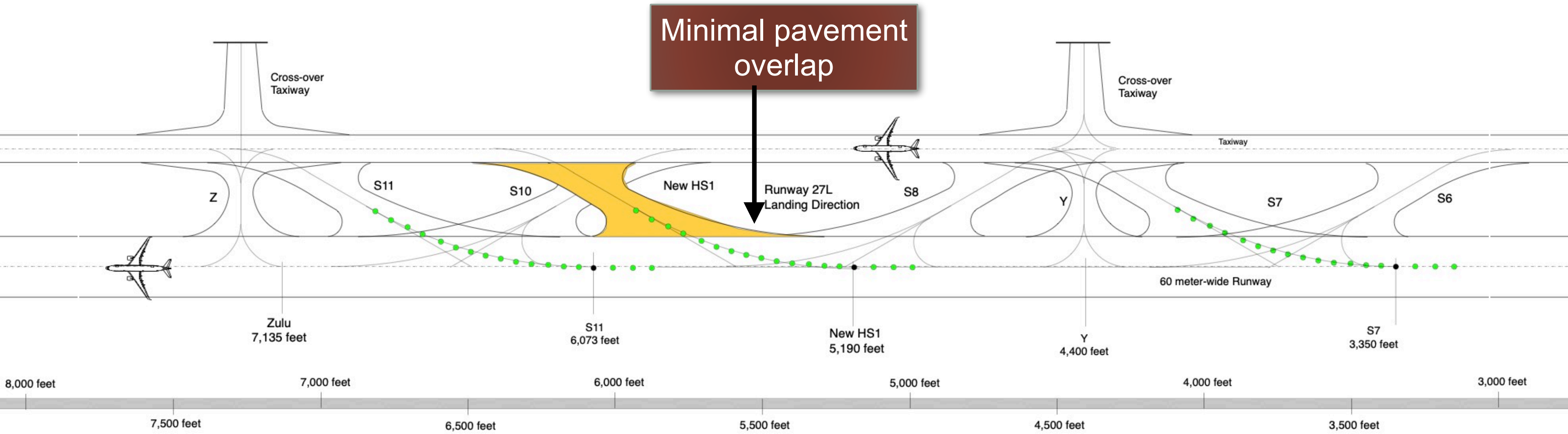
Scenario	Location of New Optimal High-Speed Exit (ft)	Wet/Dry Mix (%/%)	Remarks
Baseline	Not applicable	10/90	Open exits: U, S7, Y, S9, S11, S12 and S13
One High-Speed Runway Exit, 10/90	5,190	10/90	Open exits: U, S7, Y, NewHS1, S11, S12 and S13
One High-Speed Runway Exit, 20/80	5,280	20/80	Open exits: U, S7, Y, NewHS1, S11, S12 and S13

Optimal locations found using REDIM 3 dynamic programming algorithm
The backup slides contain probabilities of precipitation at PHL

Case: One New High-Speed Runway Exit, 10/90 (wet/dry pavement design)

- Optimal location of a **new High-Speed Runway exit** designed for 10/90% wet/dry pavement conditions is **<u>5,190 feet</u>** (point of curvature)
- Runway exit Sierra-9 is eliminated
- **883 feet** - distance between new exit high-speed exit HS1 and Sierra-11

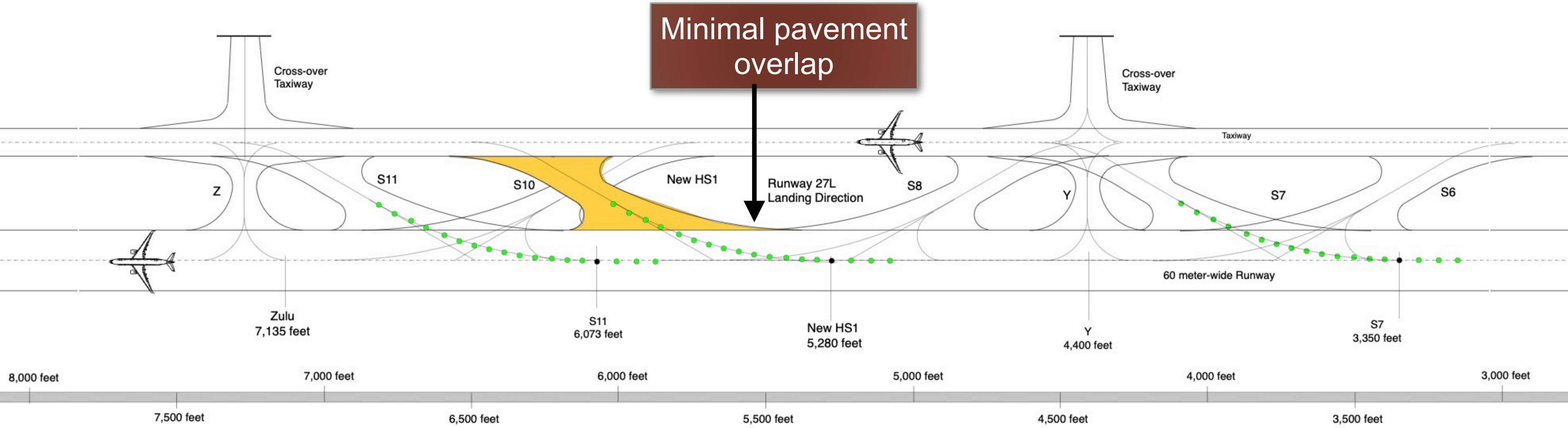
Optimally located runway exit in yellow



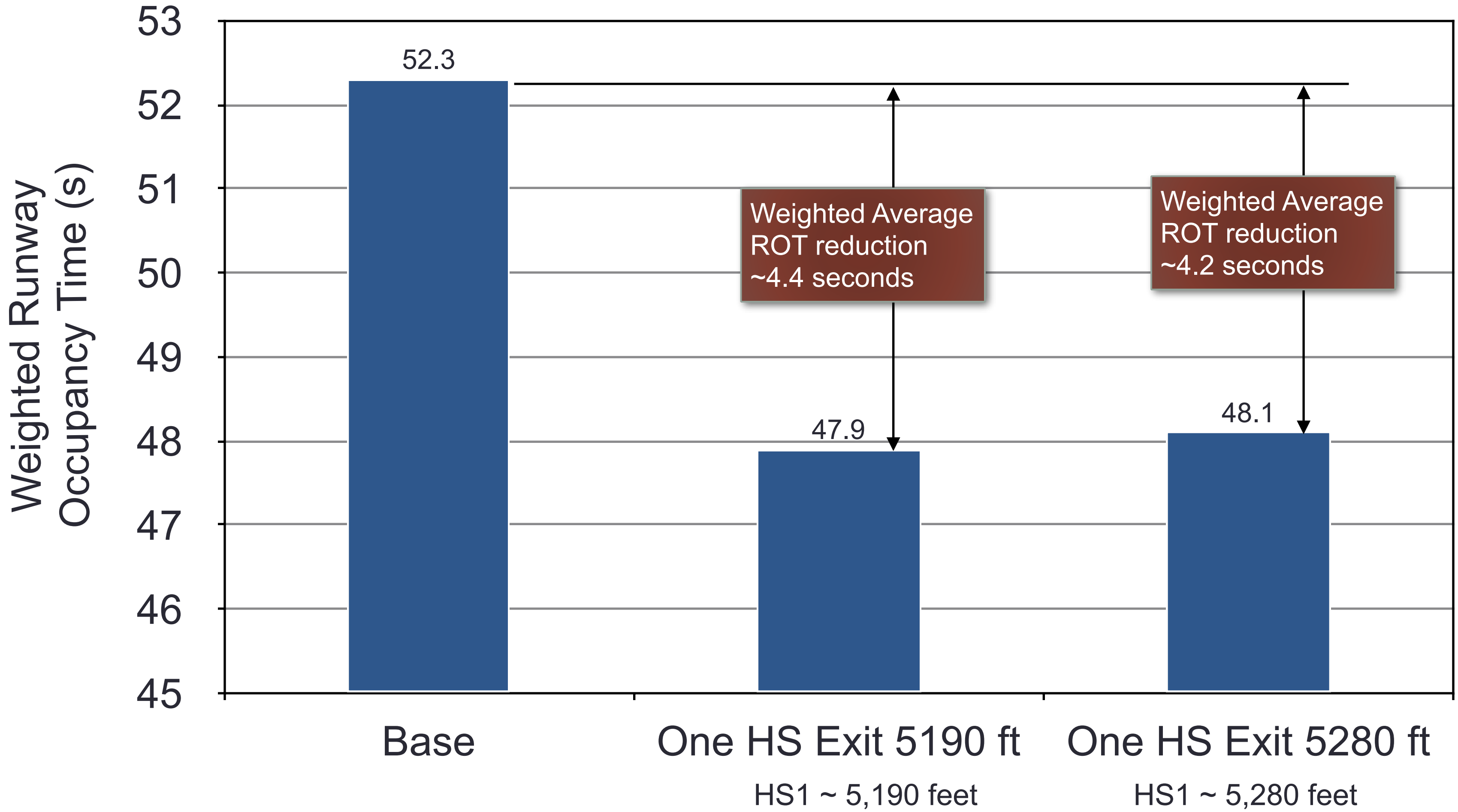
Case: One New High-Speed Runway Exit, 20/80 (wet/dry pavement design)

- Optimal location of a **new High-Speed Runway exit** designed for 20/80% wet/dry pavement conditions is **5,280 feet** (point of curvature)
- Runway exit Sierra-9 is eliminated
- **793 feet** - distance between new exit high-speed exit HS2 and Sierra-11

Optimally located runway exit in yellow

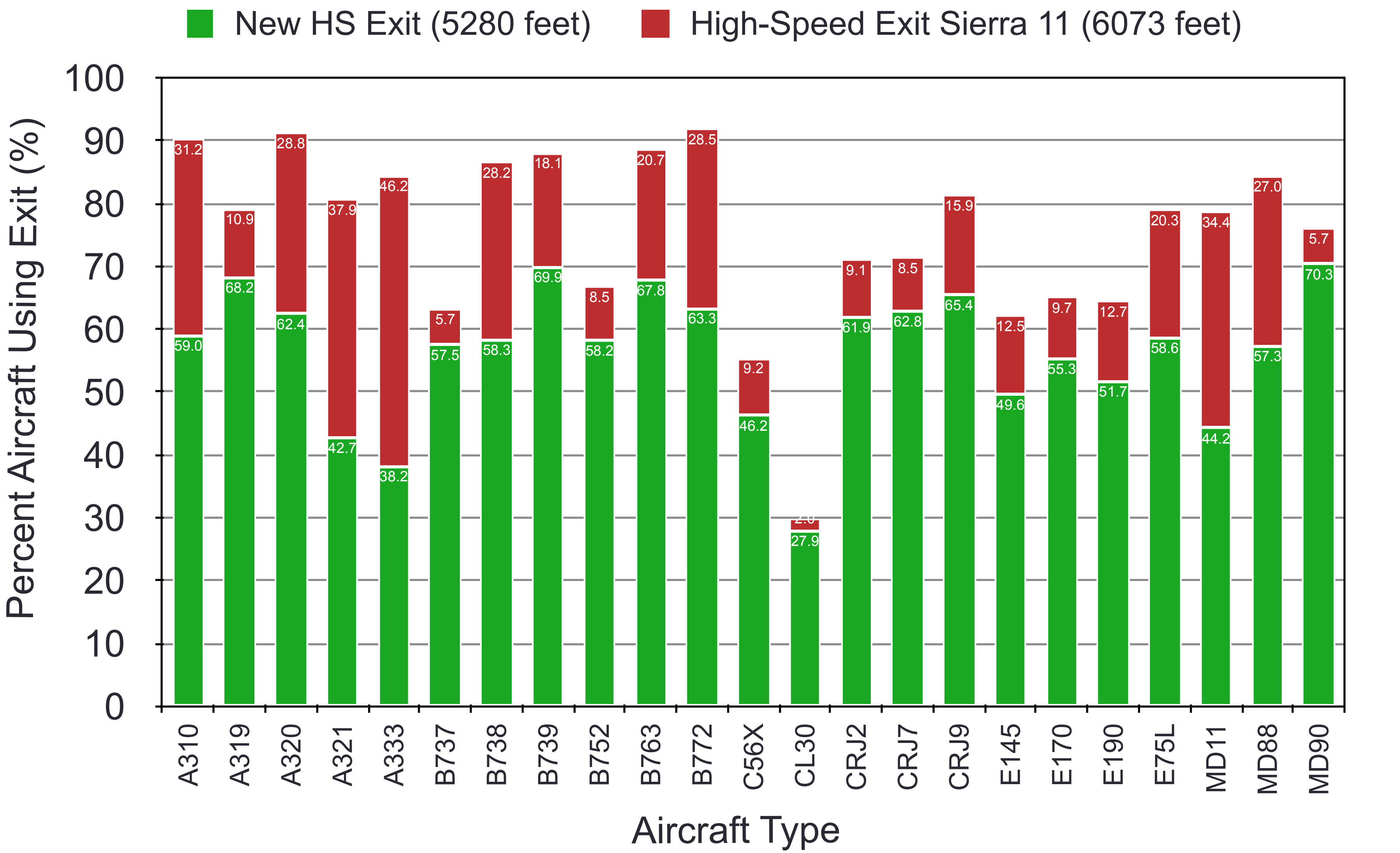


An Optimally Located High-Speed Runway Exit at PHL Runway 27L Could Reduce the Weighted Average Runway Occupancy Time by 4.4 to 4.2 Seconds



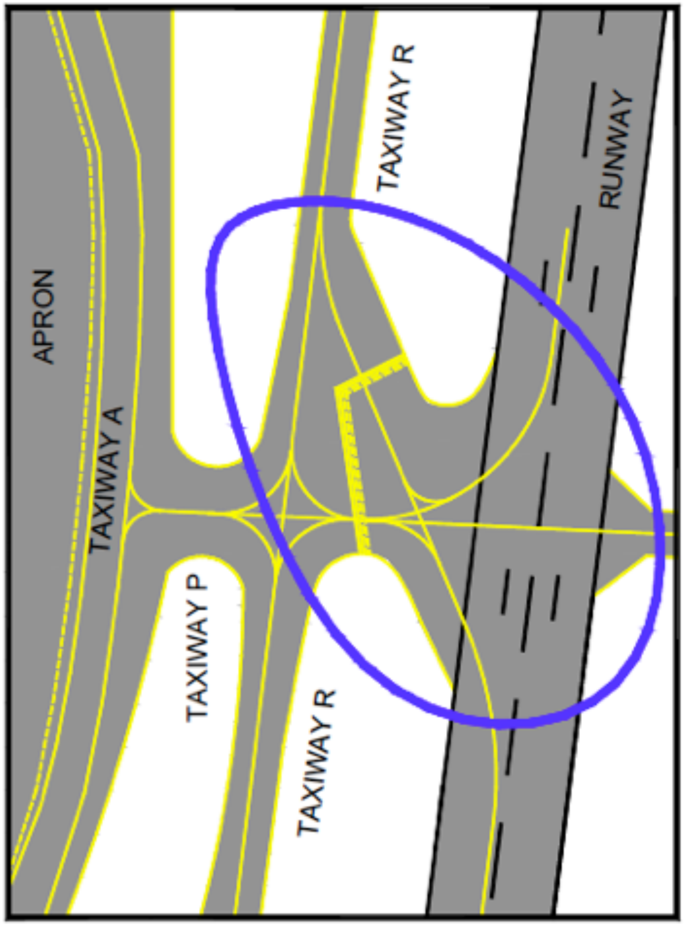
PHL Fleet Mix (Jan/2018 to Aug/2019) provided by FAA

54% of Landings on Runway 27L Could Use the New High-Speed Exit at 5,280 feet (20/80 wet/dry Design Scenario)

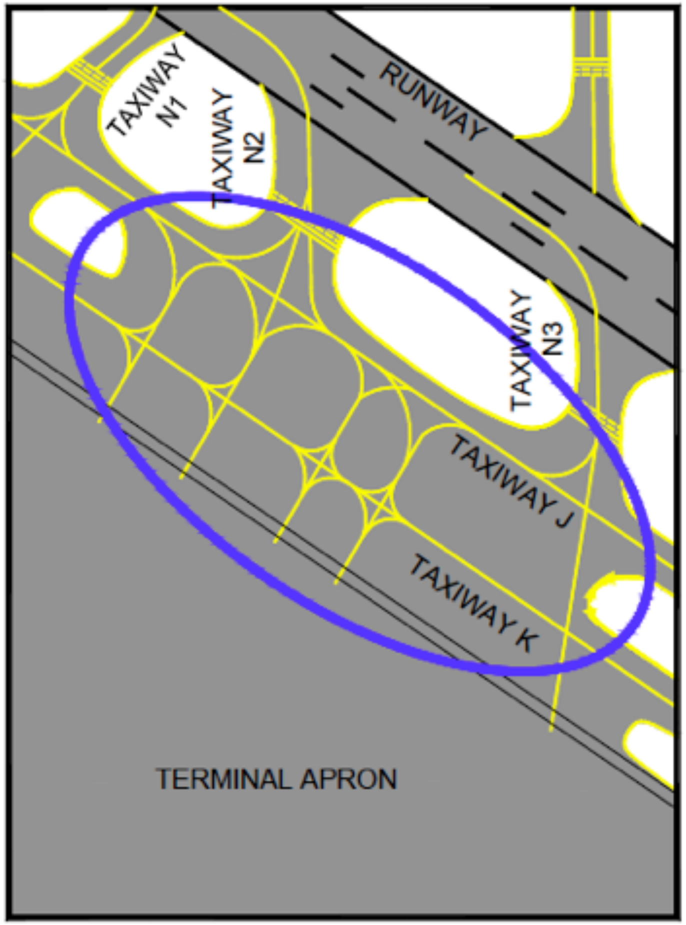


Other Runway Exit and Taxiway Considerations

Things to Avoid (1)

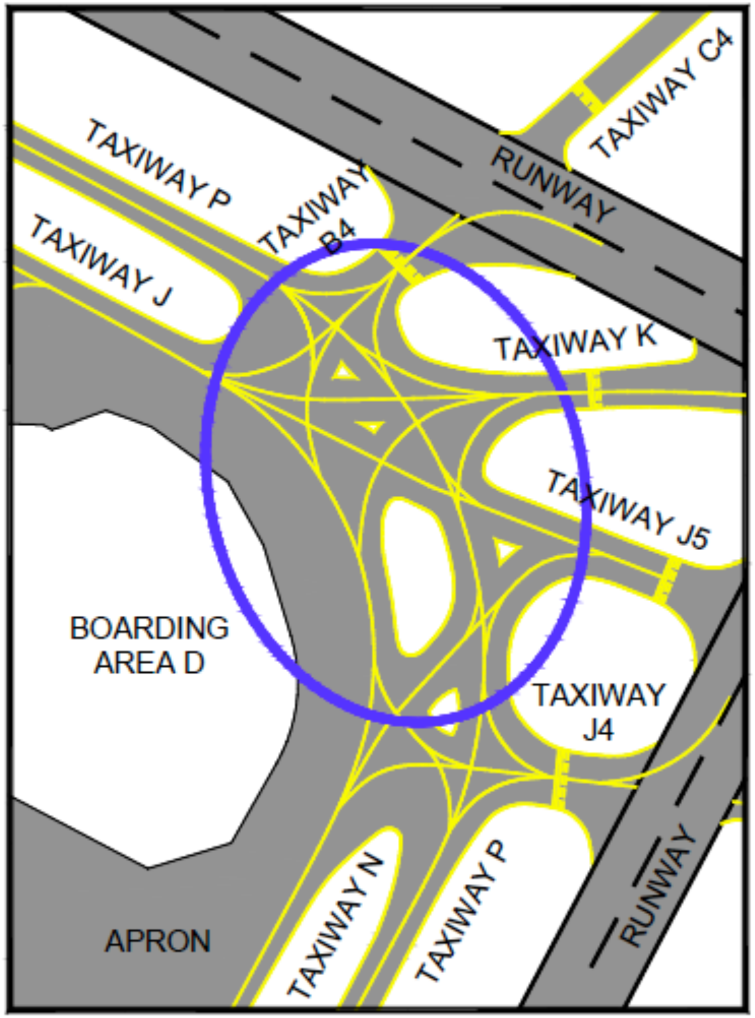


(a) Taxiway crossing high-speed exit and Wide throated runway entrance

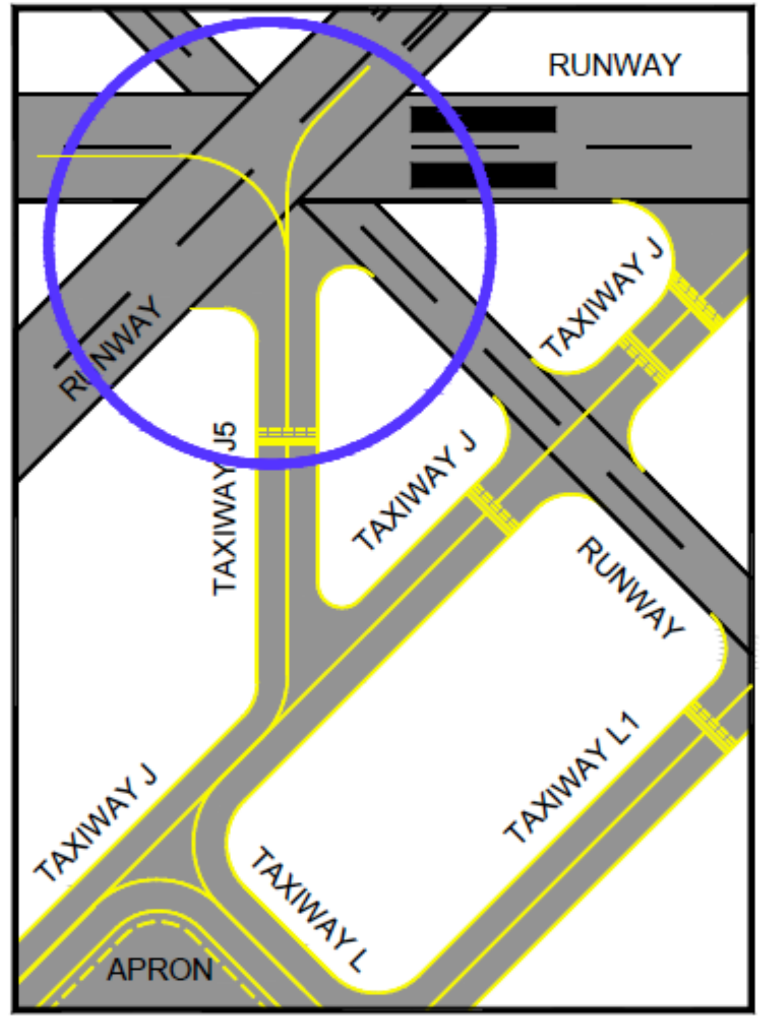


(b) Extra-wide throated taxiway without "No Taxi" islands leading from the apron directly to parallel taxiways and runways

Things to Avoid (2)

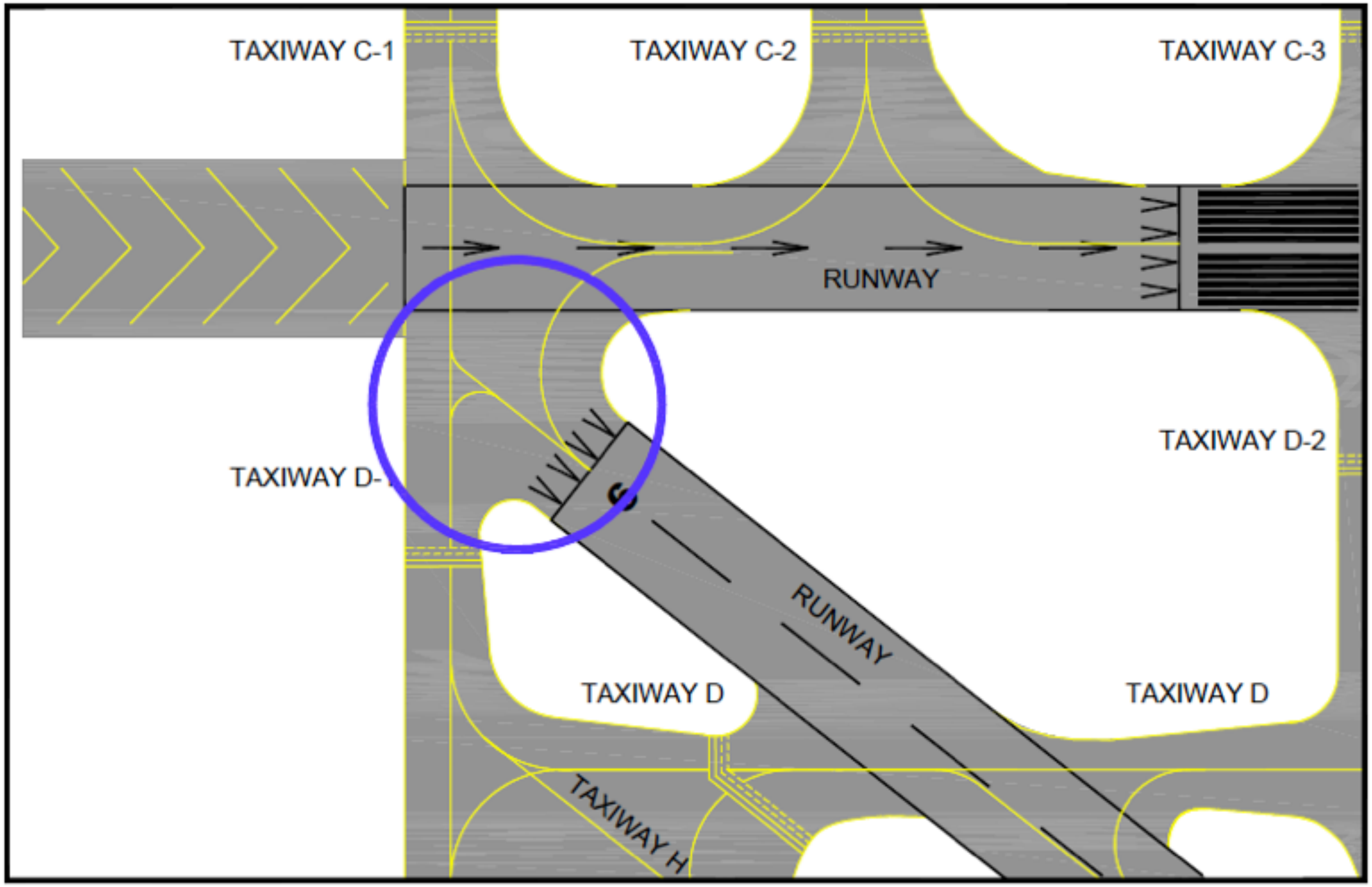


(c) Taxiway intersection exceeds "3-node" concept



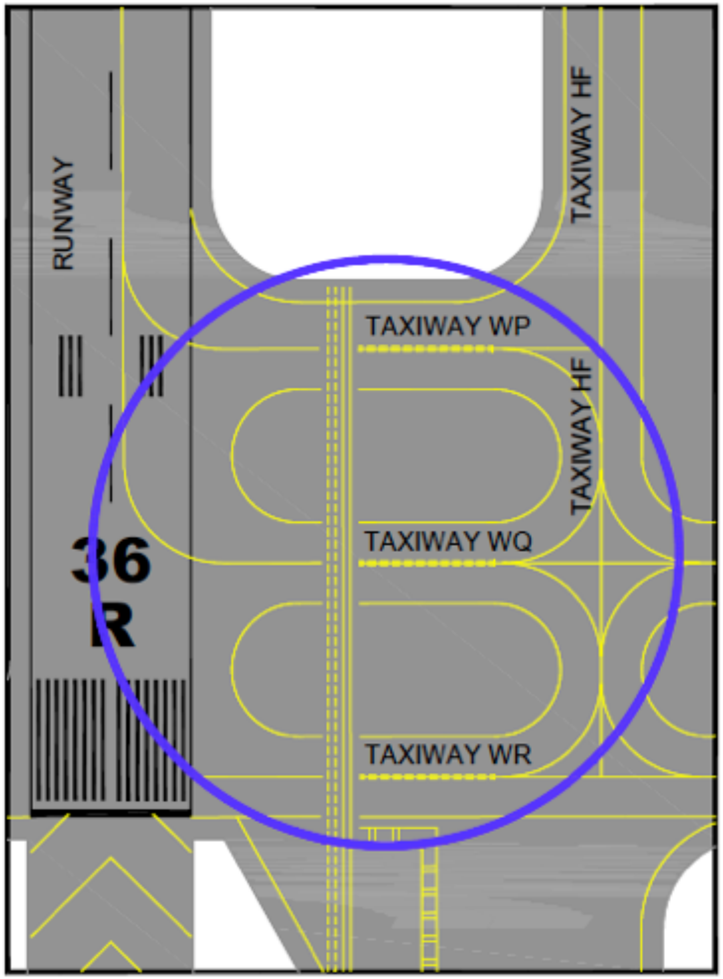
(d) Taxiway intersecting two or more runways

Things to Avoid (3)

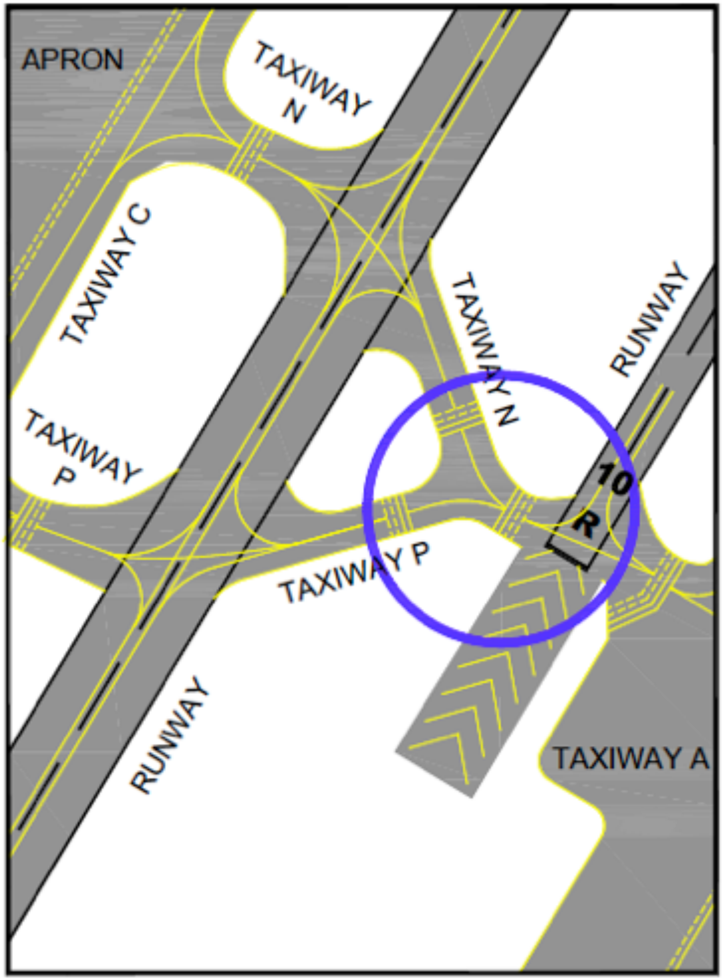


(e) Aligned taxiway between two closely spaced runway ends

Things to Avoid (4)

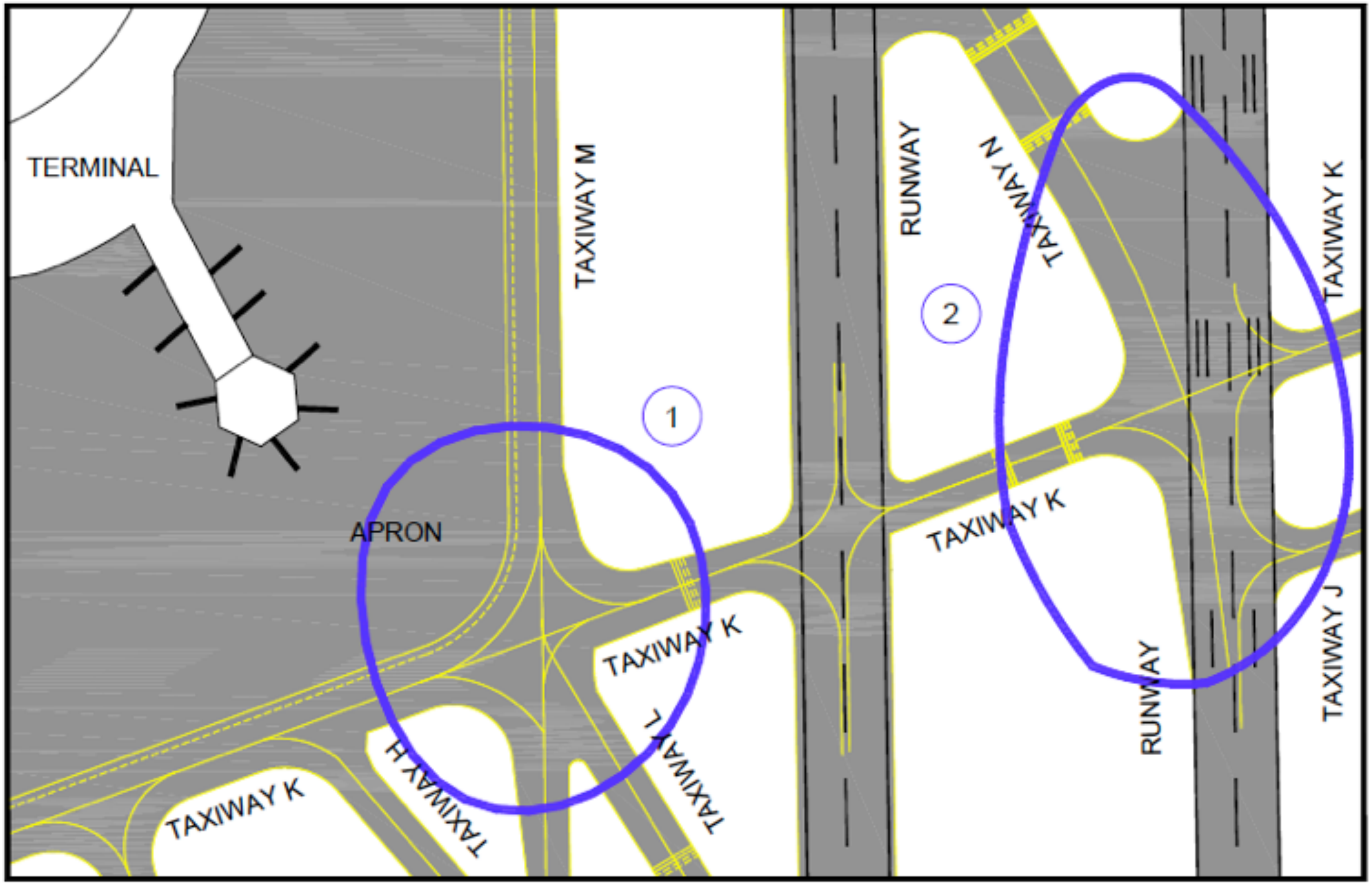


(f) Two or more taxiway entrances lacking "No Taxi" islands



(g) "Y" Shaped taxiway crossing a runway

Things to Avoid (5)



(1) Taxiway intersection exceeds "3-node" concept

(2) Taxiway intersecting a high-speed exit from runway.