Safety and Capacity of the Aircraft Landing Process

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Summary

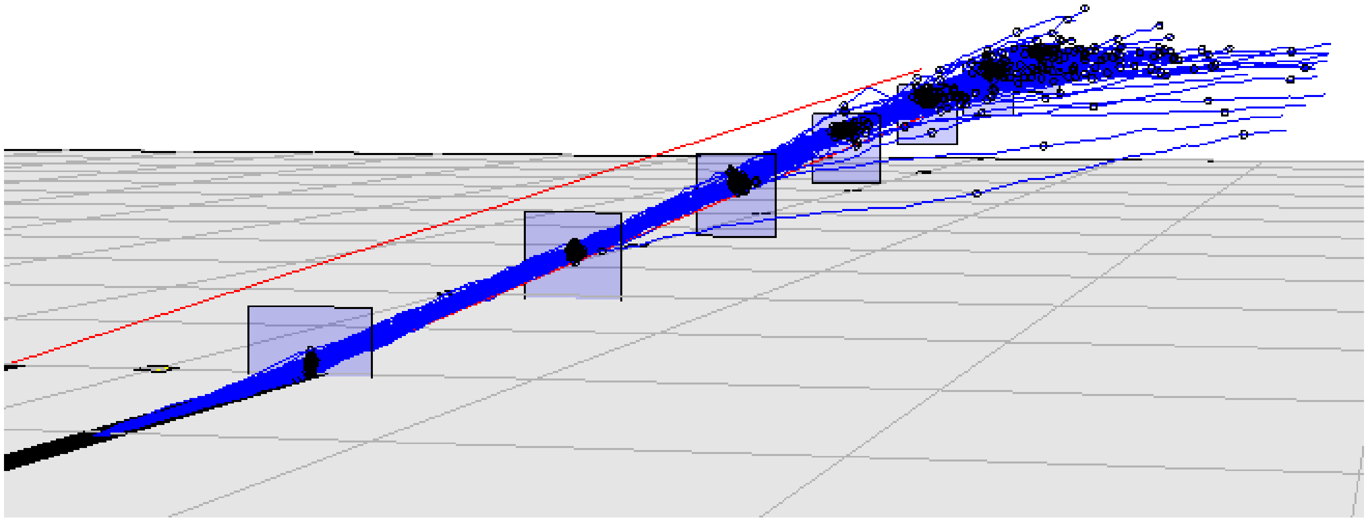
- Key Questions
  - How safe is the current system?
  - What is the safe capacity of a runway?
- Safety incidents in consideration
  - Simultaneous runway occupancy
  - Wake vortex encounter
- Approach
  - Multilateration data analysis
  - Models based on data

Detroit Airport

Detroit Airport (DTW)

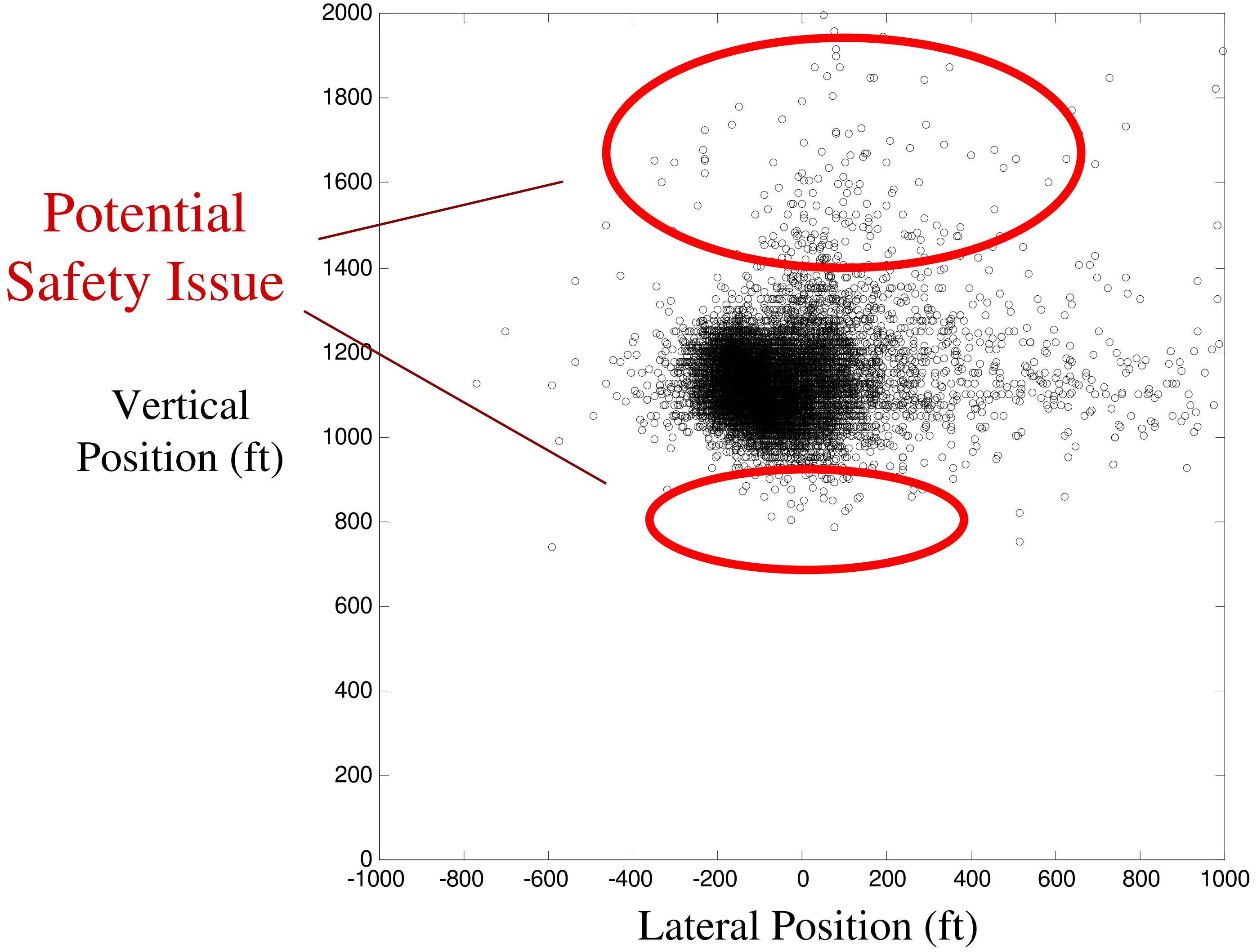
Multilateration Data

- Gives aircraft position (*x*, *y*, *z*), updated every second
- Coverage: ~10 nm radius of DTW
- Processed data
  - Data set #1: ~1,200 landings over 1 week, all runways (2003)
  - Data set #2: ~12,000 landings over 3 months, runway 21L (2002, 2003)



Jeddi, B., J. Shortle, L. Sherry. 2006. Statistics of the approach process at Detroit Metropolitan Wayne County Airport. International Conference on Research in Air Transportation. Belgrade, Serbia & Montenegro.

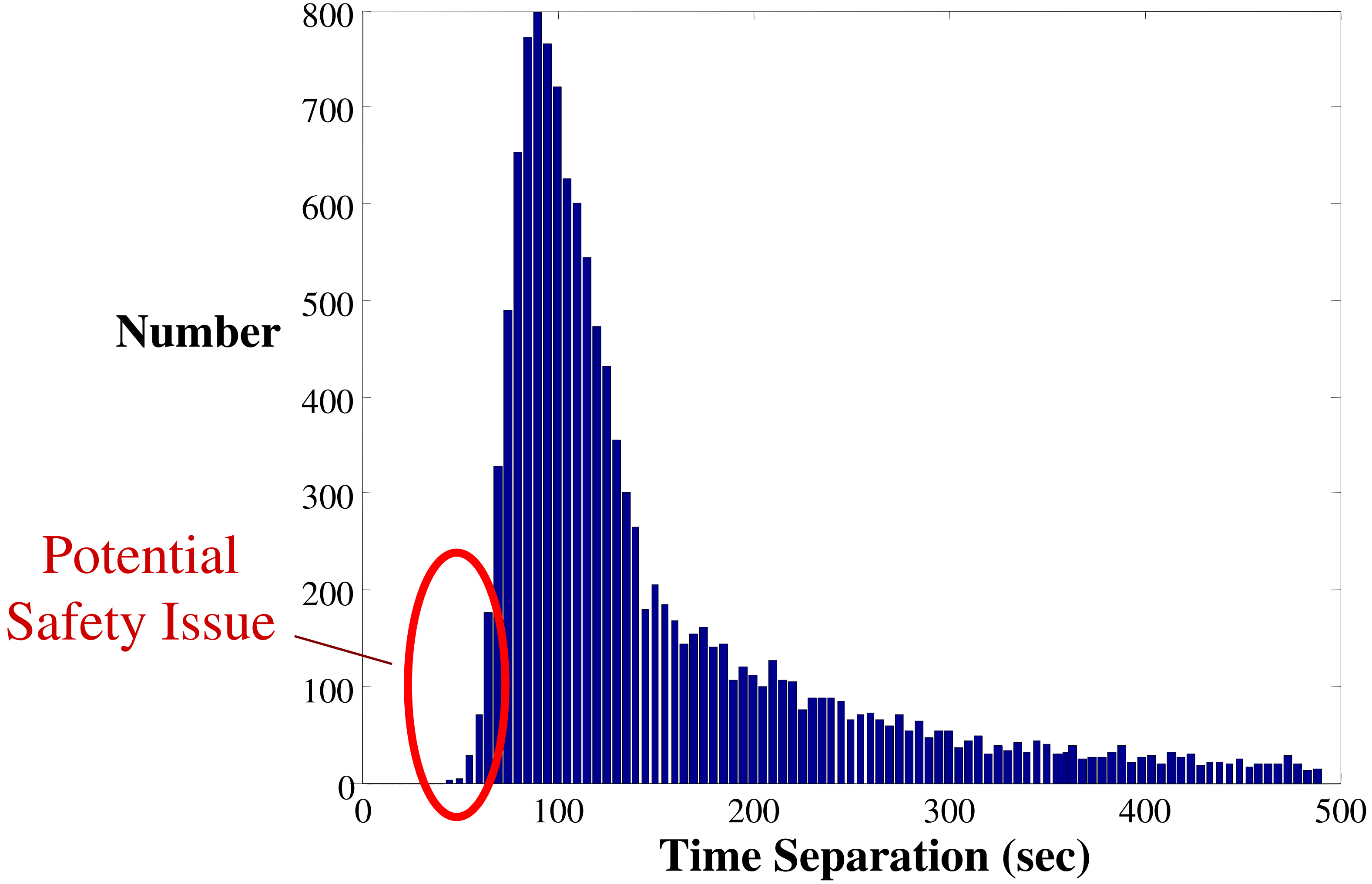
Flight Tracks (@ 3 nm)



Potential Safety Issue

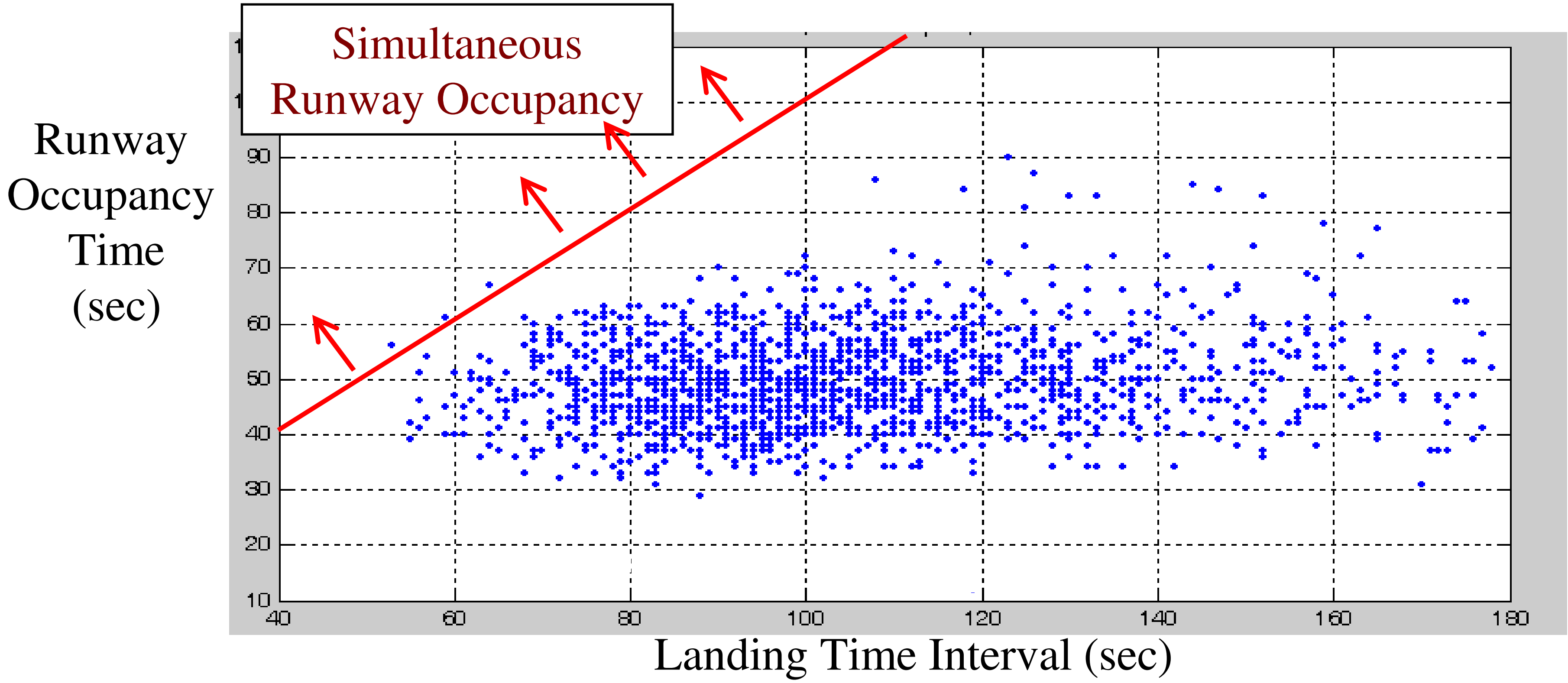
Data source: DTW 21L, ~12,000 landings, Dec ’02, Apr, Jul 03

Time Separation (at Threshold)



Data source: DTW 21L, ~12,000 landings, Dec ’02, Apr, Jul 03

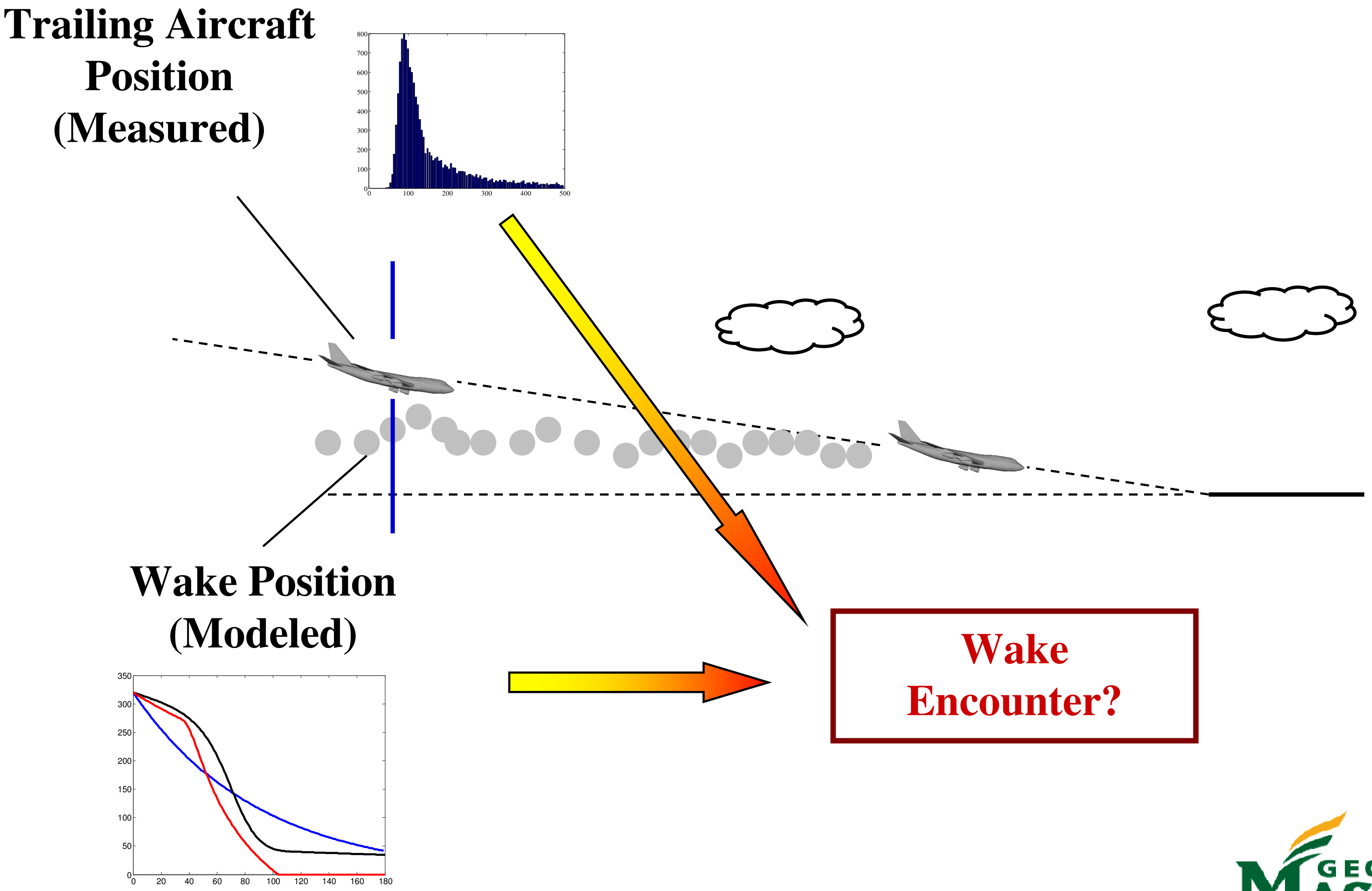
Simultaneous Runway Occupancy



Data source: DTW, ~1,200 landings, Feb '03

Jeddi, B., J. Shortle, L. Sherry. 2006. Statistics of the approach process at Detroit Metropolitan Wayne County Airport. International Conference on Research in Air Transportation. Belgrade, Serbia & Montenegro.

Wake Vortices on Approach

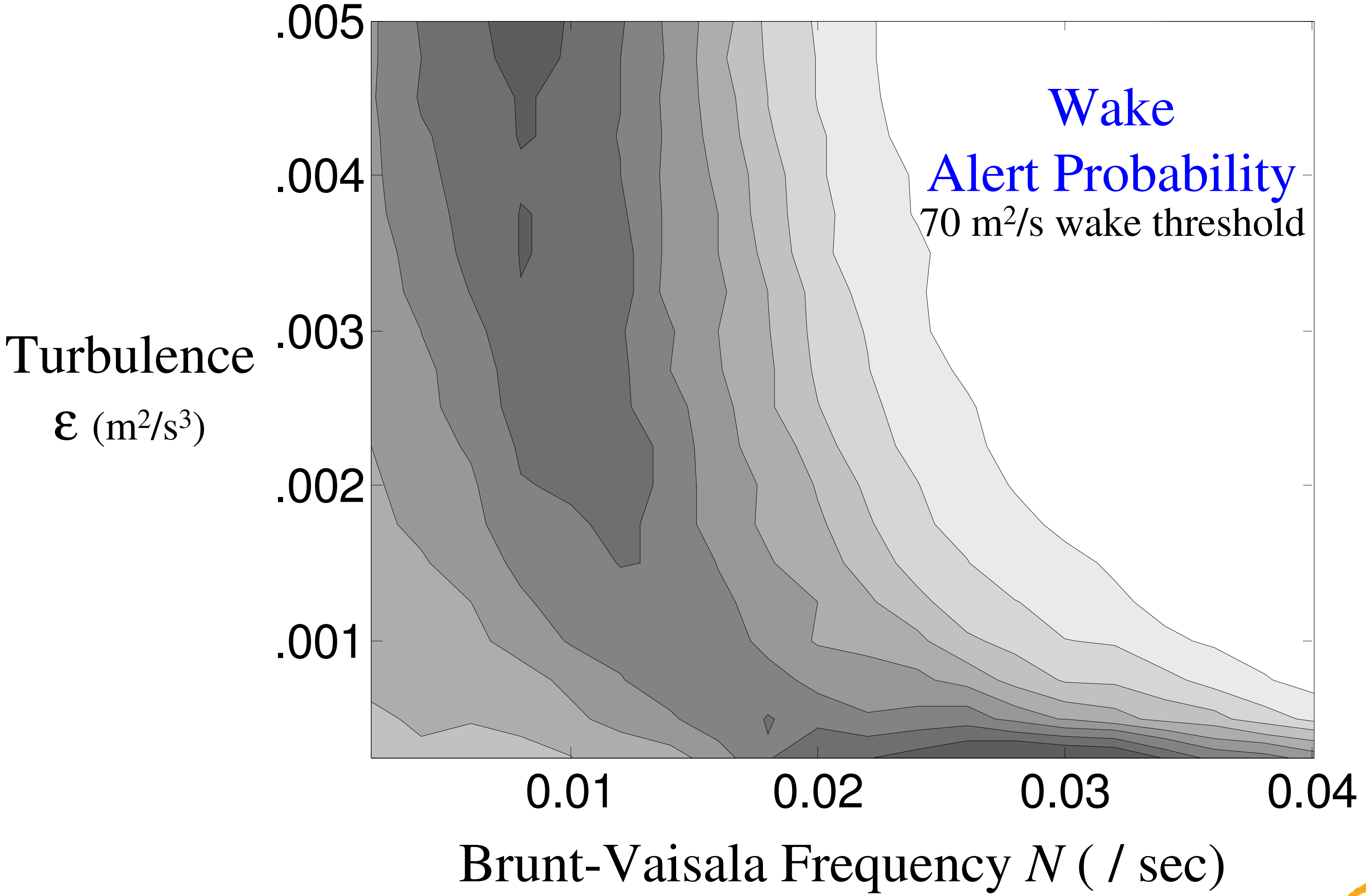


Trailing Aircraft Position (Measured)

Wake Position (Modeled)

Wake Encounter?

Sample Results



Data source: DTW 21L, ~1,200 landings, Jun '03, Wake model = P2P

Summary

- Used multilateration data to estimate incident probabilities
  - Simultaneous runway occupancy
  - Wake encounters

- What is the *safe* capacity of an arrival-only runway?

(“safe” = no SRO, no wake encounters)

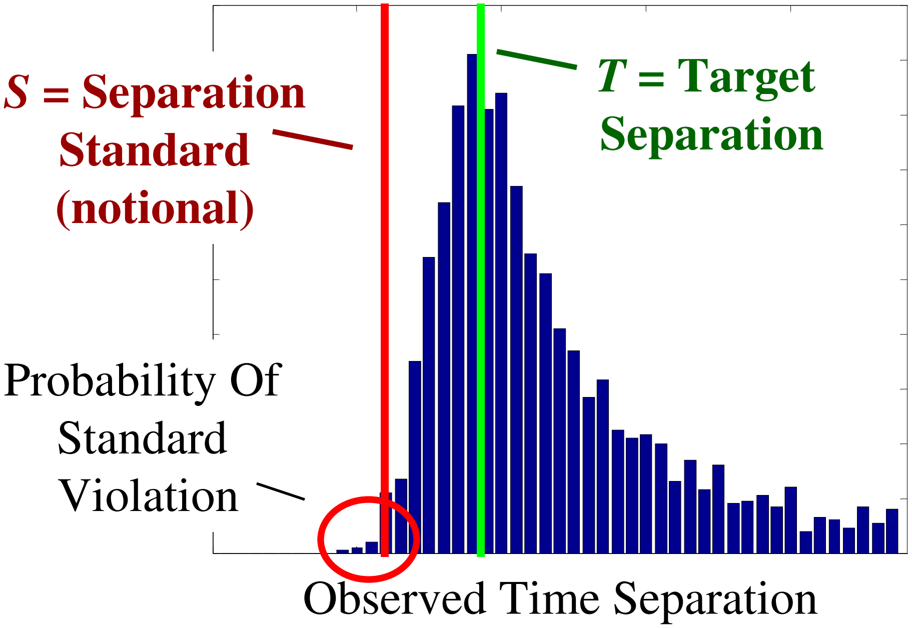
Capacity

Capacity: Maximum achievable throughput on average

- Separation requirement: S time units
- Assume
  - No gaps in arrival process
  - Arrivals are separated by exactly S

- Capacity = 1 / S
- Example: S = 90 seconds, Capacity = 40 / hr
- Problem: Separation standard not always met

A Revised Definition

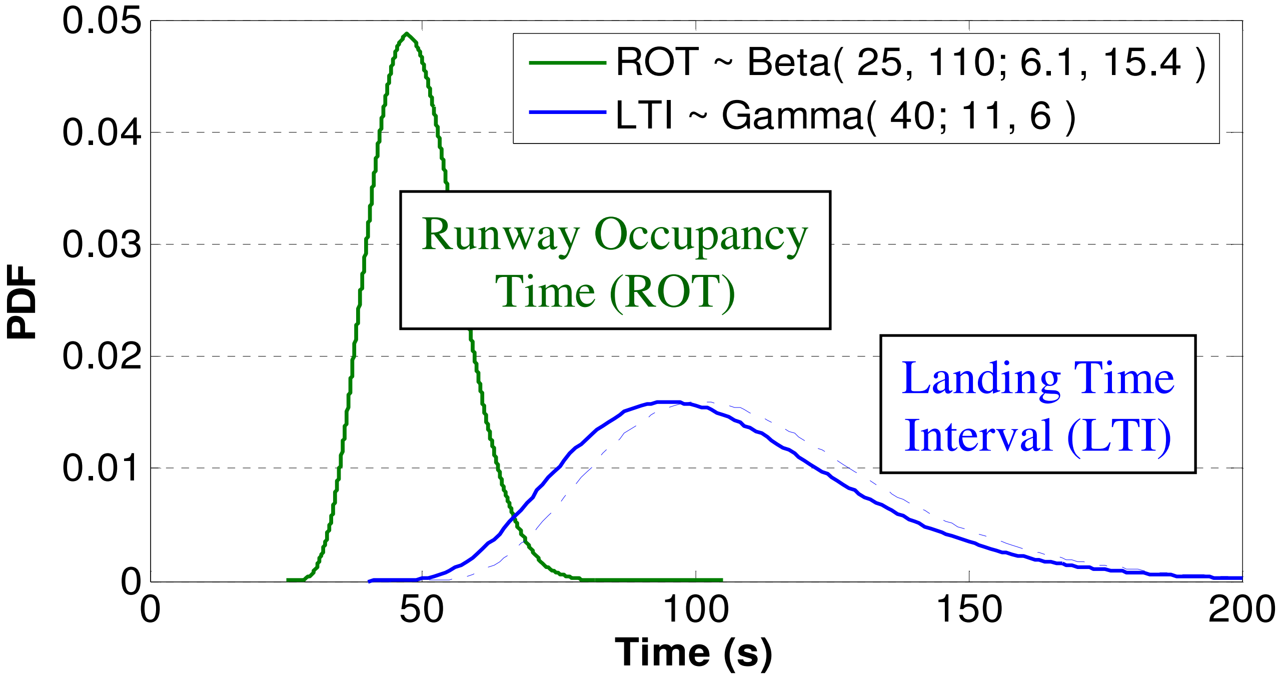


- Choose target separation *T* so that probability of separation violation is less than some small value.
- Restrict observations to peak periods
- Capacity = 1 / Expected Separation
- "Buffer-adjusted" capacity

Jeddi, B., J. Shortle, L. Sherry. 2006. Statistical separation standards for the aircraft approach process. Proceedings of the 25th Digital Avionics Systems Conference, Portland OR, 2A1-2A1-13.

Runway Incursion-Based Capacity

- Determine target separation so that $P\{LTI < ROT\} < \alpha$
- Shift LTI distribution to the left or right
- Example: for $\alpha = 10^{-4}$, increase separation by 15 sec

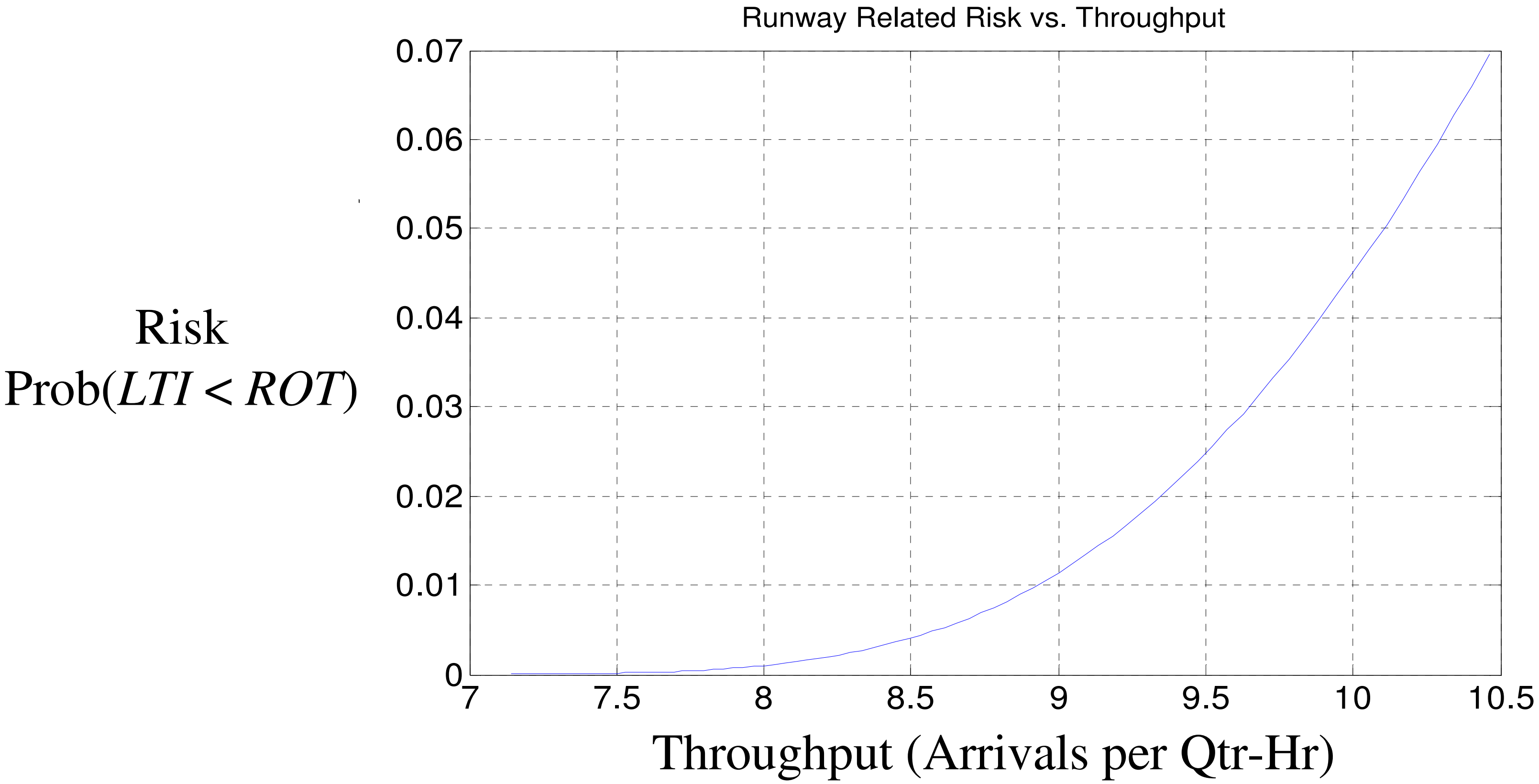


Target separation from 95 to 110 sec

Jeddi, B., J. Shortle, L. Sherry. 2006. Statistical separation standards for the aircraft approach process. Proceedings of the 25th Digital Avionics Systems Conference, Portland OR, 2A1-2A1-13.

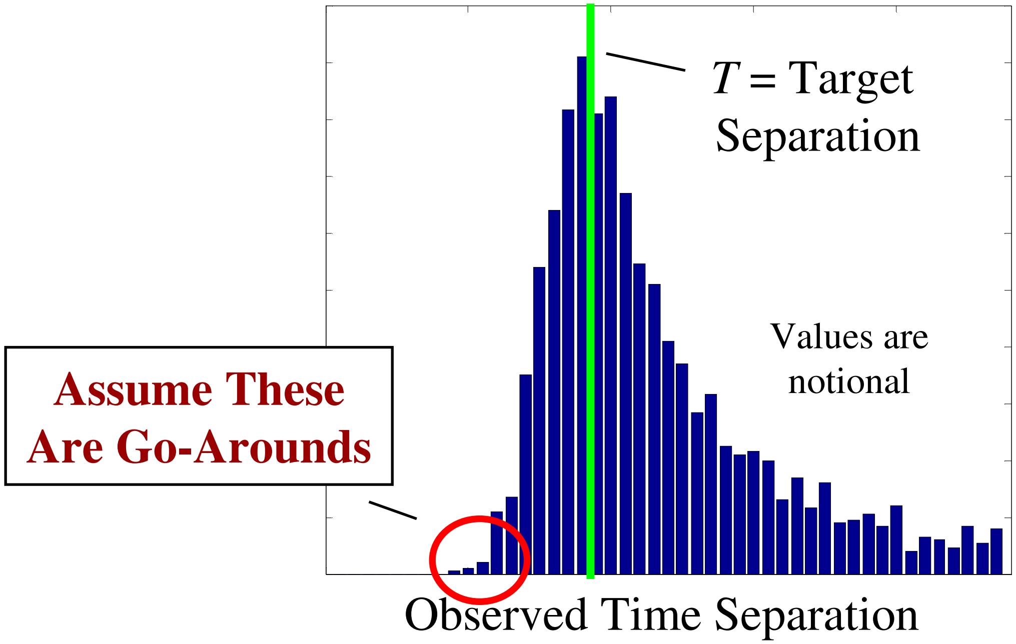
Risk vs. Throughput

- Use different safety thresholds α to evaluate risk versus throughput



Jeddi, B., J. Shortle, L. Sherry. 2006. Statistical separation standards for the aircraft approach process. Proceedings of the 25th Digital Avionics Systems Conference, Portland OR, 2A1-2A1-13.

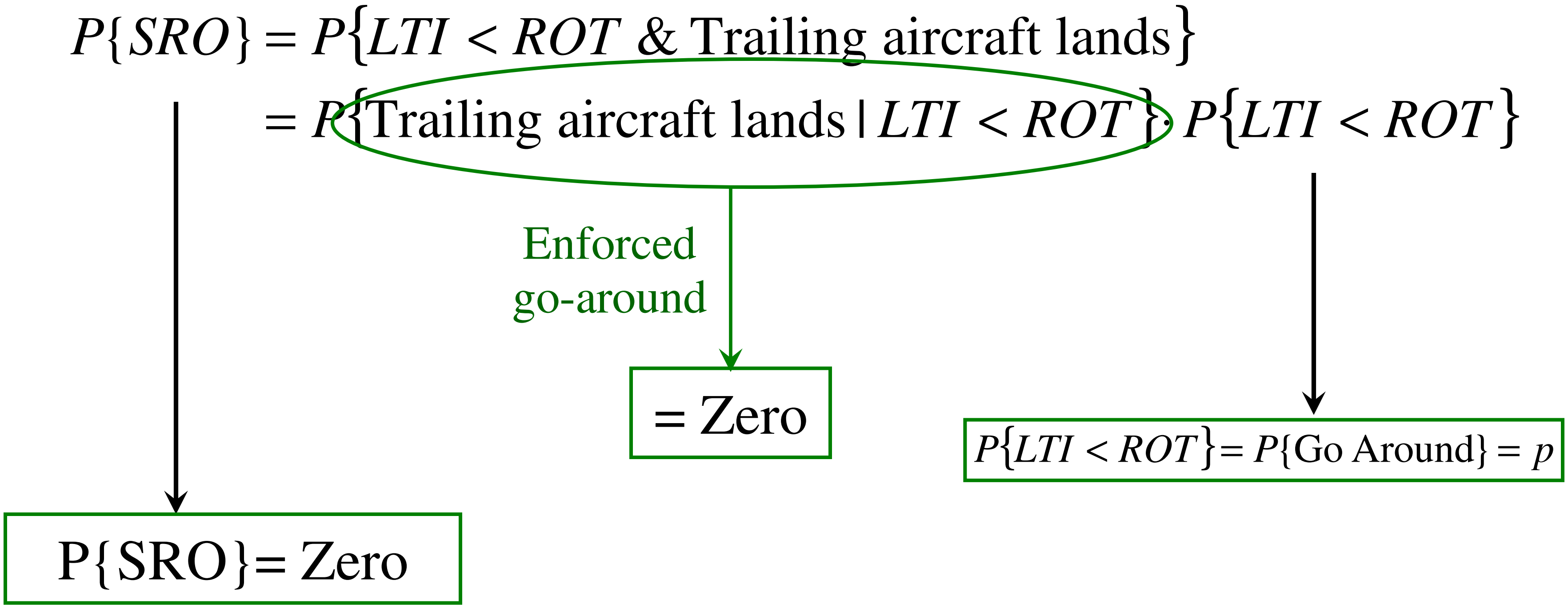
A Risk-Free Capacity Definition



Assume **the system is** ***completely*** **safe** (safe = no SRO)

- Simultaneous runway occupancy (SRO) is eliminated by go-around
- Assume pilot *always* takes go-around to avoid SRO
  (perfect information & execution)

Simultaneous Runway Occupancy



$$
\begin{aligned}
P\{SRO\} &= P\{LTI < ROT \ \&\ \text{Trailing aircraft lands}\} \\
&= P\{\text{Trailing aircraft lands} \mid LTI < ROT\} \cdot P\{LTI < ROT\}
\end{aligned}
$$

Enforced go-around

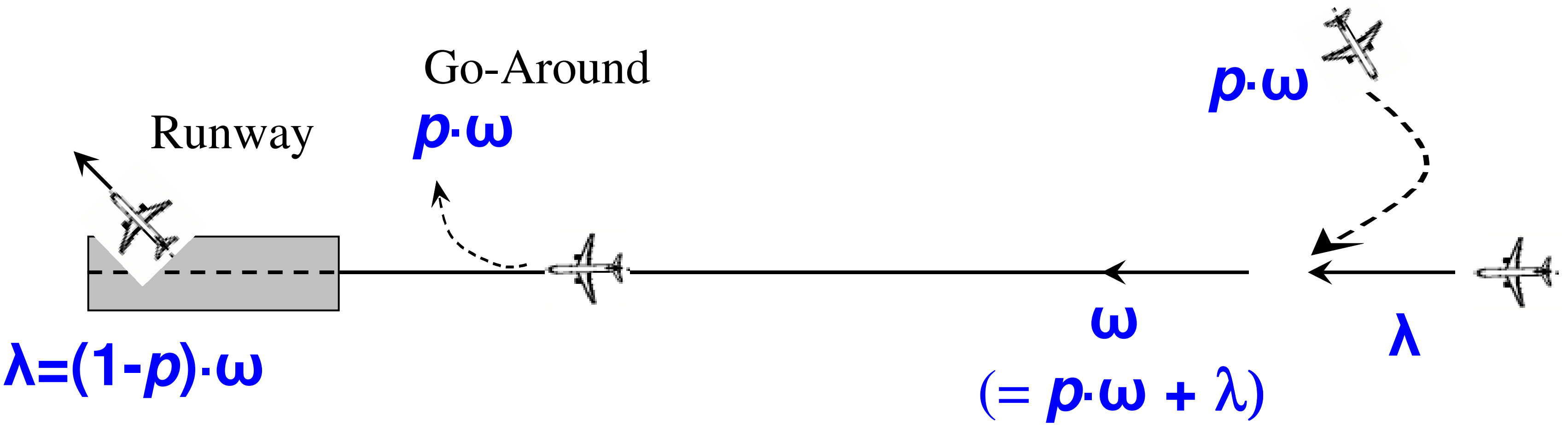
$$\boxed{= \text{Zero}}$$

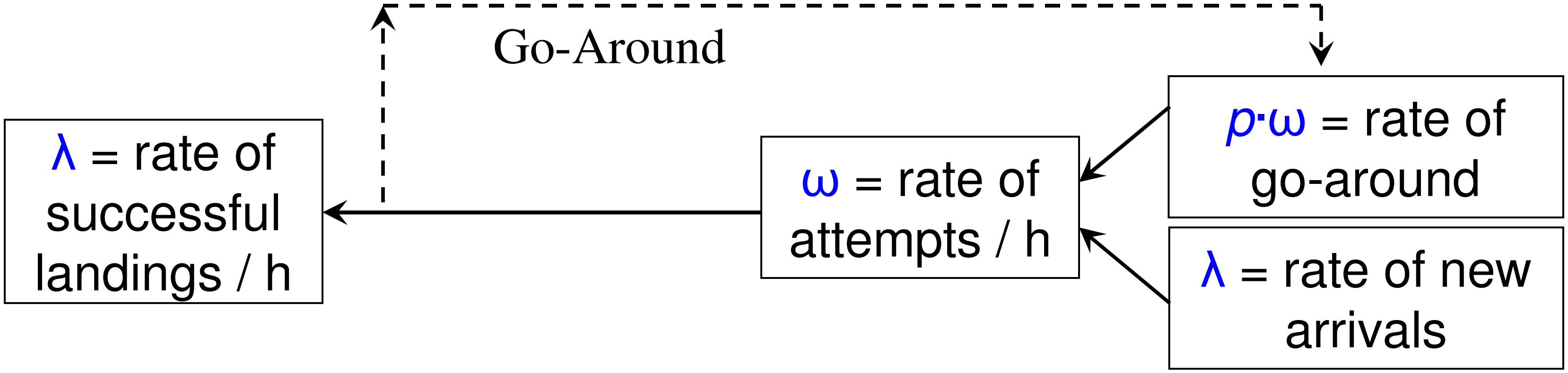
$$\boxed{P\{LTI < ROT\} = P\{\text{Go Around}\} = p}$$

$$\boxed{\text{P}\{\text{SRO}\} = \text{Zero}}$$

LTI:	Landing Time Interval
ROT:	Runway Occupancy Time
SRO:	Simultaneous Runway Occupancy

Landing and Go-around Process





λ = rate of successful landings / h

ω = rate of attempts / h

$p \cdot \omega$ = rate of go-around

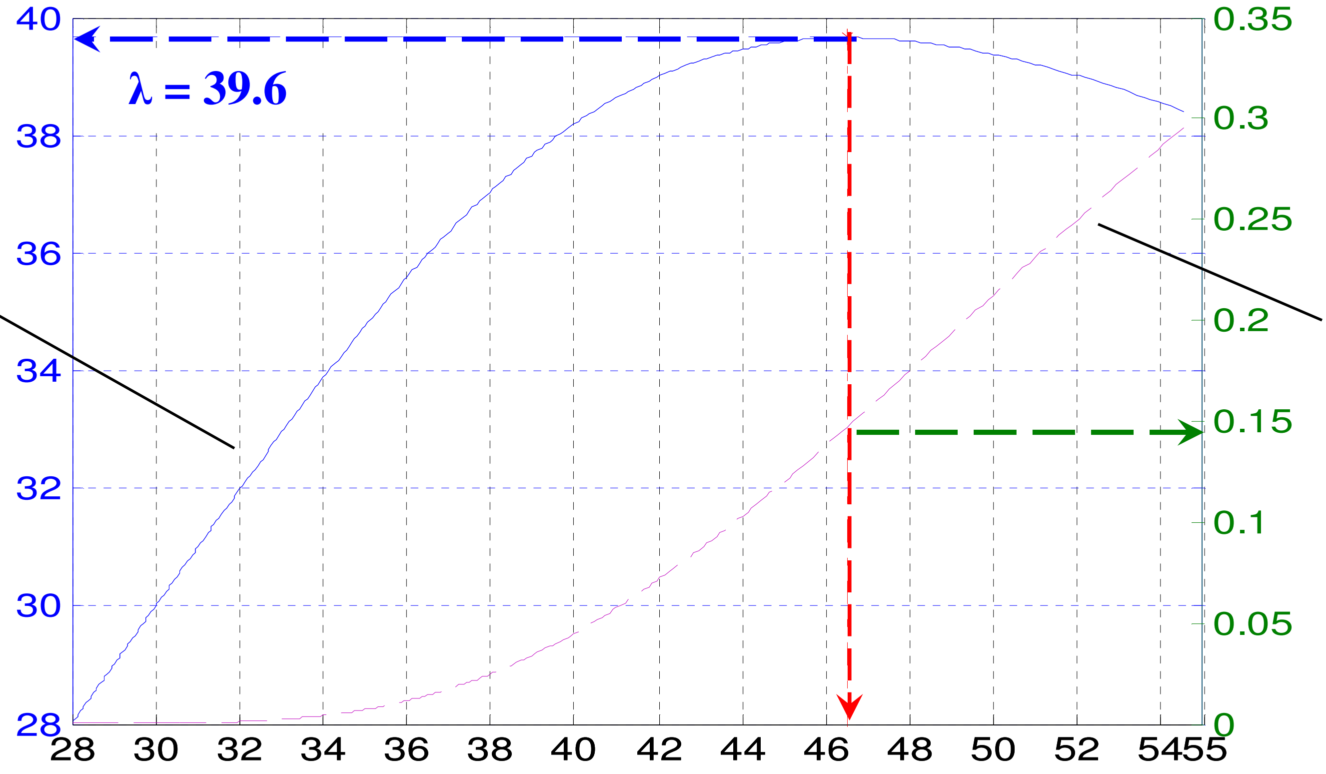
λ = rate of new arrivals

Goal: Maximize $\lambda(\omega) = [1 - p(\omega)] \cdot \omega$

Assumptions

- Distribution of time-separation unchanged along approach
- LTI and ROT of a lead-follower pair are independent
- Shifting LTI distribution to left or right does not change its shape
- Go-around is executed with perfect information

Maximizing Throughput



Successful Landings per Hour (λ)

Prob. of Go-Around (p)

Landing Attempts per Hour (ω)

Economic Optimality

<u>Definitions</u>

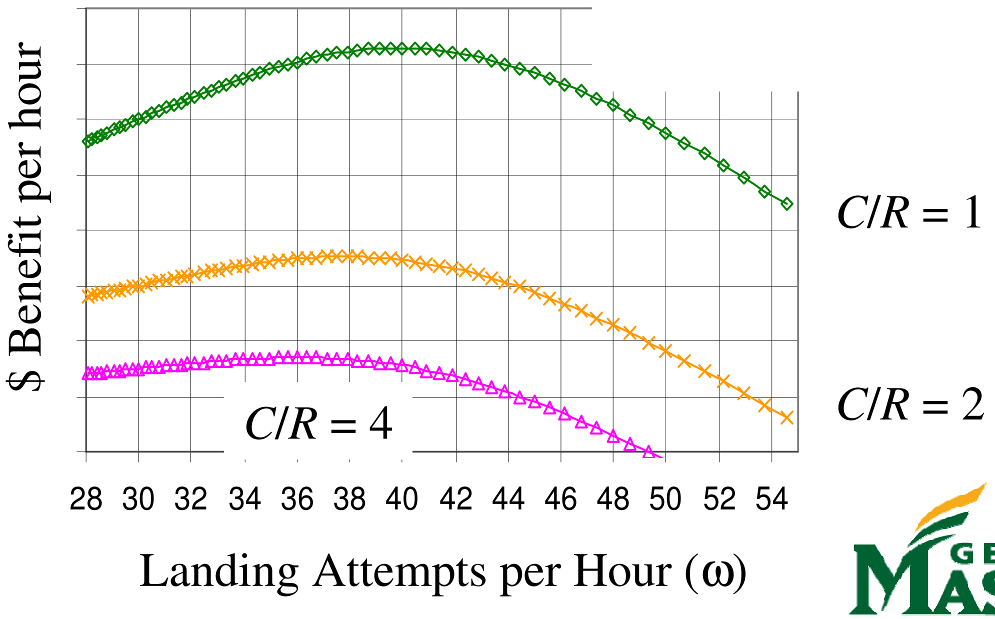
R: dollar benefit of a successful landing for all beneficiaries

C: expected average cost of a go-around

$$\text{Maximize } ES(\omega; R, C) = [1 - p(\omega)] \cdot \omega \cdot R - p(\omega) \cdot \omega \cdot C$$

Illustration:

- For DTW distributions under IMC, 3 nmi sep.
- Without wake constraint
- *C* held constant



Summary

- Analysis of multilateration data
  - Estimates of various safety indicators
  - Simultaneous runway occupancy, wake vortex encounters
- Definition of capacity that
  - Takes into account statistical variation of arrival process
  - Does not have an asterisk by it (e.g., $P(SRO) < 10^{-5}$)
- Capacity models are notional and demonstrate principles
- Potential applications
  - Show capacity resulting from new technology (e.g., smaller variance in LTI)
  - Relative benefits of addressing wake technology and constraints vs. runway occupancy constraint

Acknowledgments

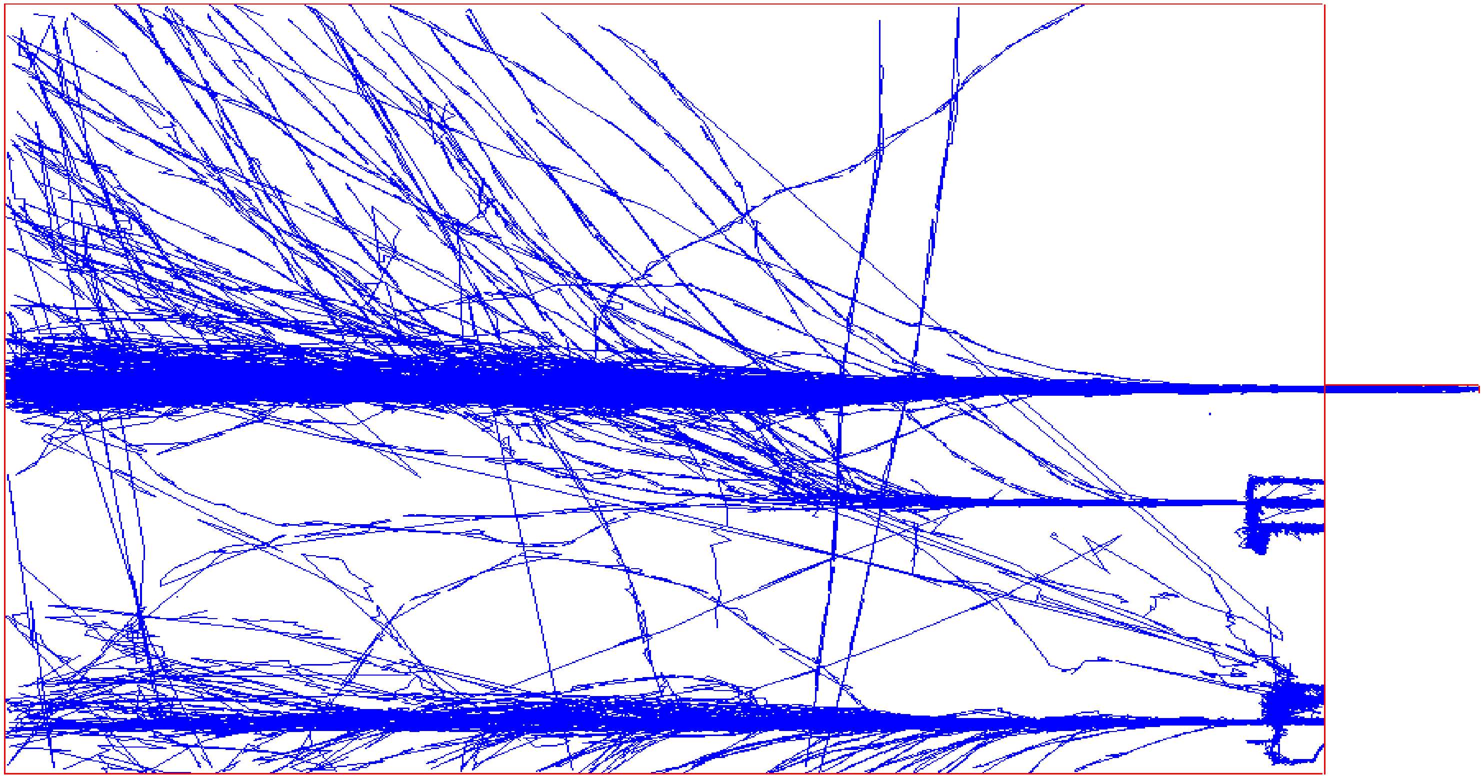
- Wayne Bryant, Ed Johnson, NASA
- This talk solely represents the opinions of the authors

Questions

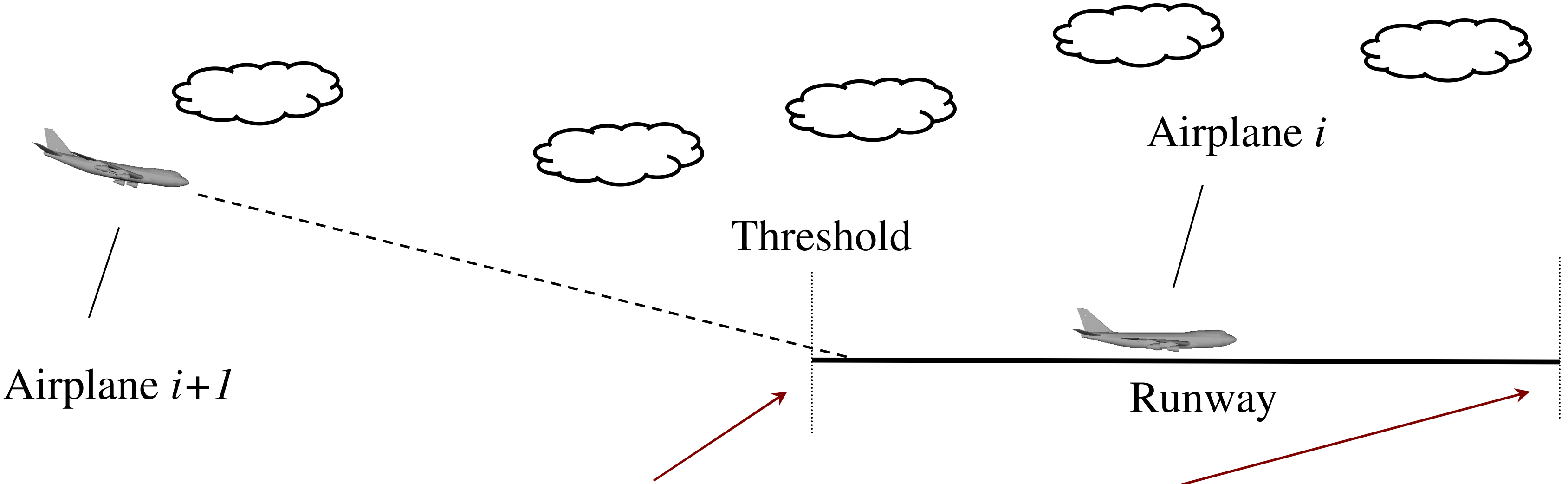
Separation Violations

- Three dimensions of separation
    - Lateral (y)
    - Vertical (z)
    - Longitudinal (x) or time (t)

Sample Data



Sample Collection Process



Airplane i

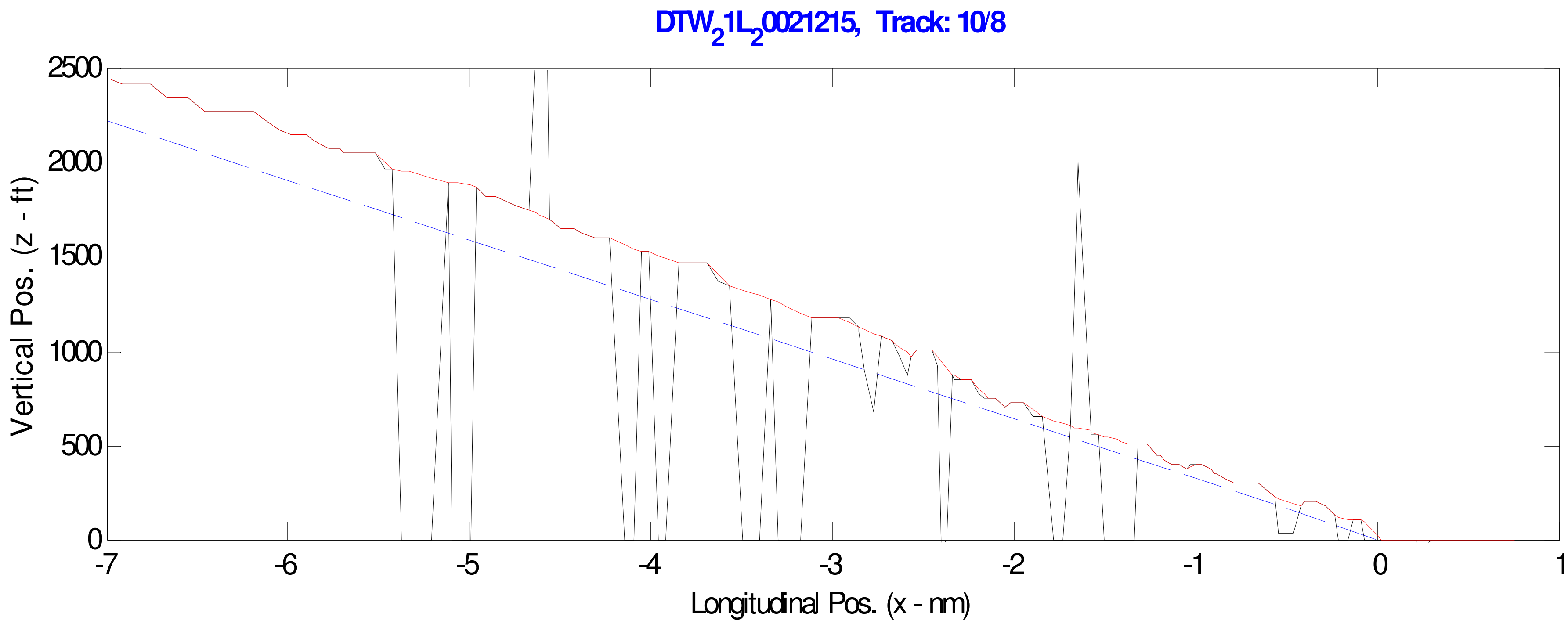
Threshold

Airplane $i+1$

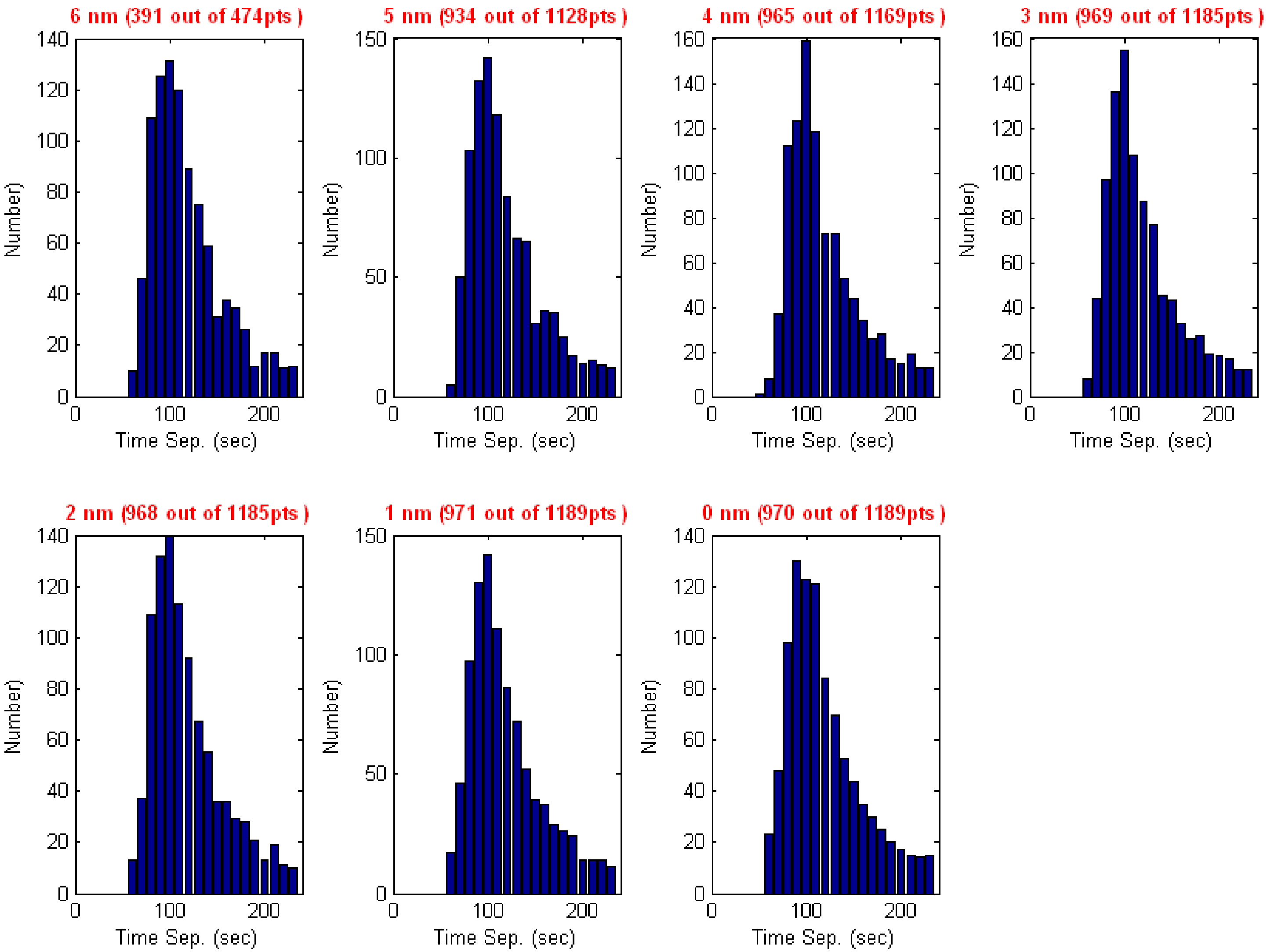
Runway

Aircraft Type	Threshold	Leave Runway
Heavy	10:23:14	10:24:04
Large	10:24:28	10:25:13
Large	10:26:16	10:27:12
Small	10:28:32	10:29:28
⋮	⋮	⋮

Fixing Vertical Measurements



Time Separations


6 nm (391 out of 474pts)

5 nm (934 out of 1128pts)

4 nm (965 out of 1169pts)

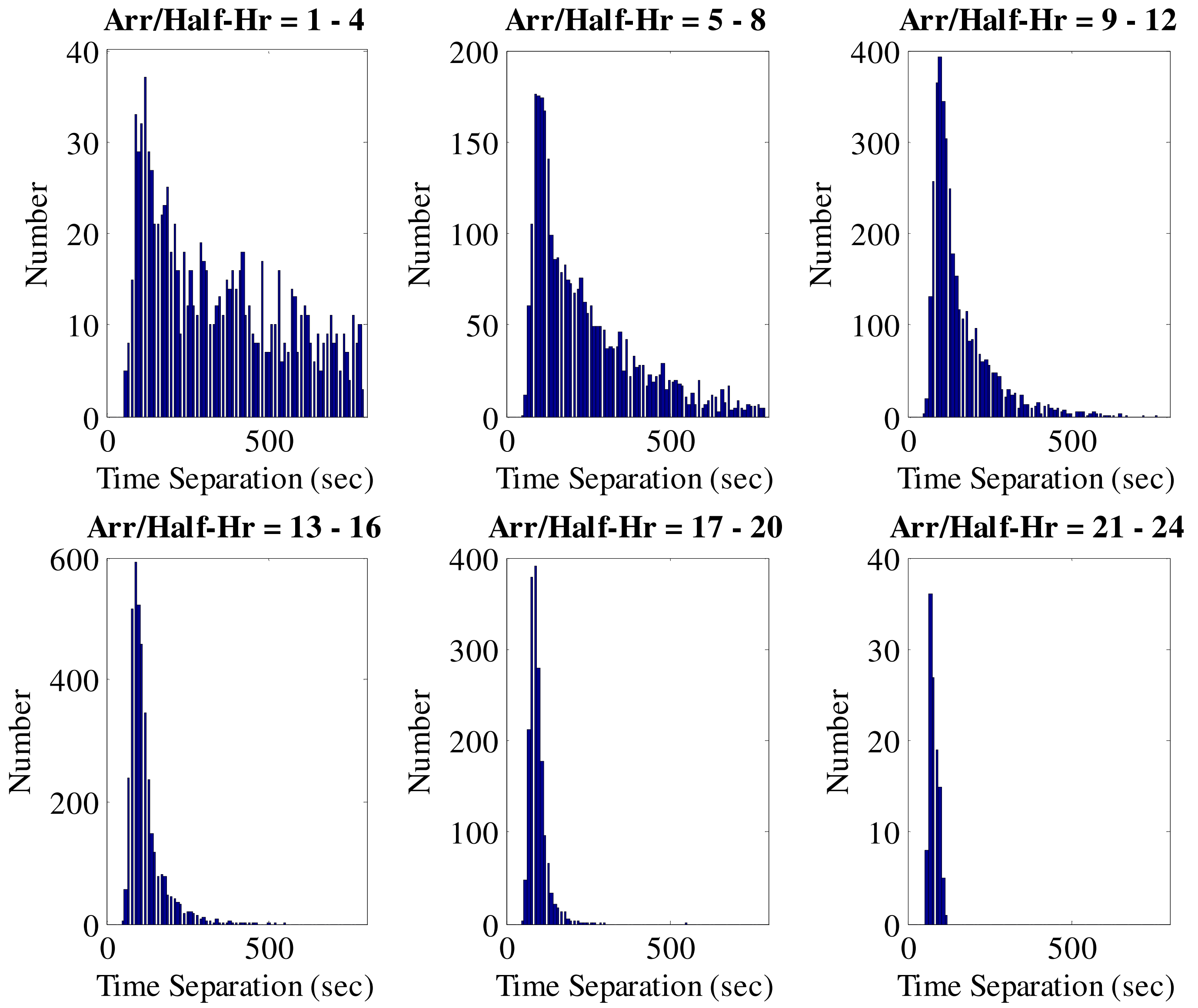
3 nm (969 out of 1185pts)

2 nm (968 out of 1185pts)

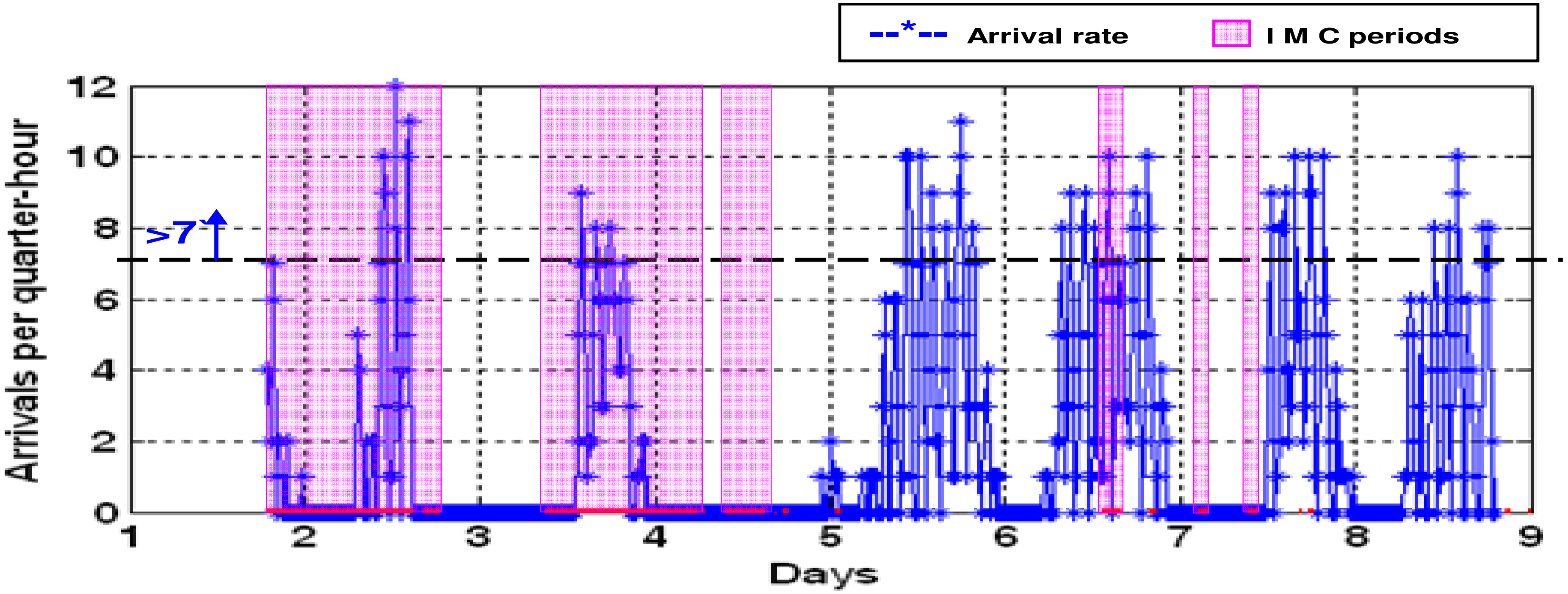
1 nm (971 out of 1189pts)

0 nm (970 out of 1189pts)

Time Separation by Arrival Rate

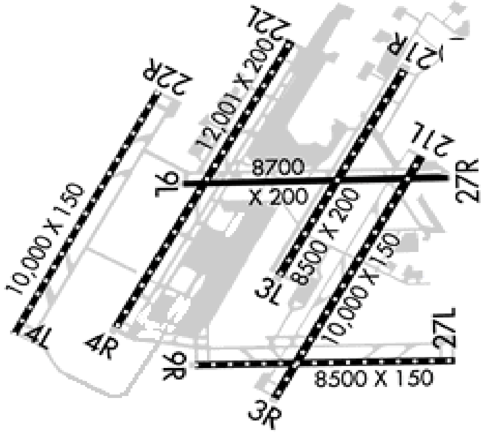


Arrival Rates in every quarter hour, Runway 21L



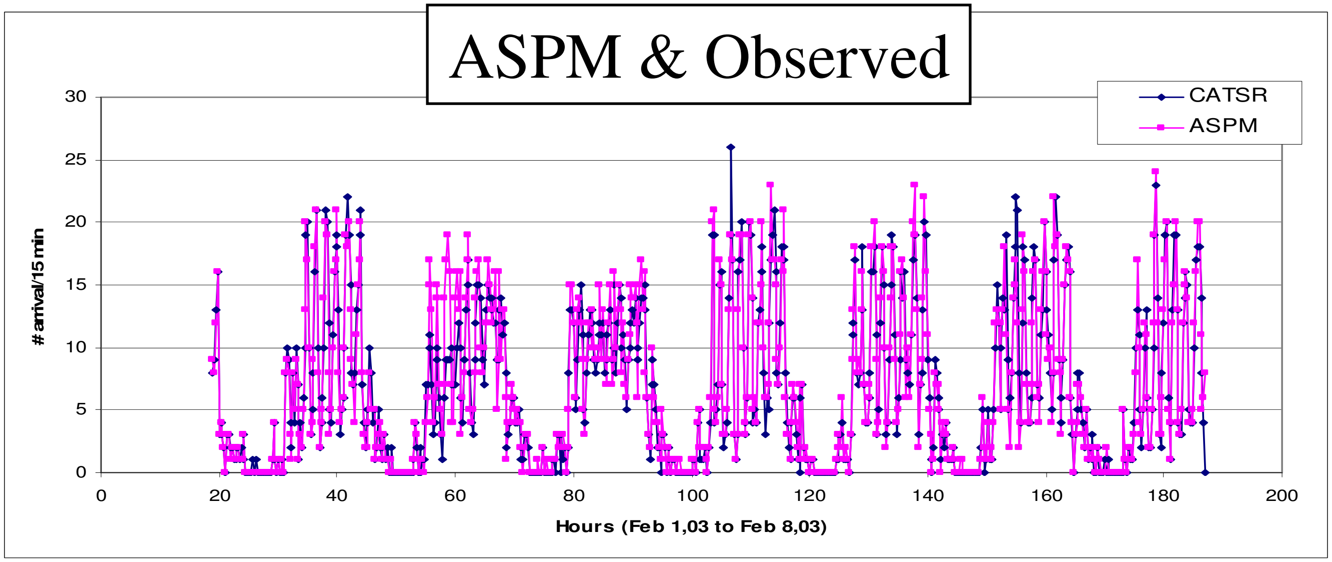
Total Observations in peak periods

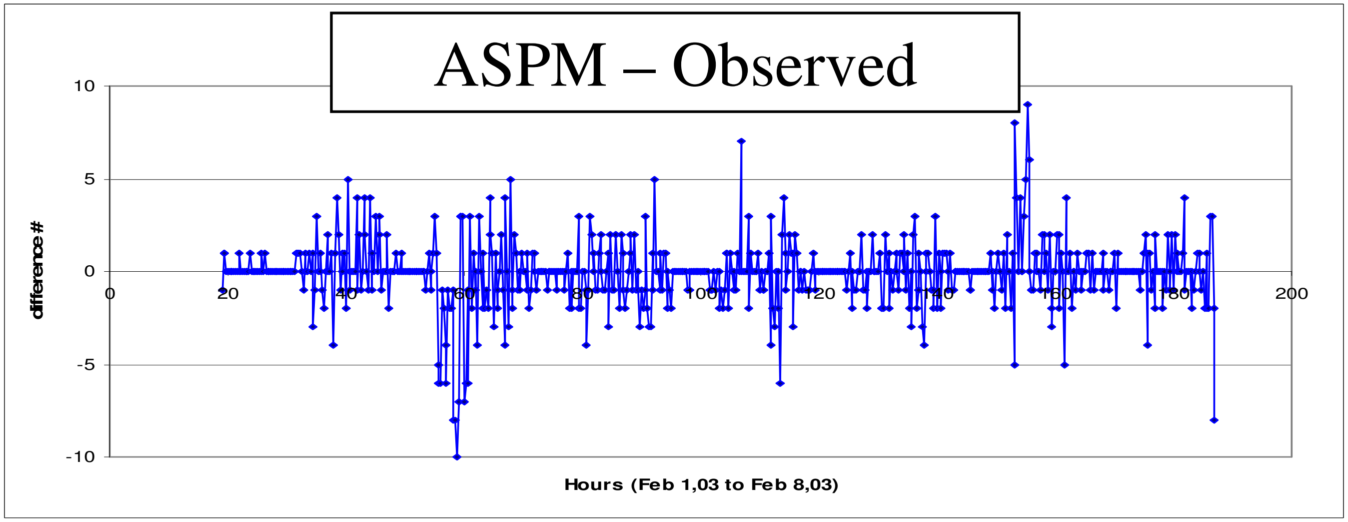
a/c Type	Runway													%
	03L	03R	04L	04R	09L	09R	21L	21R	22L	22R	27L	27R	Total	
Not Available	-	1	3	-	-	-	11	0	0	7	1	2	26	1.4
Small	-	19	26	-	-	-	98	0	3	101	18	17	280	15.1
Large	-	96	158	-	-	-	445	1	18	483	107	111	1418	76.2
B757	-	8	15	-	-	-	39	0	0	51	5	11	129	6.9
Heavy	-	0	4	-	-	-	1	0	1	1	0	0	7	0.4
Total	0	**124**	**206**	0	0	0	**594**	1	22	**643**	**131**	**141**	1862	100



- 4313 landings, 2 Feb 03 – 8 Feb 03 on all twelve runways
- 1862 in periods with arrival rate per quarter hour >= 7 (peak periods)

Comparison with ASPM Rates





Average Difference:
0.24 arrivals / qtr-h

Standard Deviation:
1.70 arrivals / qtr-h

Total difference: 160 landings or 3.6%

ASPM: Aviation System Performance Metrics

Lead-Follow Mixes

Percentage (out of 1805 pairs)

Follow \ Lead	Small	Large	B757	Heavy	Sum
Small	1.7	12.5	1.2	0.1	15.5
Large	12.8	**58.8**	5.4	0.3	77.3
B757	0.9	5.4	0.6	0.0	6.9
Heavy	0.1	0.3	0.0	0.0	0.4
Sum	15.5	77.1	7.1	0.3	100

Separation Minima Standards

ILS Approach In-Trail Threshold Separation Minima (nm)[1]

Follow\ Lead	**Small**	**Large**	**B757**	**Heavy**
Small	3	4	5	6
Large	3	3	4	5
B757	3	3	4	5
Heavy	3	3	4	4

class 6nm

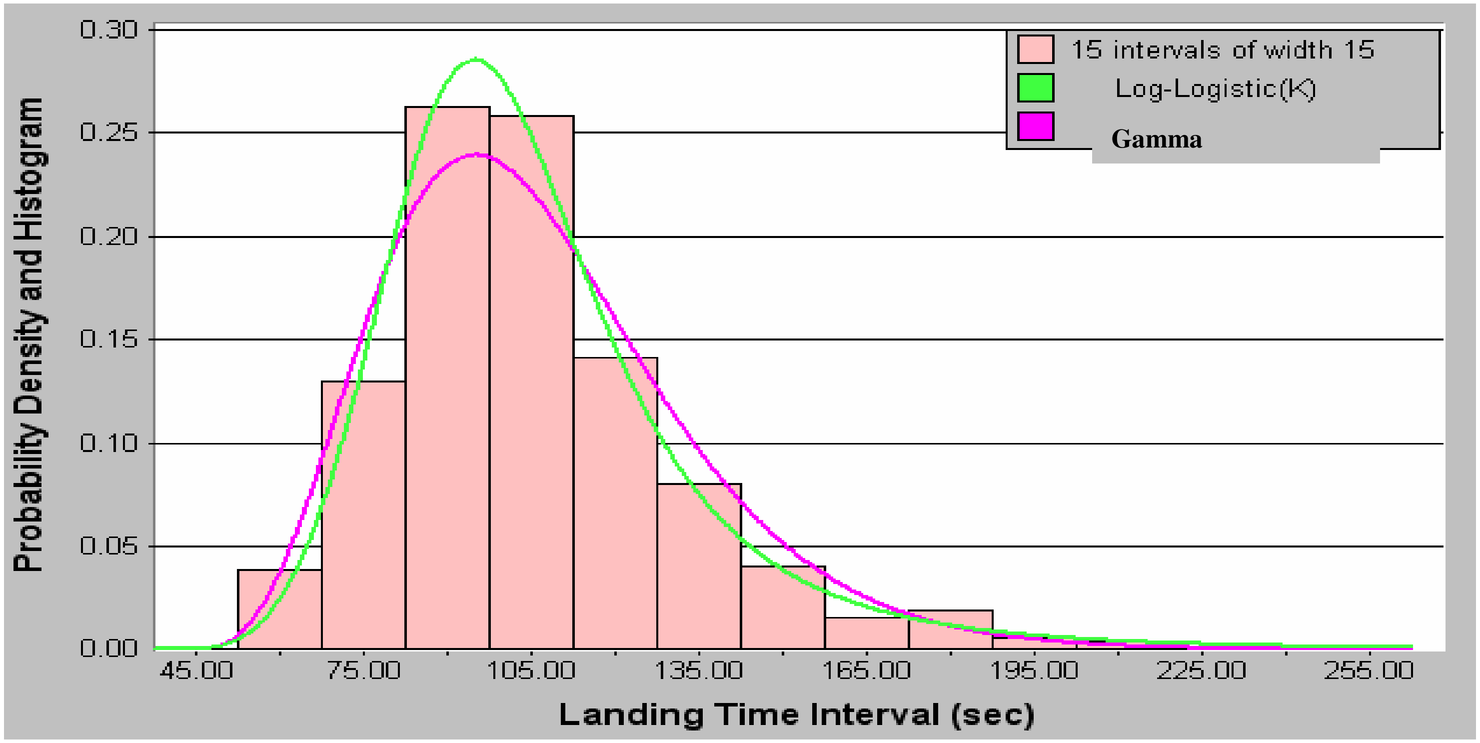
class 5nm

class 4nm

class 3nm

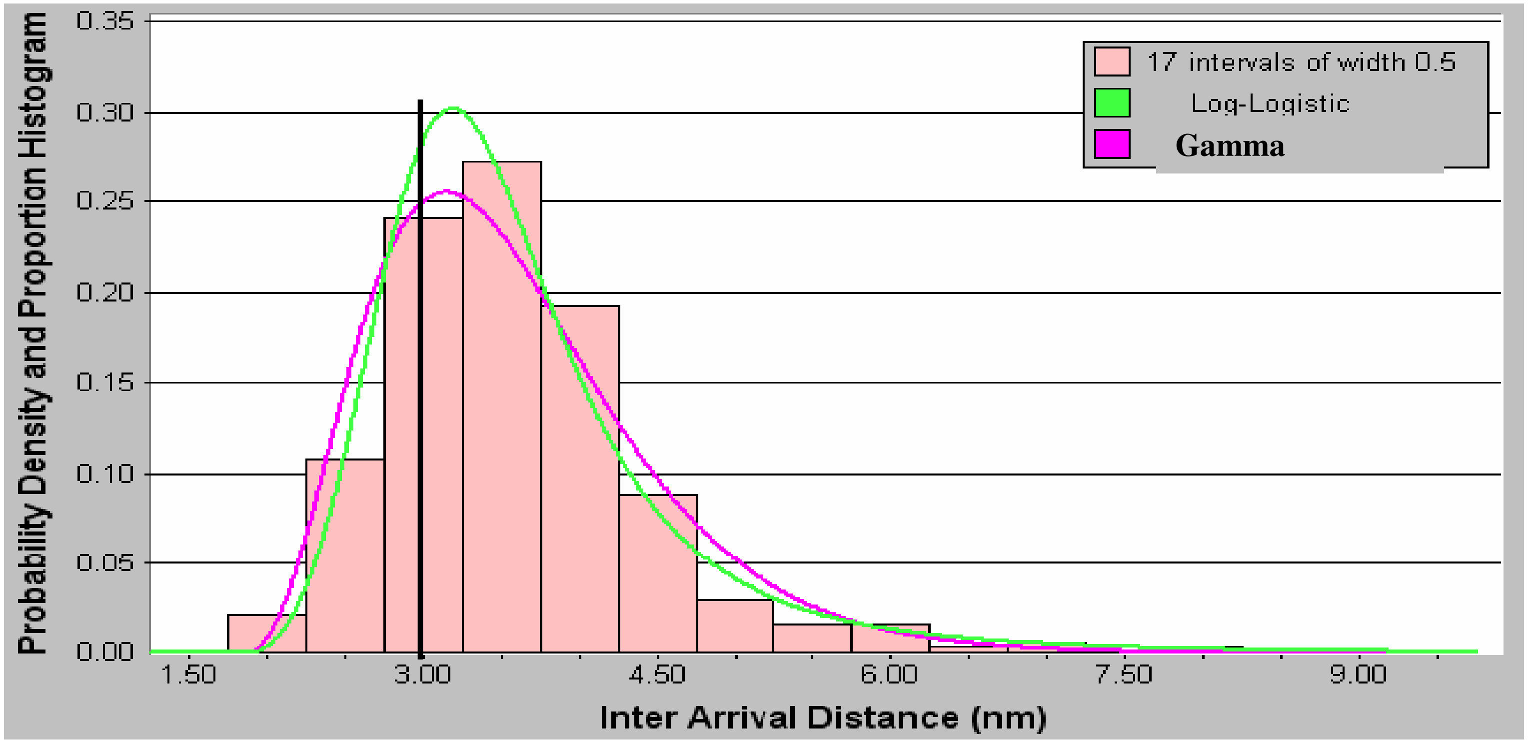
1) Ref: FAA 7110.65 Separation Rules For Arrivals and departures

Landing Time Interval (LTI)



- LTI over the runway threshold
- Instrument meteorological condition (IMC)
- 3 nm pairs
- 523 samples (during IMC peak periods)
- Fit: Gamma(40;11,6): mean 106 sec, std. dev. 27 sec.

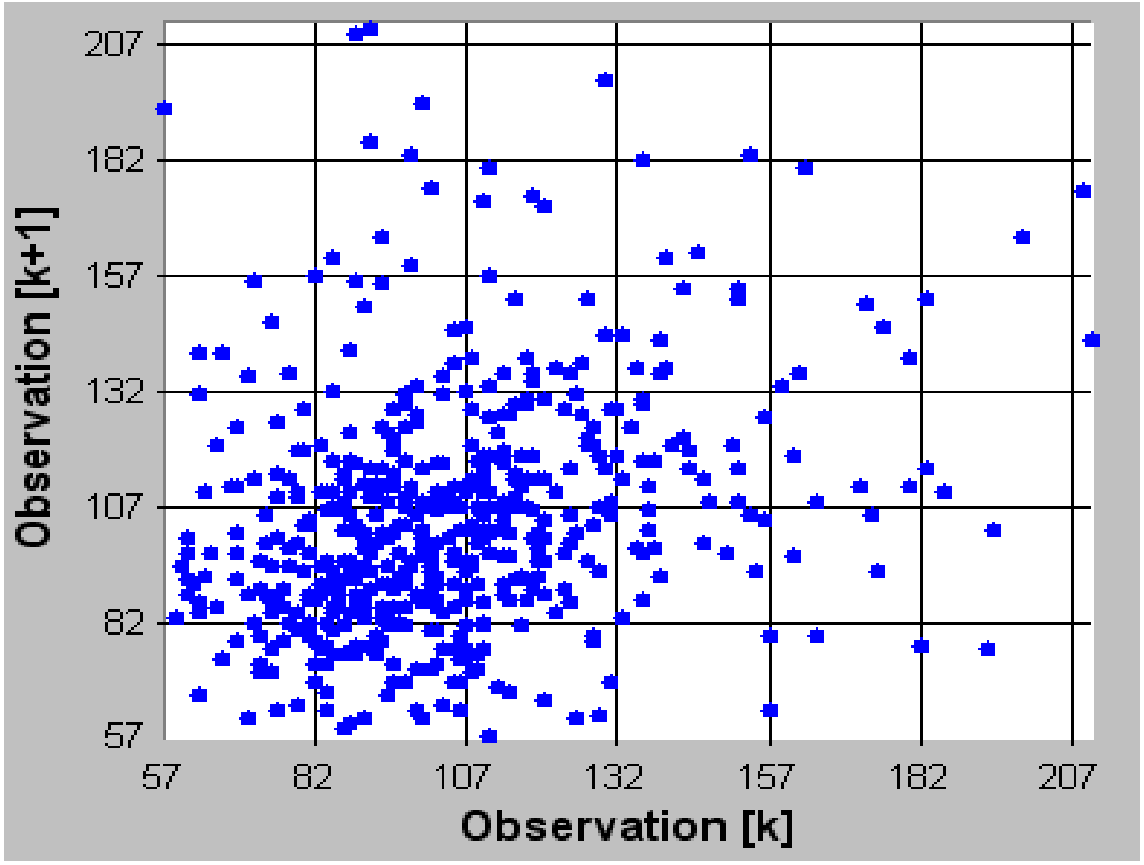
Inter-Arrival Distance (IAD)



- IAD to the runway threshold
- Instrument meteorological condition (IMC)
- 3 nm pairs
- 523 samples (during IMC peak periods)
- Fit: Gamma(1.5;0.35,6): mean 3.6 nm, std. dev. 0.86 nm.

Independence of LTI

One-Lag Scatter Plot

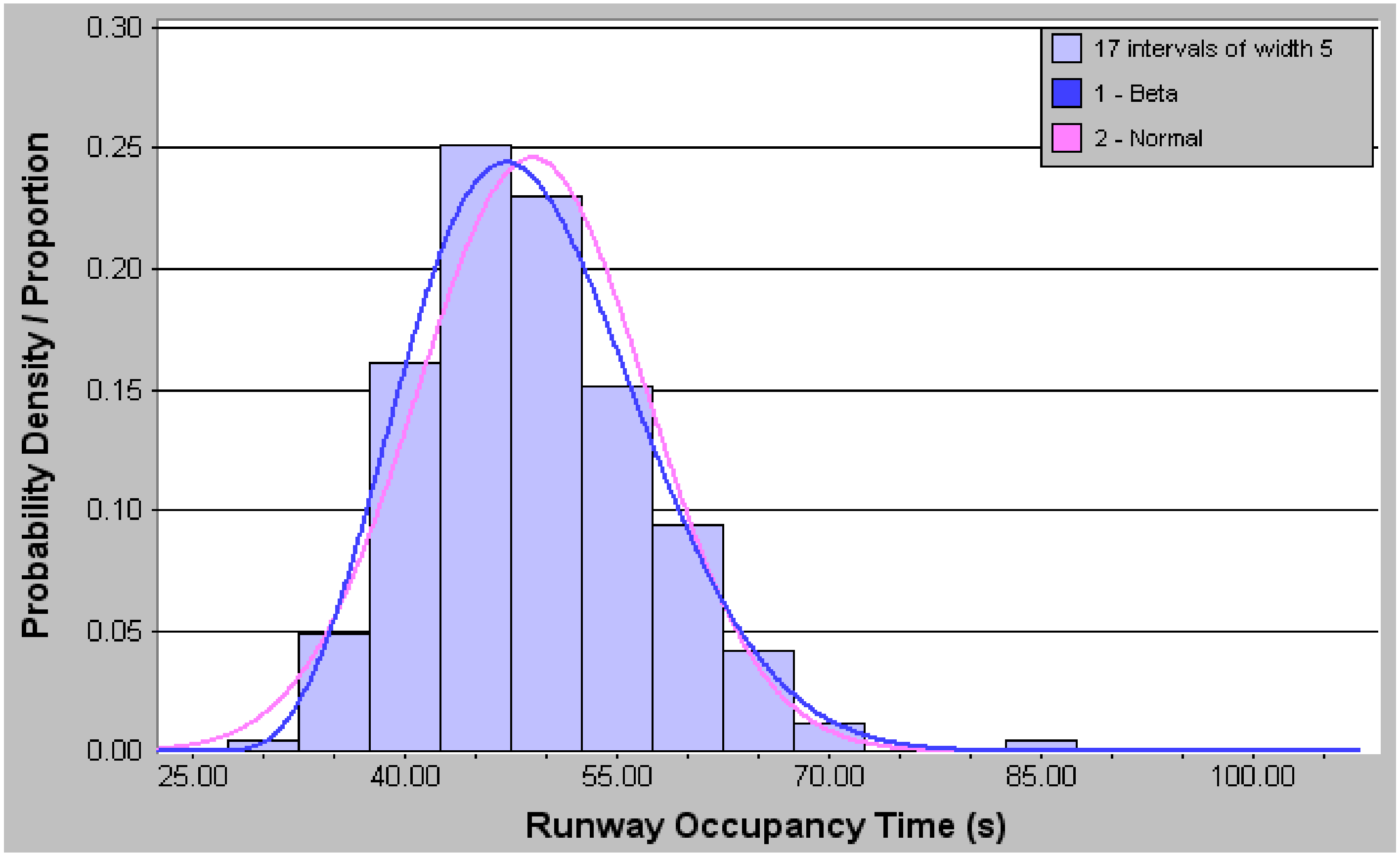


Landing Time Interval (s)

.One-lag correlation coefficient: 0.25

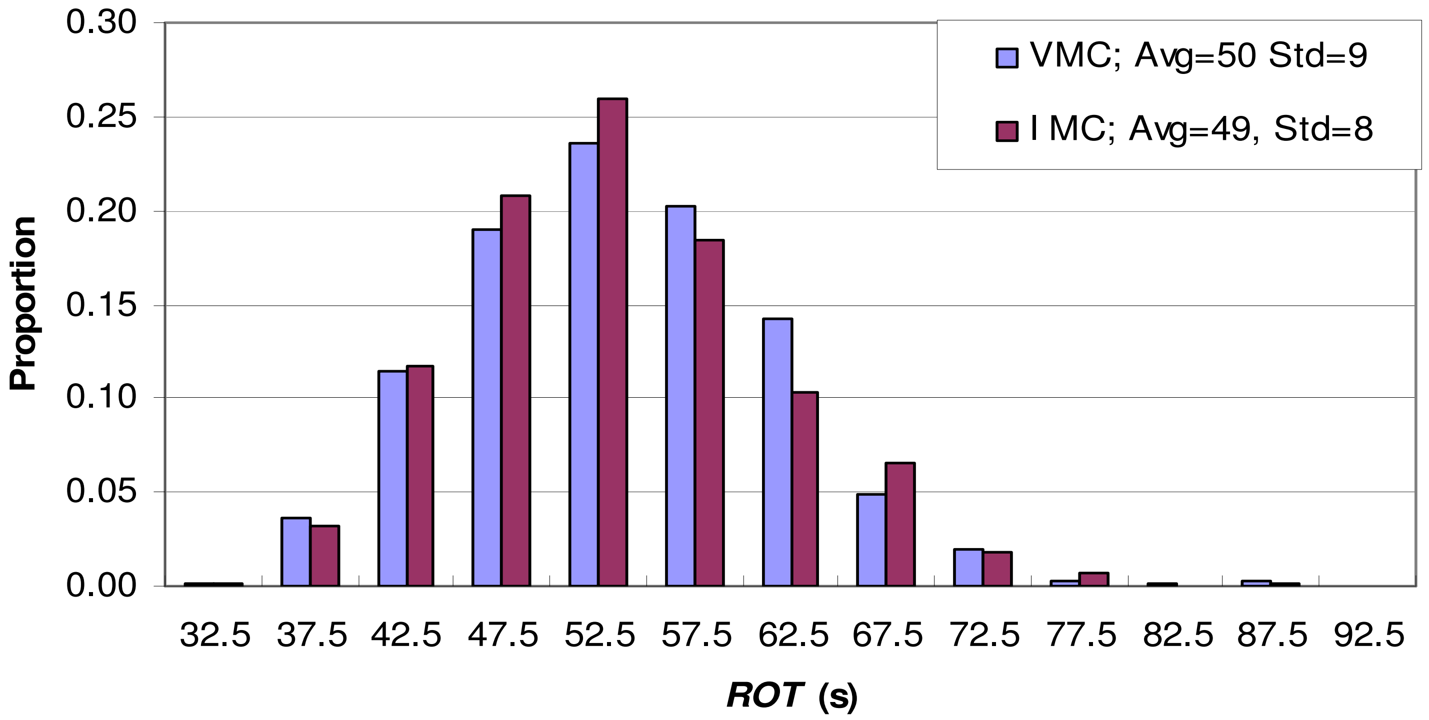
- Correlation coefficients for higher degrees of lags are smaller
- With some compromise, we decide the samples are independent
- In similar manner, we accept sample independence for *IAD.*

Runway Occupancy Time (ROT)



- 669 samples for *all* aircraft types, peak IMC periods
- Sample mean 49.1 s, standard deviation 8.1 s
- Beta(6.1,15.4) in the (25,110)s
- N(49, 8.1^2) is rejected in the 0.10 significance level

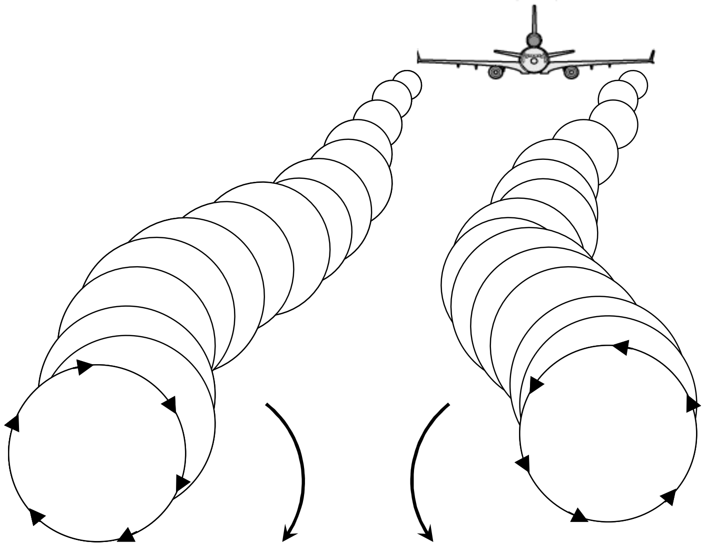
ROT: IMC vs. VMC



- *ROT* for runways 21L/03R and 22R/04L
- IMC (590 samples), VMC (895 samples)
- No significant difference between IMC and VMC observed

Wake Analysis

Wake Vortex Encounters



Problems

- A trailing aircraft may fly through a vortex generated by the leading aircraft, resulting in an un-commanded roll and possibly a crash.
- Wakes are generally hard to "see" and measure

Some Wake Models

TDAWP (TASS Driven Algorithms for Wake Prediction) (NASA)

- Derived as a fit to large eddy simulations

APA (AVOSS Prediction Algorithm) v. 3.2 (NASA)

- Combines several models
- Includes near-ground and in-ground effects

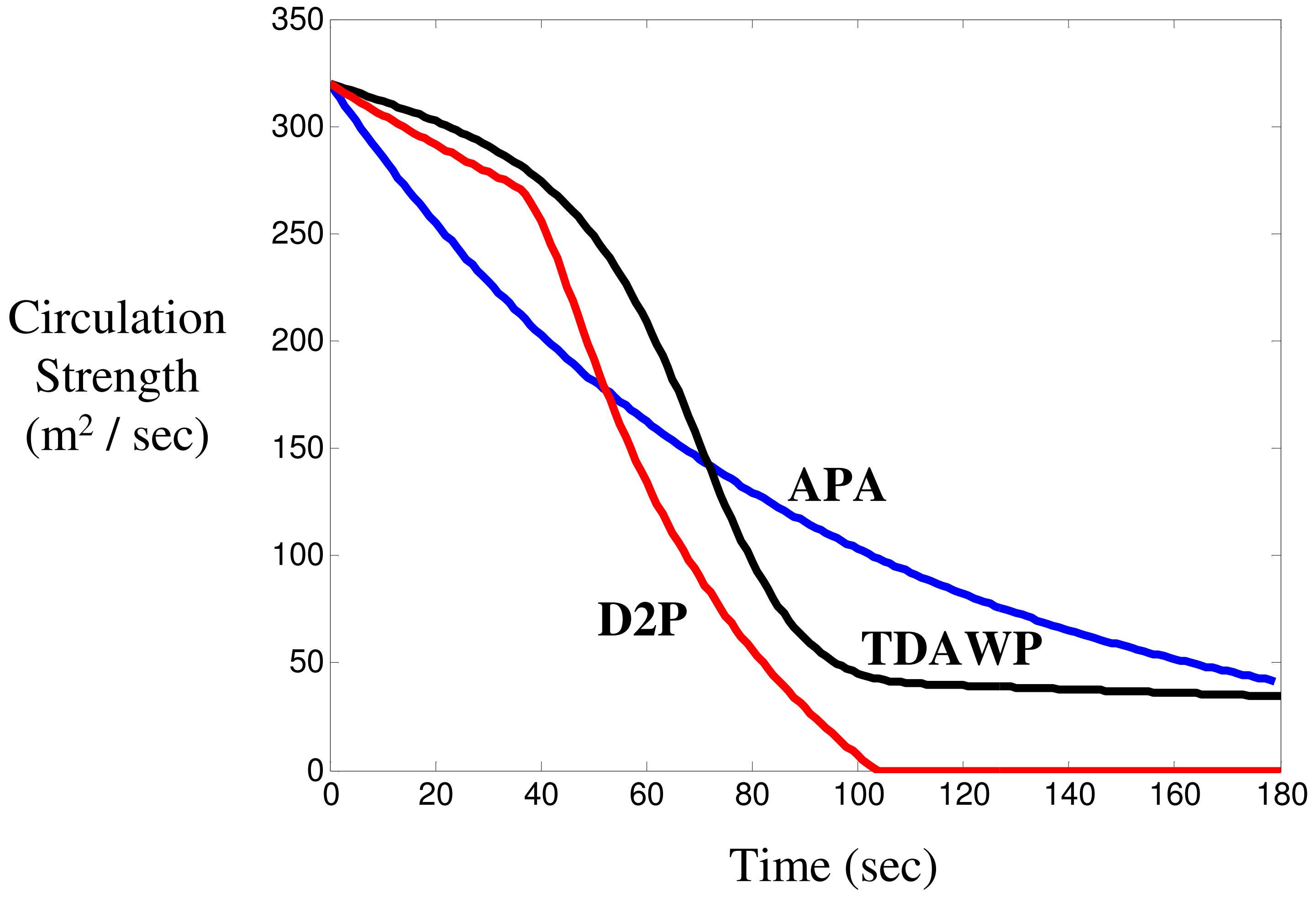
D2P / P2P (Deterministic / Probabilistic 2-Phase) (DLR)

- Derived as a fit to large eddy simulations

Acronymetafication – using acronyms recursively

- Holzapfel, F. 2003, Probabilistic two-phase wake vortex decay and transport model, *Journal of Aircraft*, **40**(2), 323-331.
- Proctor, F., D. Hamilton. 2006. TASS driven algorithms for wake prediction. 44th AIAA Aerospace Sciences Meeting and Exhibit. Reno, Nevada.
- Robins, R., D. Delisi. 2002. NWRA AVOSS wake vortex prediction algorithm version 3.1.1. NASA technical report NASA / CR-2002-211746.

Sample Wake Model: Circulation



Weight = 76,000 kg

Velocity = 65 m/s = ~135 knots

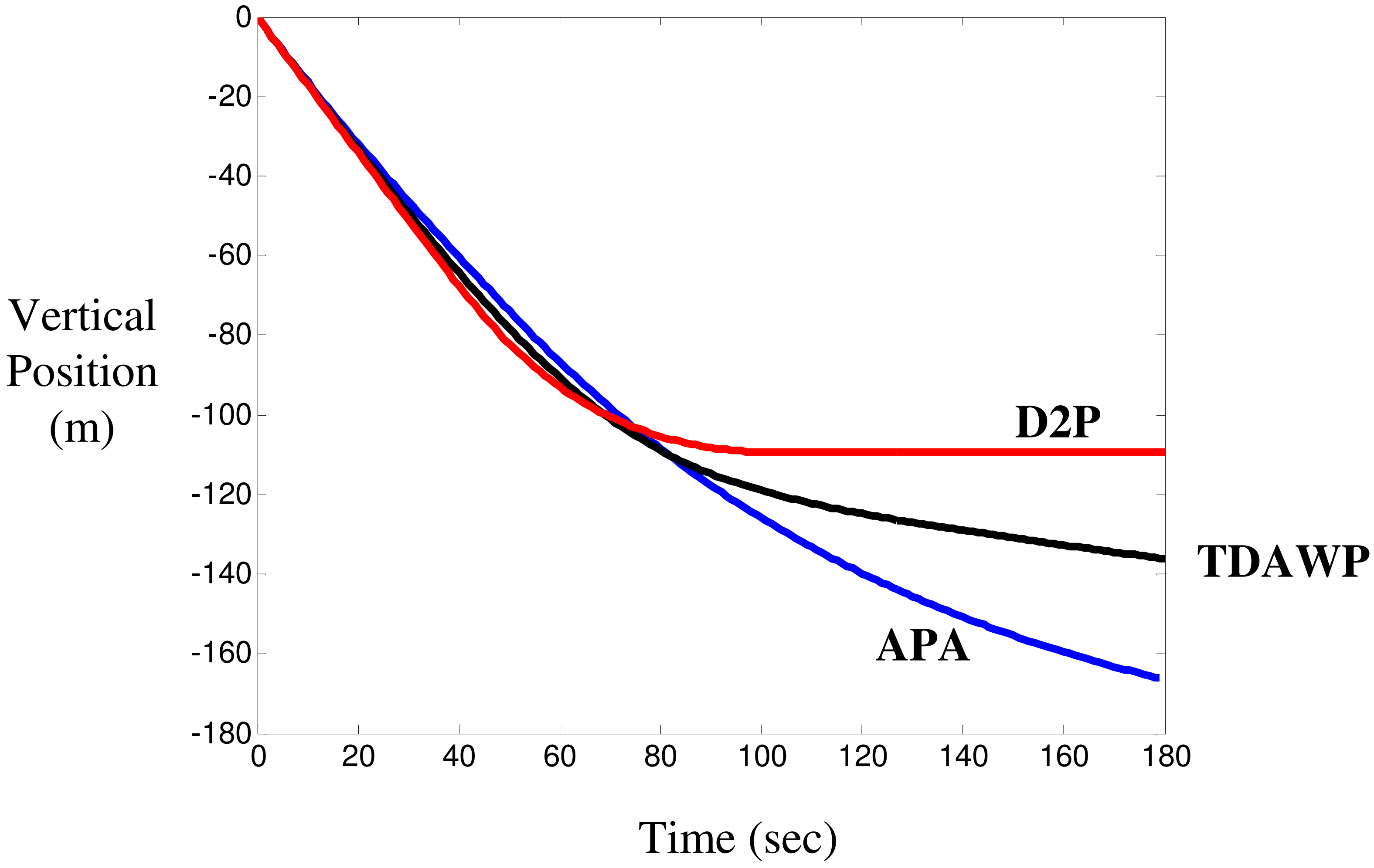
$N = 0.0$ / sec

Wing span = 38 m

Height = 1,000 m

$\varepsilon = 0.001\ m^2 / s^3$

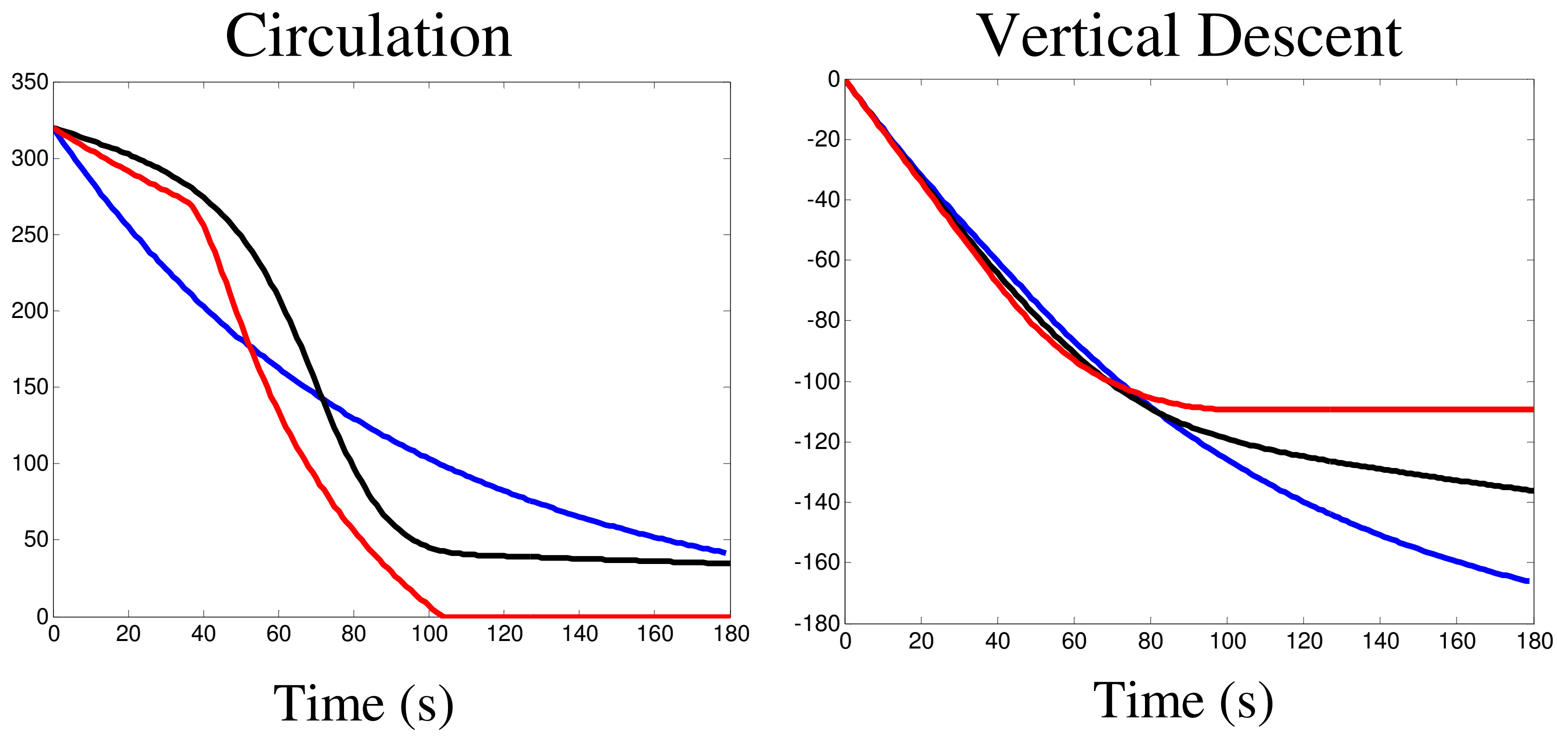
Sample Output: Vertical Descent



Weight = 76,000 kg
Velocity = 65 m/s = ~135 knots
N = 0.0 / sec

Wing span = 38 m
Height = 1,000 m
$\varepsilon = 0.001\ \mathrm{m}^2/\mathrm{s}^3$

Circulation and Descent



Basic Effects

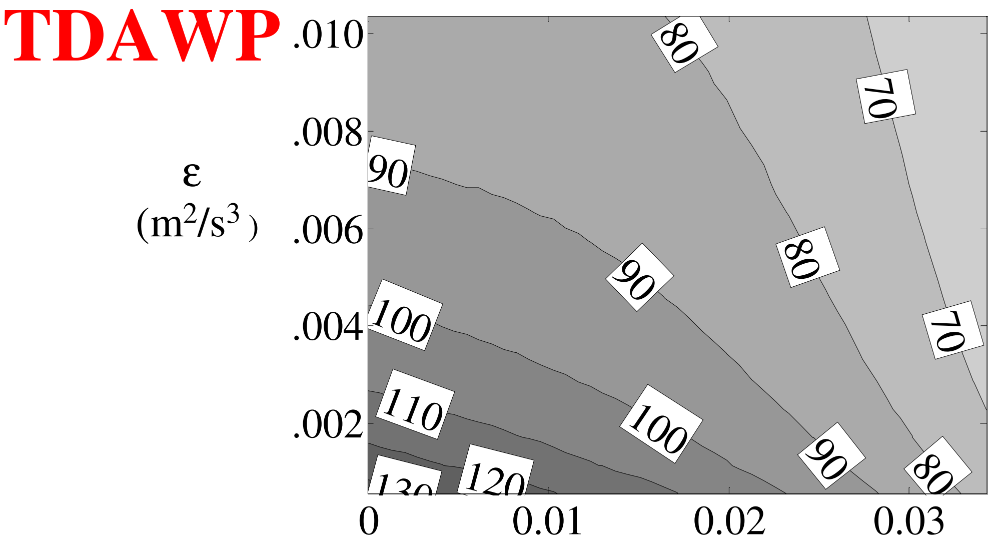
- Stronger wakes sink more quickly
- Wakes that decay faster sink more slowly

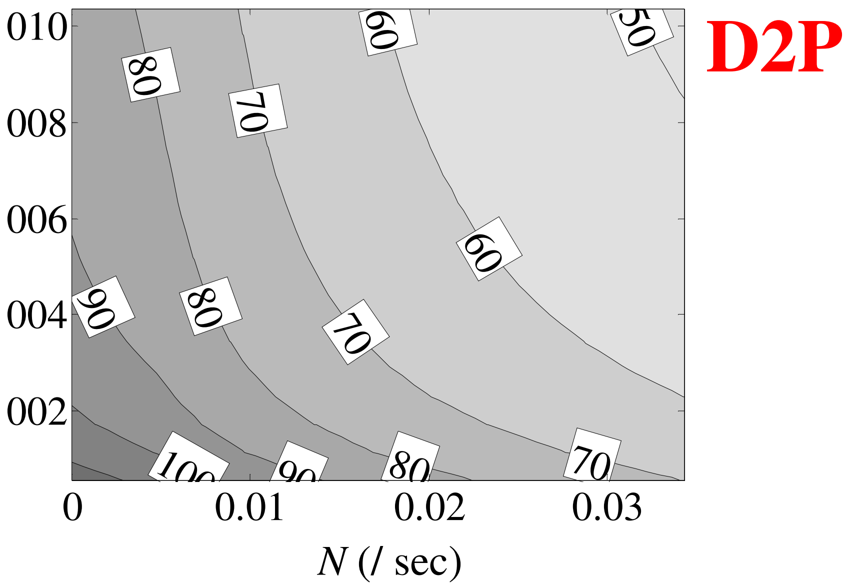
Key Atmospheric Parameters

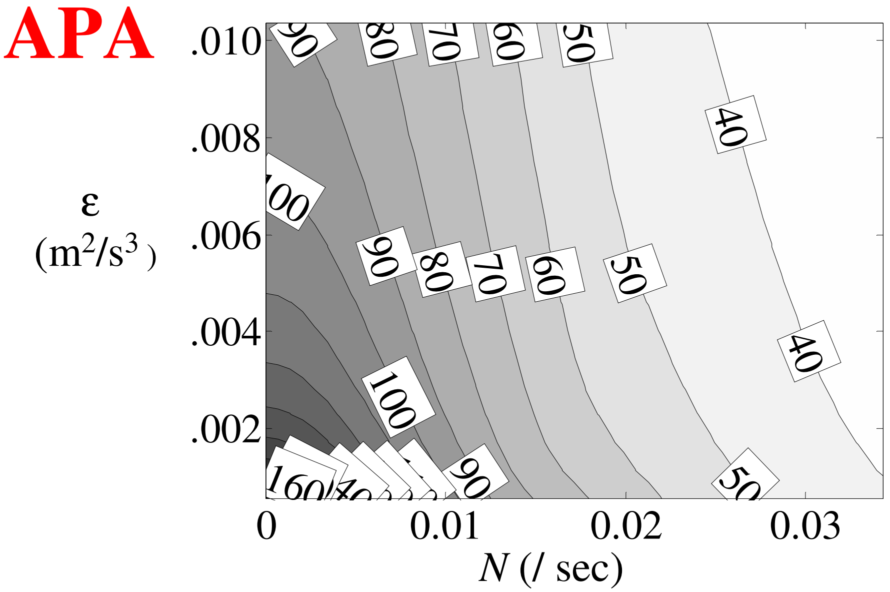
- Eddy dissipation rate ε
  - Units $\frac{\text{energy}}{\text{time}\times\text{mass}} = \frac{\text{kg}\times\text{m}^2/\text{s}^2}{\text{s}\times\text{kg}} = \frac{\text{m}^2}{\text{s}^3}$
  - A measure of turbulence
  - Higher values result in faster vortex decay
- Brunt-Vaisala frequency *N*
  - Oscillation frequency of displaced mass of air
  - Related to vertical gradient of potential temperature
  - Higher values result in
    - Fast vortex decay
    - Slower vortex sink and possible "bounce"

Potential temperature: Temperature that a volume of air would be at if brought adiabatically to a reference pressure.

Comparison of Models



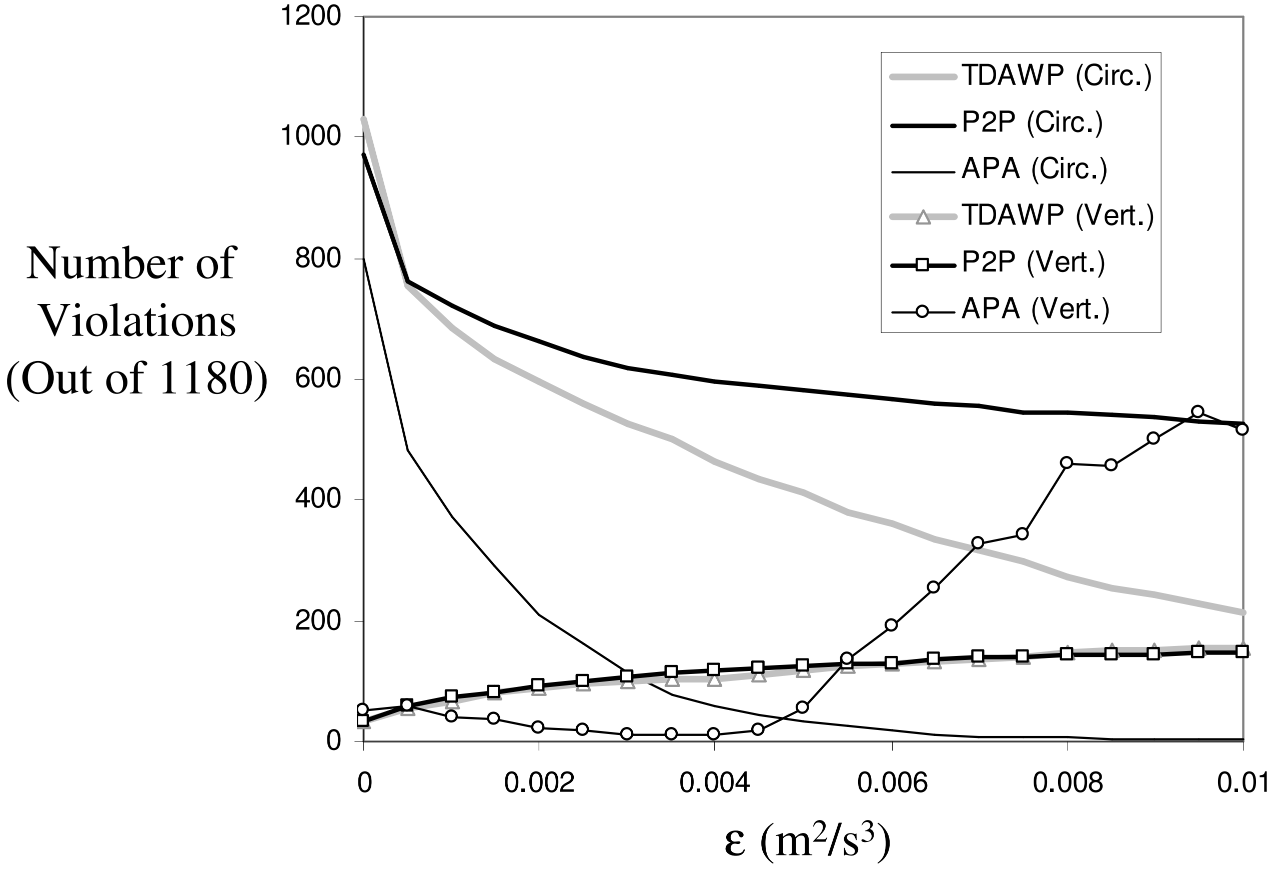




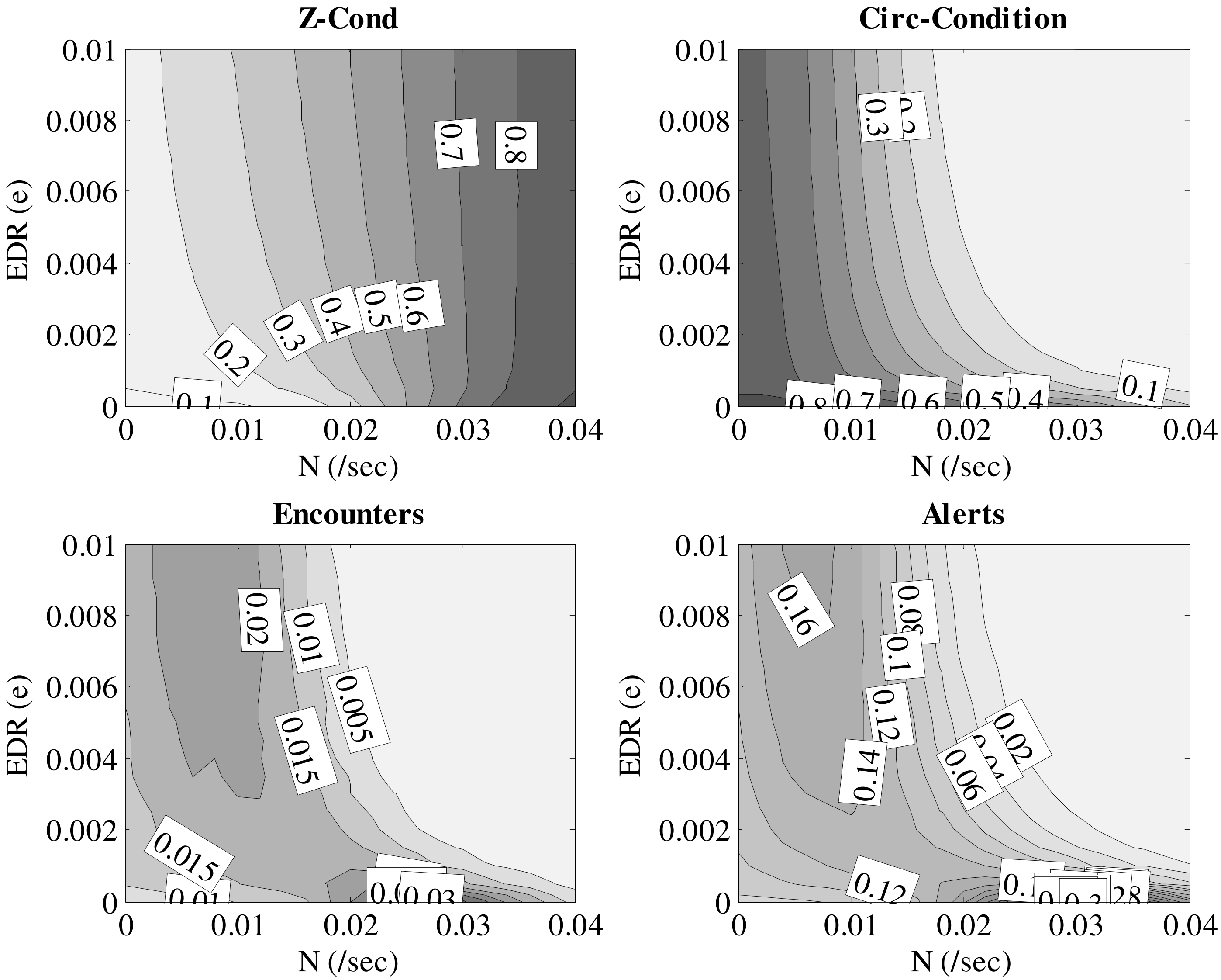
Figures show:
time to decay to 40% of initial circulation (seconds)

Weight = 273,000 kg
Velocity = 80 m/s = ~155 knots
Wing span = 64.4 m
Height = 1,000 m

Comparison of Models



Wake Encounters / Alerts



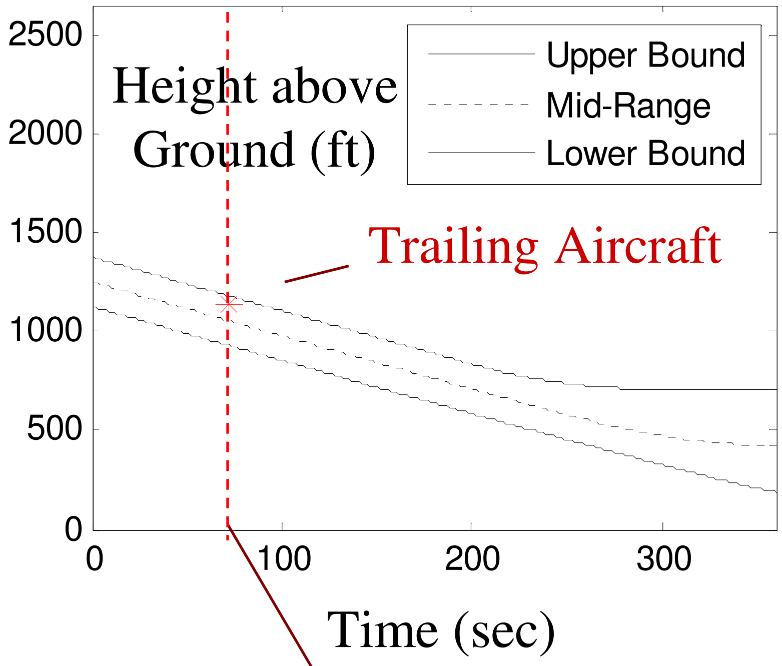
Definitions

1. **Lateral (*y*) condition**: The lateral positions of the trailing aircraft and the wake overlap
2. **Vertical (*z*) condition**: The vertical positions of the trailing aircraft and the wake overlap
    a) **Modified**: The vertical position of the trailing aircraft is *below* the wake.
3. **Circulation condition**: The circulation of the wake has not decayed below a specified threshold.

- ***Wake encounter*** = (1) and (2) and (3)
- ***Wake alert*** = (2a) and (3)

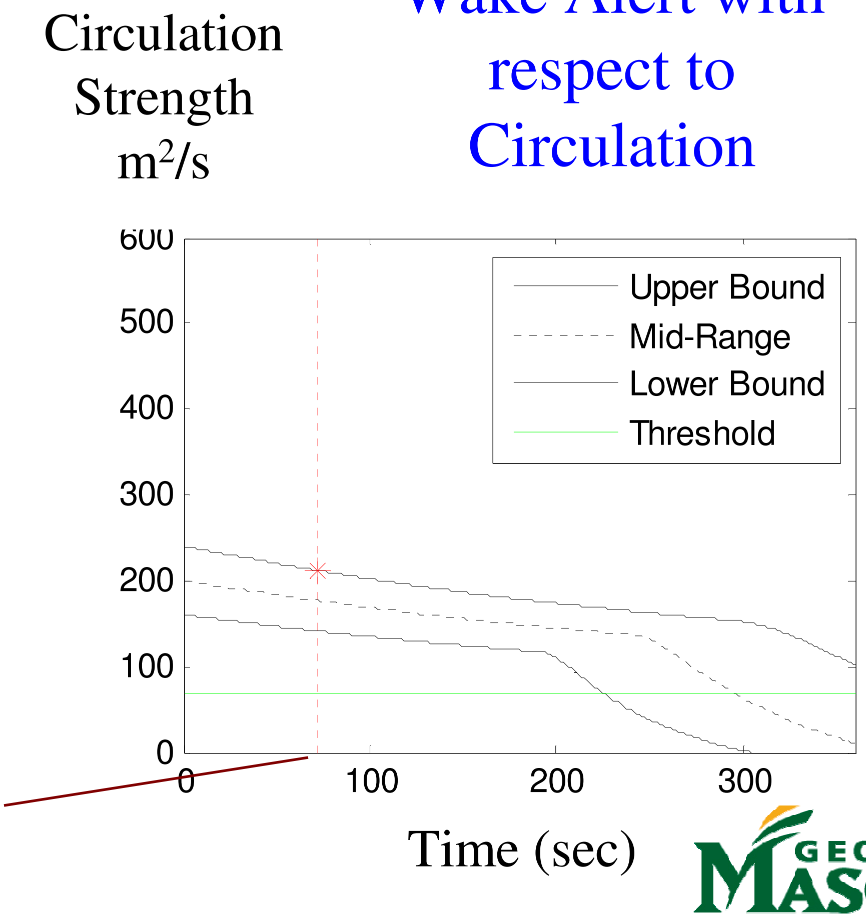
Sample Wake Alert

Wake Alert in Vertical Dimension



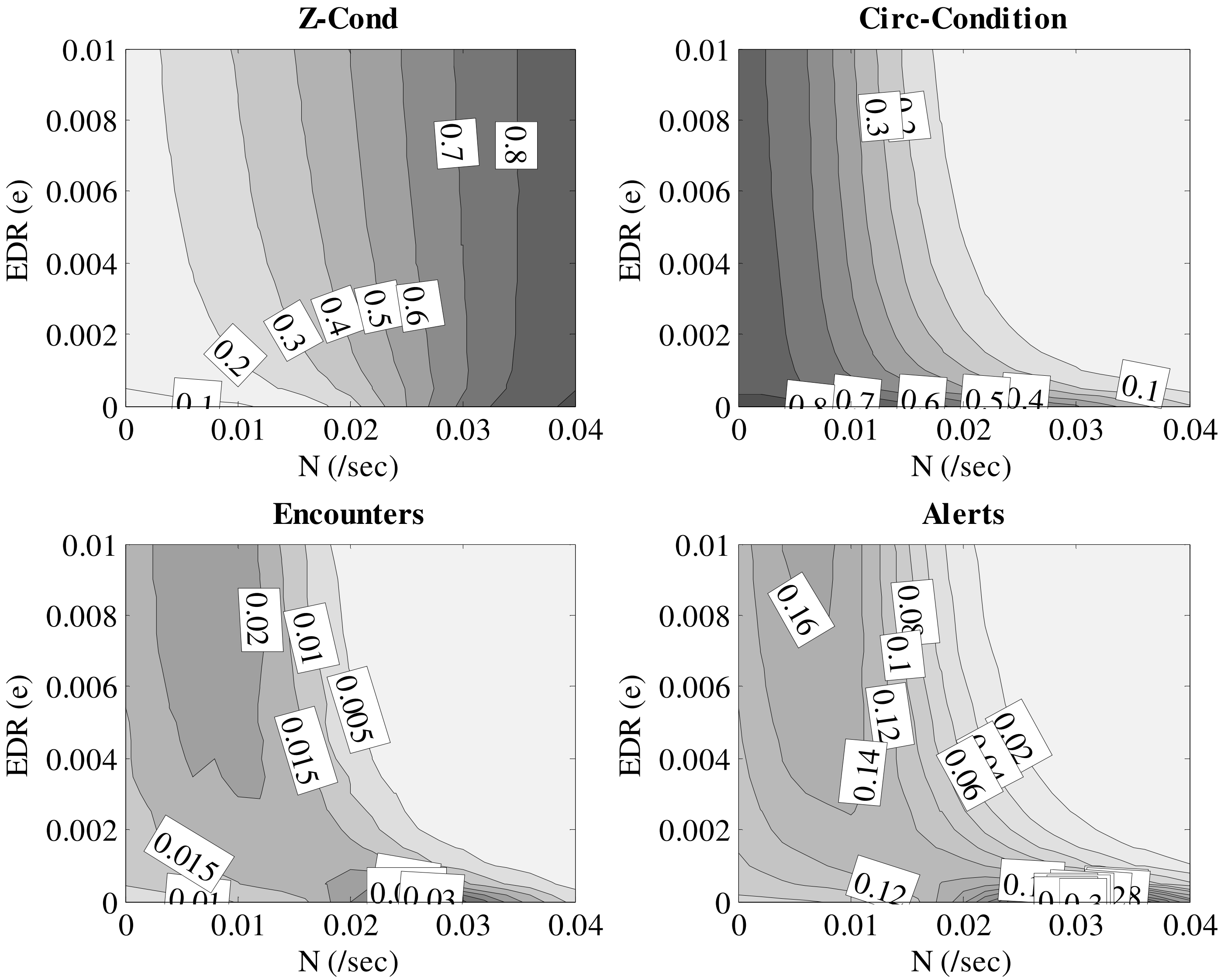
Trailing Aircraft

Wake Alert with respect to Circulation

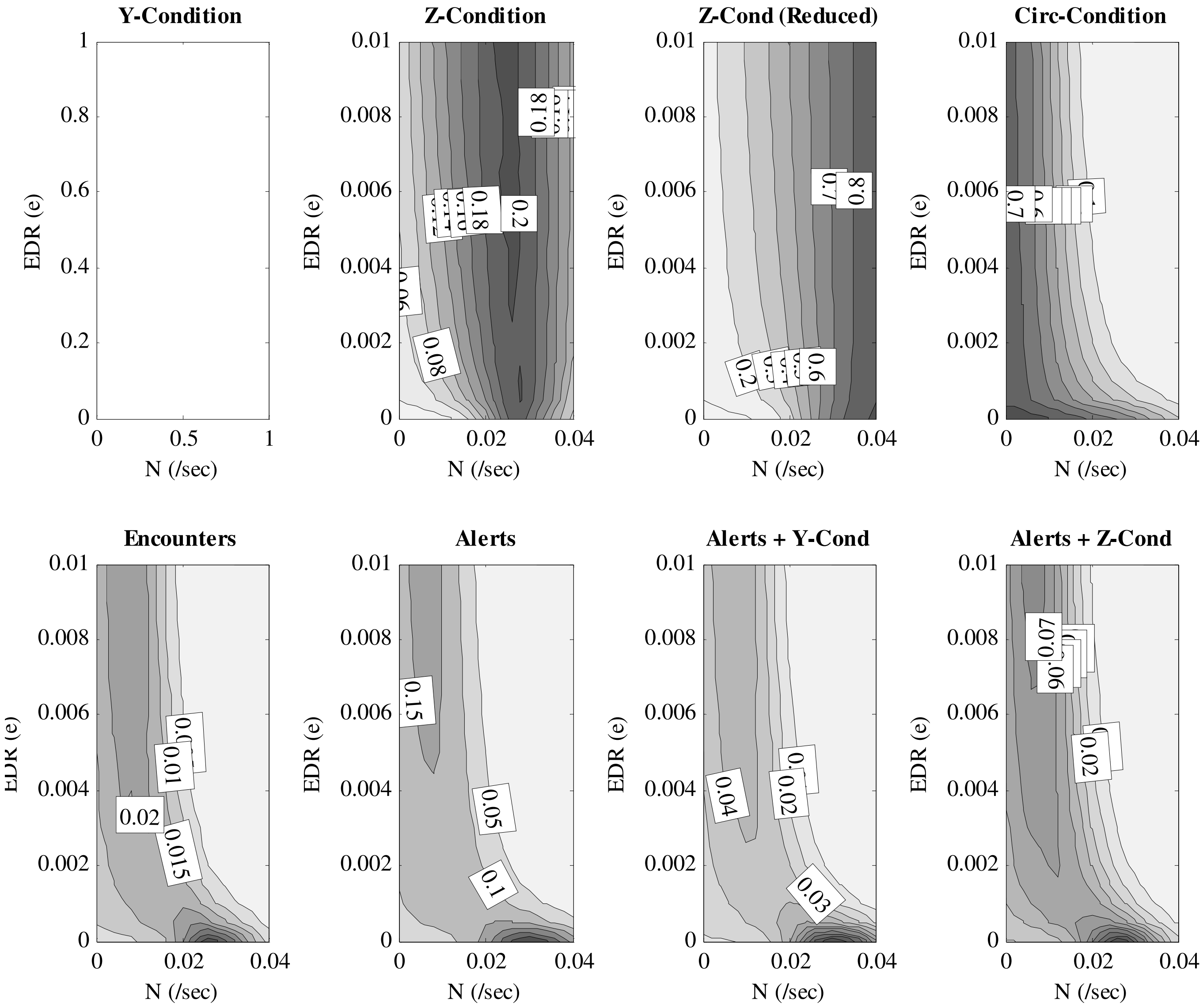


Time Separation of Aircraft Pair ~70 sec

Wake Encounters / Alerts



Wake Encounters / Alerts

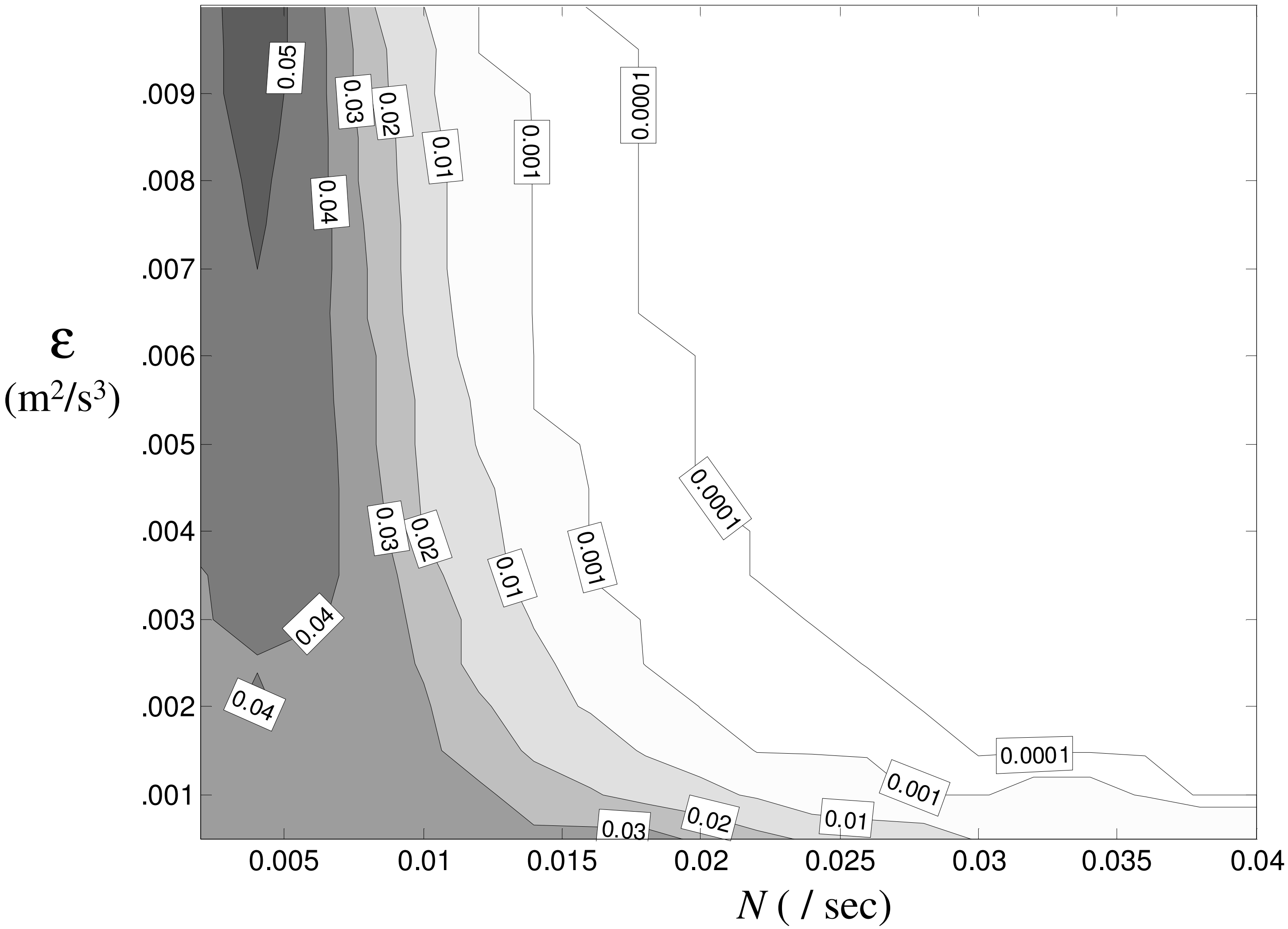


Detroit Airport

Detroit Airport (DTW)

Effects of Atmospheric Parameters

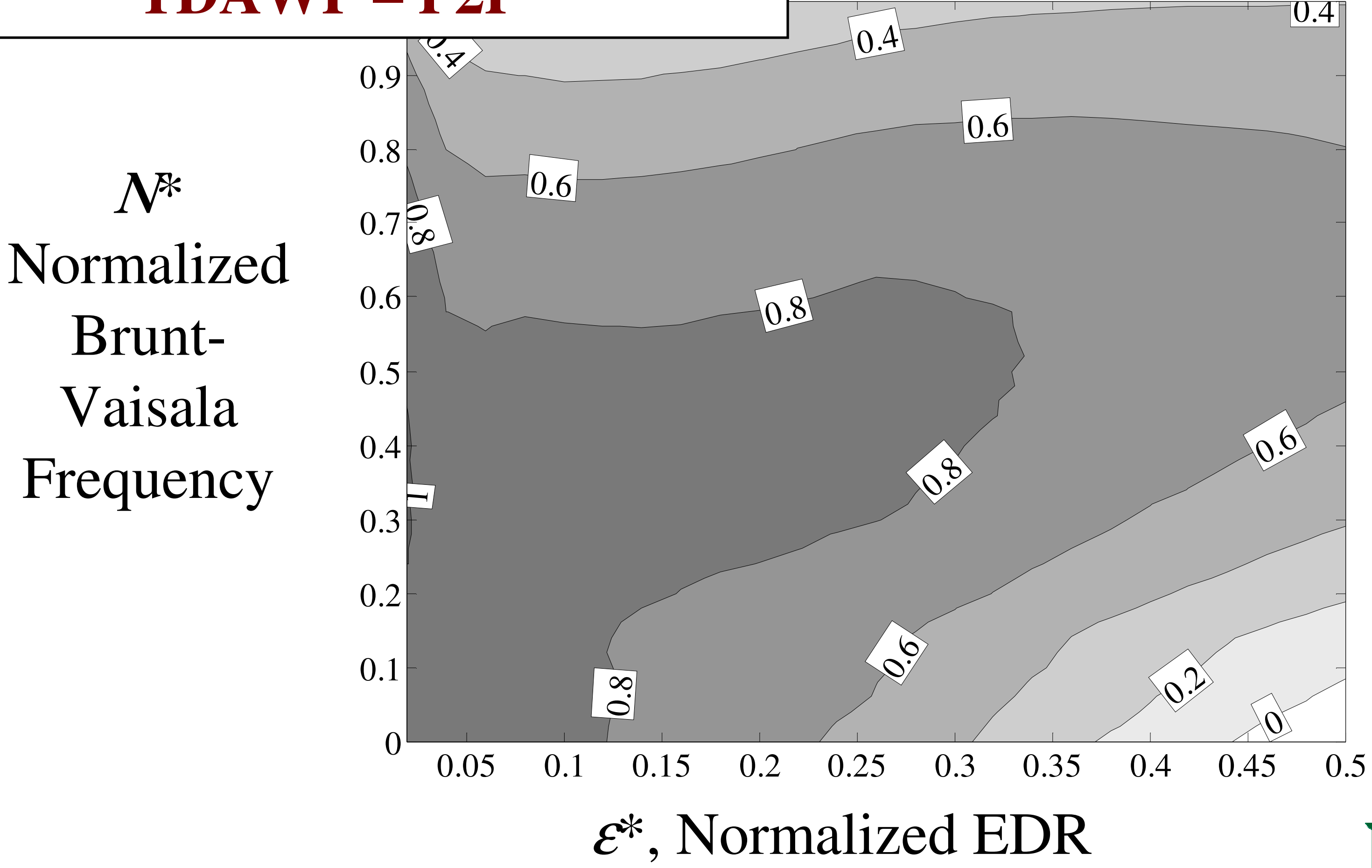
Wake Threshold = 125 m^2/s



Data source: DTW 21L, ~1,200 landings, Jun '03

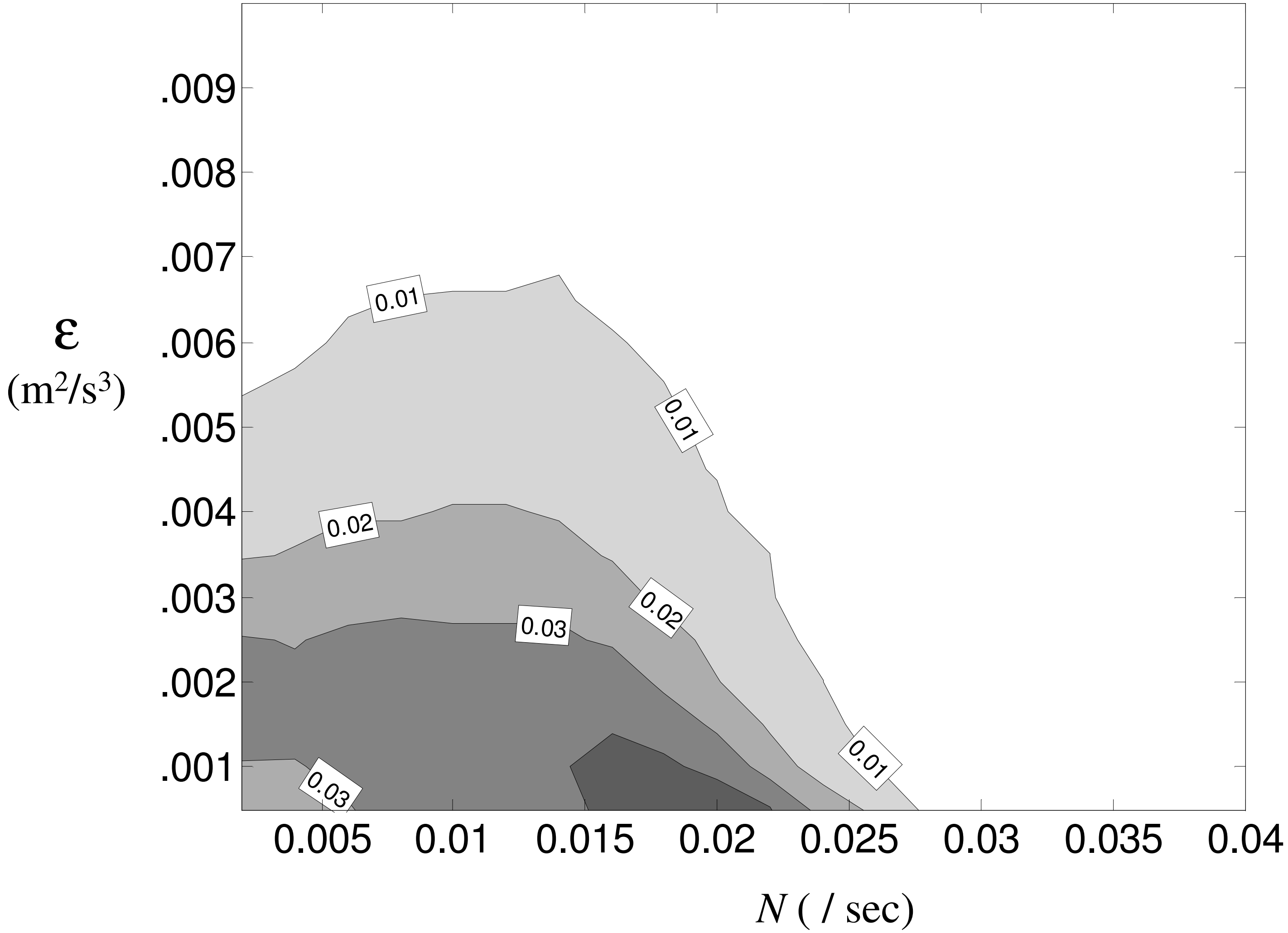
Comparison of Wake Models Work

Difference in normalized time
To reach 40% of initial circulation
TDAWP – P2P



TDAWP

Wake Threshold = 125 m^2/s



Standard Inputs and Parameters

Key Inputs

Description	Variable	Units	Sample Value
Mass of airplane	M	kg	273,000 kg (747)
Velocity of airplane	V	m/s	80 m/s (~155.5 knots)
Wing span of airplane	B	m	64.4 m (747)
Air density	ρ	kg/m^3	1.2 kg / m^3 (near ground)
Eddy dissipation rate	ε	m^2/s^3	0 (low);
Brunt-Vaisala frequency	N	1/s	0 (low); 0.04 / s (high)

Reference Values

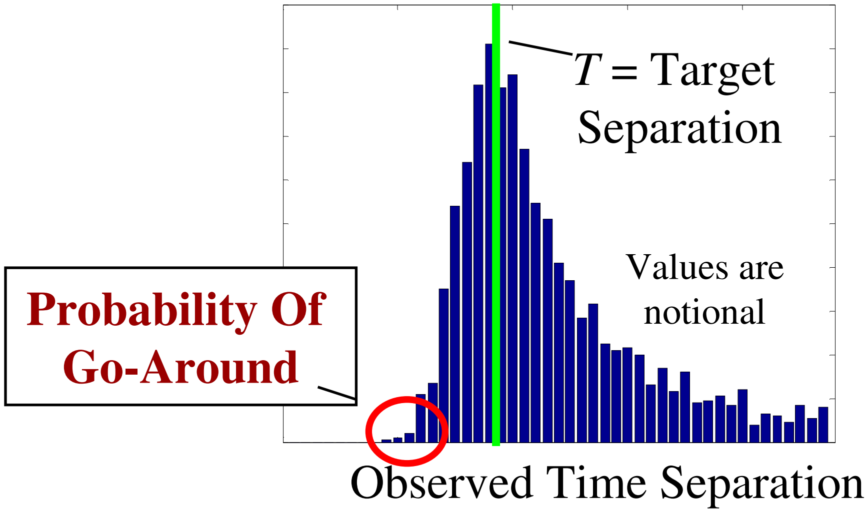
Description	Formula	Units	Sample Value
Initial circulation	$\Gamma_0 = \frac{Mg}{\rho s B V}$	m^2/s	551 m^2/s (for 747 landing)
Initial vortex spacing	$b_0 = sB$	m	50.6 m (for 747)
Initial descent speed	$w_0 = \frac{\Gamma_0}{2\pi b_0}$	m/s	1.73 m/s (for 747 landing)
Appx. time to descend one initial vortex spacing	$t_0 = \frac{b_0}{w_0} = \frac{2\pi b_0^2}{\Gamma_0} = \frac{8s^4 B^3 \rho V}{Mg}$	s	29.2 sec (for 747 landing)

Normalized Values

Description	Formula	Sample Value
Normalized EDR	$\varepsilon^* = \frac{(\varepsilon b_0)^{1/3}}{w_0} = \frac{2\pi\varepsilon^{1/3} b_0^{\ 4/3}}{\Gamma_0}$	0.0 = low 0.7 = very high
Normalized Brunt-Vaisala Frequency / Ambient stratification	$N^* = N \cdot t_0 = N \cdot \frac{b_0}{w_0}$	0.0 = neutrally stratified 1.2 = high value

Optimal Throughput

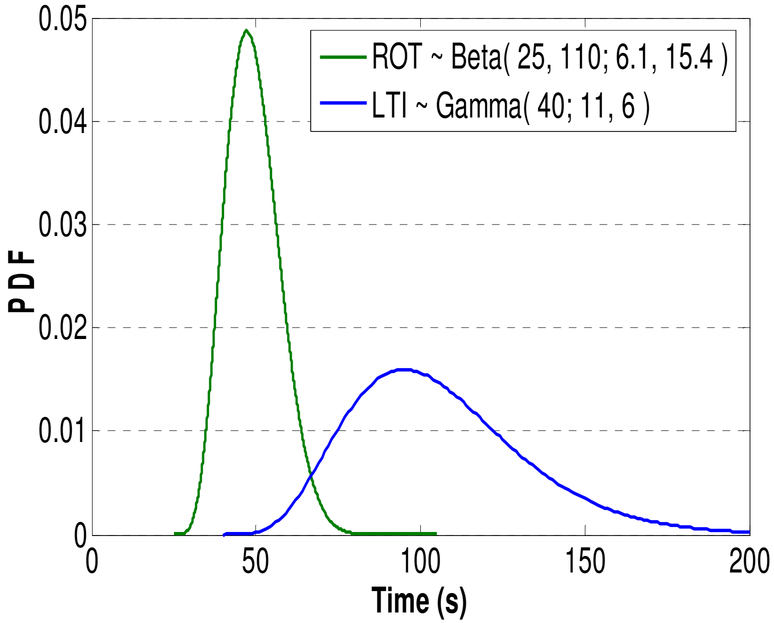
Trade-offs



- Lowering the target separation allows more aircraft to land
- However, this also increases the rate of go-arounds
- At some spacing *T*, a maximum throughput is achieved
- Capacity = 1 / Expected Separation

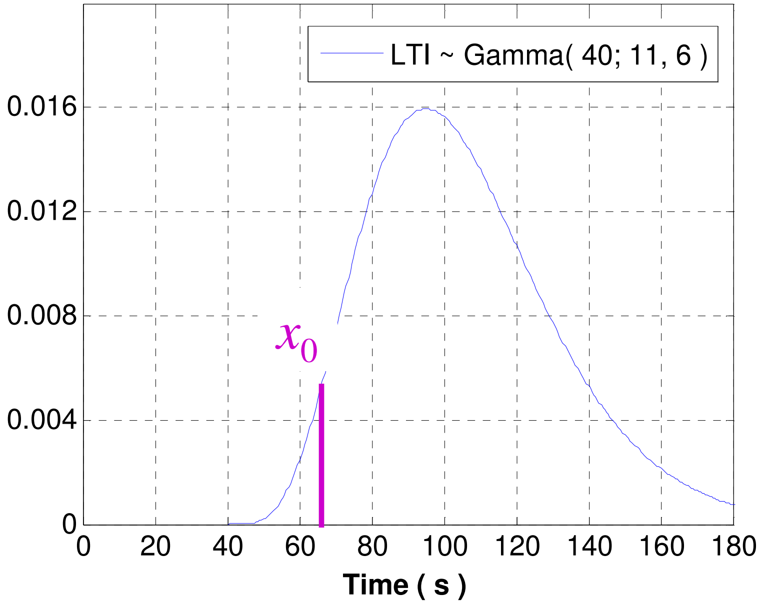
SRO and Wake Constraints

Simultaneous Runway Occupancy



$$\text{Prob}\{\text{Go-around to avoid SRO}\} = \text{Prob}\{LTI < ROT\}$$

Wake Vortex Hazard

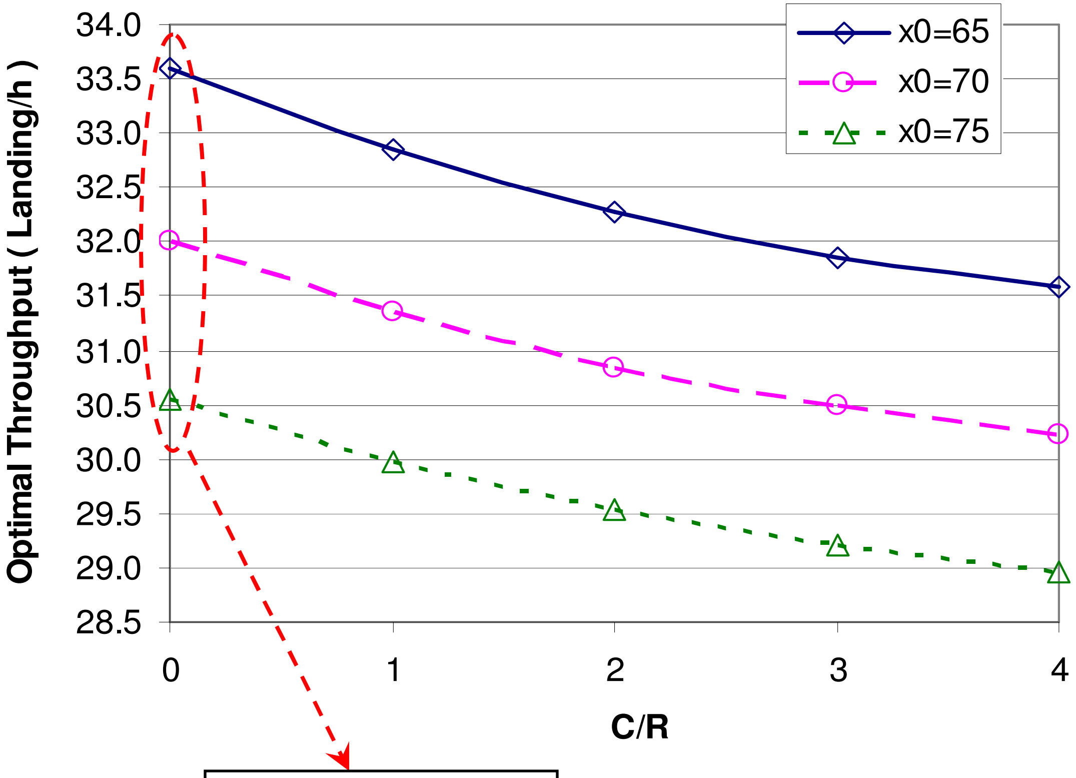


$$\text{Prob}\{\text{Go-around to avoid wake hazard}\} = \text{Prob}\{LTI < x_0\}$$

- Underlying model structure is same
- Different constraints yield different functions:

$$\text{Prob}\{\text{Go-around}\} = p(\omega)$$

Dependency on Cost / Revenue



Wake Constraint

= 65 sec

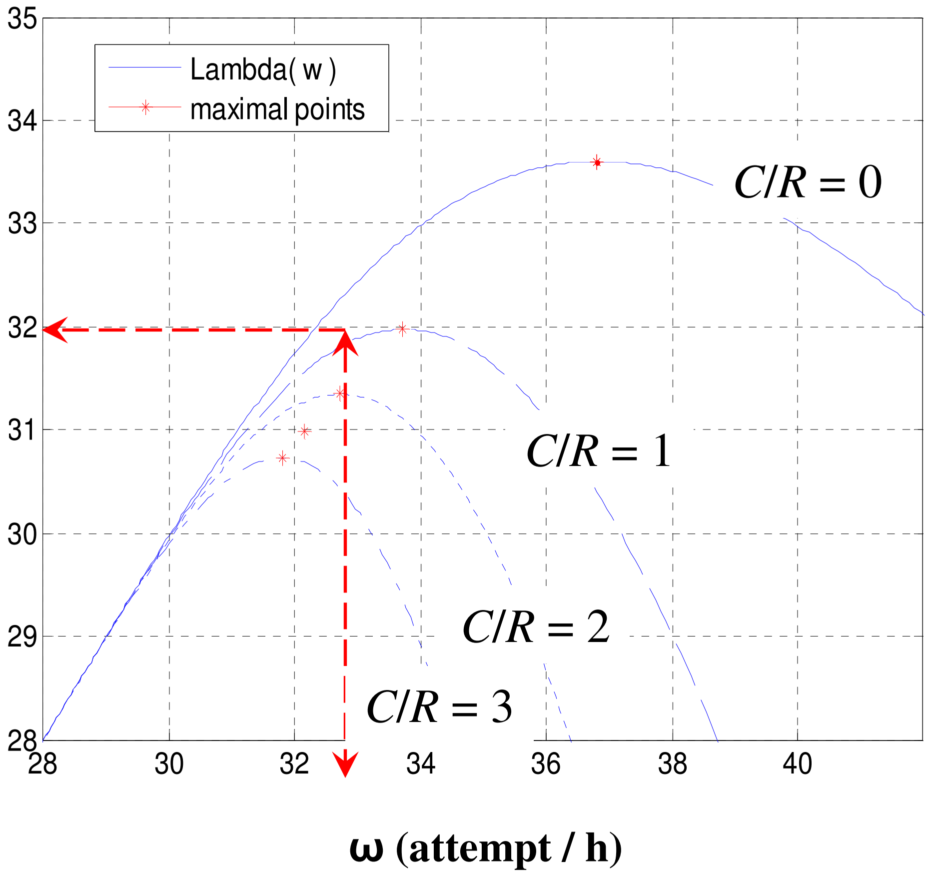
=70 sec

=75 sec

Landing
Capacity

Optimal Capacity

Landings
Equivalents
per Hour
(λ)
(Assume *R*=1)



x_0= 65s	*C/R*	ω^*	λ*	*P** %
	0	**36.8**	**33.6**	**8.7**
	1	**33.7**	**32.8**	**2.6**
	2	**32.7**	**32.3**	**1.4**
	3	**32.1**	**31.9**	**0.9**
	4	**31.8**	**31.6**	**0.7**

(with wake constraint)

With Wake Vortex Constraint

Objective: Maximize $\lambda(\omega) = [1-p(\omega)]\cdot\omega$

Assume wake separation requirement $x_0 = 65$ sec