AATT RTO 52 Final Briefing

Benefits Assessment Compilation
for the
En Route Descent Advisor (EDA) AATT Decision Support Tool

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December 2000

EDA Motivation

RTO52 Scope:
Evaluate EDA benefit mechanisms relative to common baseline, updating previous efforts

Key EDA Elements:

1. **Flow-Rate Restriction Strategy**
   - Arrival metering (Descent Advisor)
   - Miles-in-Trail (Spacing Tool)
2. **Integration with Conflict Probe**
   - Conflict-free EDA advisories
   - Improve conflict probe intent
3. **"Trajectory" Orientation**
   - Accommodate user preferences
   - Distribute controller workload

Potential EDA Benefit Mechanisms:

DST Performance Benefits

✓ Improve Arrival Trajectory Prediction
✓ Improve Metered Arrival Flight Intent.

User Benefits

✓ Increase Airport Throughput
✓ Improve Center/TRACON Delay Distribution
✓ Improve Metering Conformance Efficiency
✓ Improve Separation Assurance Interruptions
✓ Arrival Trajectory Optimization
• Improved ATM Flow-Conformance Strategy

Controller Benefits

• Easier Controller Clearance Development
✓ Reduced False/Missed Conflict Alert
• Improved Controller Workload Distribution
• Reduced Corrective Clearances

EDA+Data Exchange Benefits

✓ Data Calibration of EDA Functions
✓ FMS-EDA Descent Profile Negotiation
• Uplink of Trajectory Constraints
• Improved Clearance Delivery with Datalink
• Automatic Flight Intent Update.

Study Cases

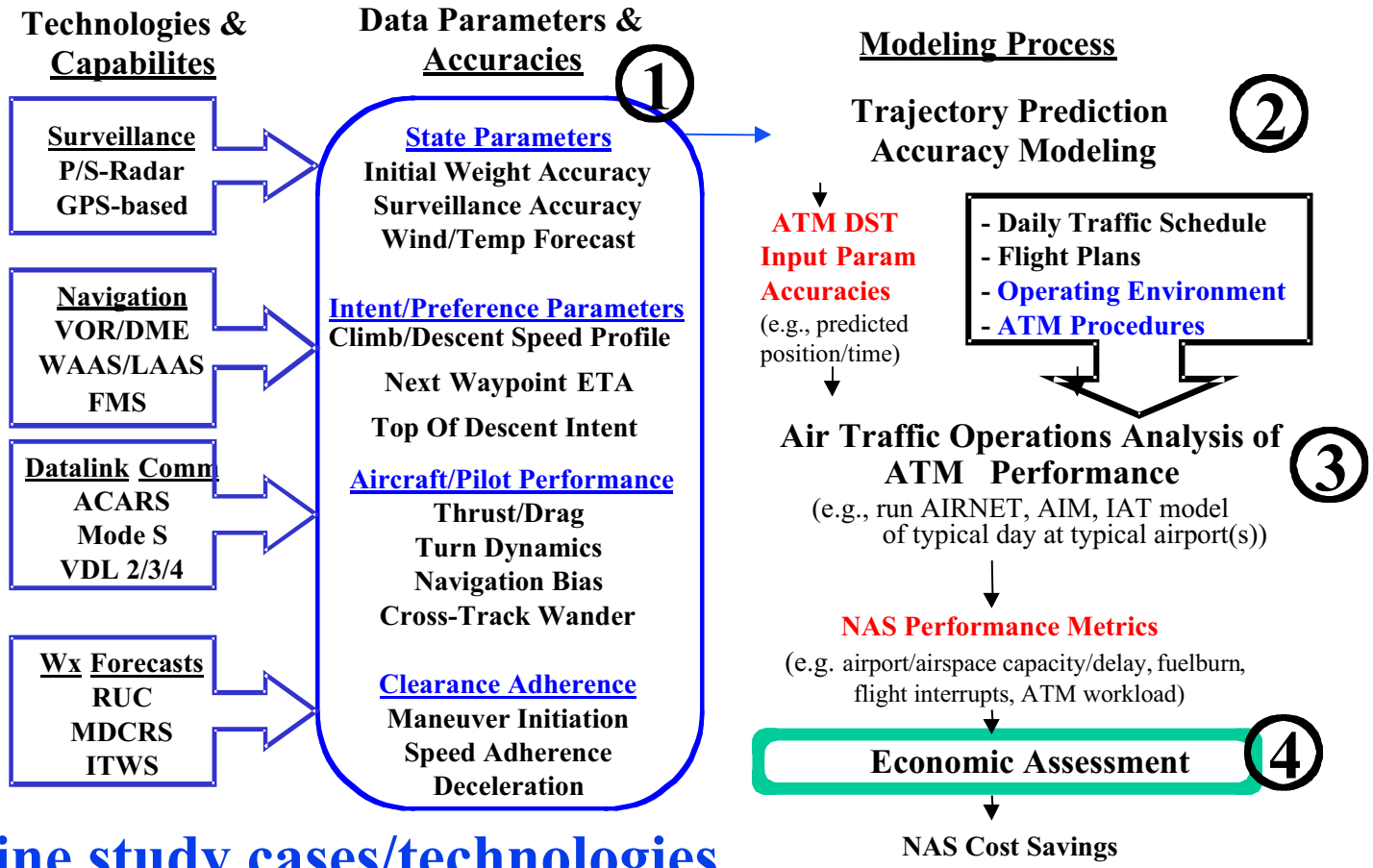
- **Free Flight Phase 1 (FFP1) Baseline**
  - SID/STAR routing
  - TMA arrival scheduling/metering
  - URET CCLD conflict probe & trial planning
  - Conflict probe & metering functions NOT integrated
  - pFAST TRACON runway & sequence assignments
- **En Route/Descent Advisor (EDA)**
  - Arrival direct routing, SID departures
  - TMA/EDA arrival scheduling, metering & delay advisories
  - EDA metering conformance advisories/conflict probe
  - Integrated conflict probe & metering functions
  - EDA Spacing Tool???
  - pFAST TRACON runway & sequence assignments
- **EDA + En Route Data Exchange (EDA+EDX)**
  - Data exchange of weather, weight, speed intent (including threshold crossing speed) and near term intent (next two waypoints)
  - Data exchange of weather, weight, and FMS speed profile meeting uplinked arrival fix required time of arrival (RTA)

EDA Benefits Summary

37-Airport Annual Benefits ($) Benefit Mechanism	Study Case	AATT Benefit Categories Flight Efficiency	User Flexibility	Workload / Productivity	Throughput & Access	Environment	Safety
Airport Throughput	EDA			Downstream Merging	$42.9M 445.53 hrs	Reduced Emissions	Downstream Merging
	+EDX			Downstream Merging	$0.7M 6.80 hrs	Reduced Emissions	Downstream Merging
Center/TRACON Delay Distribution	EDA	$47.7M 477 Mlbs				Reduced Emissions	
	+EDX	$6.0M 60 Mlbs				Reduced Emissions	
ATM Metering Conformance Interruptions	EDA	$25.1M 251 Mlbs		Strategic Planning	Future	Reduced Emissions	
	+EDX	$1.1M Future	RTA Traj Negotiation	Reduced Corrective Clearances	Future	Reduced Emissions	
ATM Separation Assurance Interruptions	EDA	$2.3M 23 Mlbs		-30%MA -21%FA -5% Overall	Future	Reduced Emissions	-30%MA
	+EDX	$3.6M 36 Mlbs	Trajectory Negotiation	-25%MA -7% FA -10% overall	Future	Reduced Emissions	-25% MA
Arrival Trajectory Optimization - Existing Procedures	EDA	$84.7M 847 Mlbs	Arrival Direct Routes	Strategic Planning	Future	Reduced Emissions	
	+EDX	Future	RTA Traj Negotiation	Reduced Corrective Clearances	Future	Reduced Emissions	
Arrival Trajectory Optimization - Future Anchor Point Procedures	EDA	$88.3M 883 Mlbs	Arrival Direct Routes	Strategic Planning	Future	Reduced Emissions	
	+EDX	Future	RTA Traj Negotiation	Reduced Corrective Clearances	Future	Reduced Emissions	
ATM En Route Flow-Conformance Interruptions	EDA	TO49	Arrival Direct Routes	Strategic Planning	Future	Reduced Emissions	
	+EDX	Future	RTA Traj Negotiation	Reduced Corrective Clearances	Future	Reduced Emissions	

- 37-Airport annual EDA/EDX benefits
- Of $290M NAS-wide EDA benefits, bulk from arrival trajectory optimization ($85M existing, $88M relaxed restrictions), throughput and Center/TRACON delay distribution ($40M each), and metering conformance ($25M)
- Separation assurance and metering conformance have large ATM workload impacts (not accounted for)
- EDA may enable aircraft to routinely file direct arrival routes

General Modeling Approach



1. Define study cases/technologies
2. Identify trajectory prediction accuracies and/or strategies
3. Simulate technologies under DFW 24-hour traffic schedule
4. Extrapolate daily simulation results to annual/NAS level

Airport Assumptions

Employed Common Airport/Airspace assumptions

- 1996 Annual Airport and ARTCC Operations, 37NAS deployment
- Historical share of IMC
- FAA ACE airport delay data used to scale rush arrival frequency relative to DFW
- Cost Rates ($0.10/lb fuel, FAA-based fleet-weighted time cost rates)

		1996 Operations (000s)		1996 Airport Fleet Mix (%)			1996 Airport Cost Rates ($/min) *	
Airport	IMC%(1)	Airport	ARTCC	Small	Large	Heavy	Departure	Arrival
ATL – Atlanta	14.2%	773	2,453	4.1%	76.8%	19.1%	$27.76	$35.60
BOS – Boston	15.6%	463	1,727	33.2%	52.5%	14.3%	$19.74	$25.11
DFW - Dallas-Ft. Worth	8.4%	870	2,118	7.3%	80.6%	12.1%	$23.53	$30.08
DEN – Denver	6.0%	454	1,527	24.7%	62.9%	12.5%	$23.71	$30.25
DTW – Detroit	16.6%	531	2,870	17.0%	56.0%	27.0%	$24.54	$31.27
EWR – Newark	16.6%	443	2,040	8.5%	73.1%	18.4%	$24.99	$32.09
JFK - N.Y. Kennedy	15.0%	361	2,040	8.5%	43.0%	48.5%	$34.19	$44.75
LAX - Los Angeles	22.2%	764	1,981	29.9%	43.2%	27.0%	$26.45	$33.96
LGA - N.Y. LaGuardia	16.4%	343	2,040	15.1%	75.5%	9.4%	$23.30	$29.72
ORD - Chicago O'Hare	16.1%	909	2,894	5.2%	76.6%	18.2%	$26.91	$34.53
SFO - San Francisco	12.5%	442	1,368	17.7%	53.9%	28.4%	$27.46	$35.26

Etc….

(1) Annual Occurrence of IMC (percent) 7AM-10PM [66]

* Average value, weighted by aircraft class distribution. Departure Delay assumes pre-departure ground hold.

Rush Arrivals Rate by Airport

- **Many EDA Benefits apply only to Metered or Rush Arrival Operations**
- **Rush Arrivals at NAS airports:**
  - Used FAA ACE delay data to identify 5 Airport Delay Categories
  - Scaled airport rush arrival rate relative to simulated DFW rate based on engineering judgement

Airport Rush Arrival Rate Criteria

Category No.	CY1996 (1) Delays > 15 minutes Per 1000 Airport Ops	Proportion of DFW (category 3) Rush Arrival Rate	Rush Arrival Rate (Rush Arrivals Per 100 Airport Ops)
1	>35	130%	39.46
2	25-35	115%	34.91
3	15-25	100%	30.35 (2)
4	5-15	80%	24.28
5	<5	60%	18.21

(1) FAA CY1996 Delay Data [31],.
(2) DFW Rush Arrival Rate per ATM Interruptions Model analysis.

Note: Rush Arrival Rate is per *Airport* Operations

Airport	CY1996 Delays >15 min per 1000 ops (1)	Delay Category No.	Rush Arrival Rate per 100 ops (2) Arr	Dep
EWR - Newark	65.25	1	39.46	47.45
SFO - San Francisco	56.57	1	39.46	47.45
LGA - N.Y. LaGuardia	46.22	1	39.46	47.45
ORD - Chicago O'Hare	34.46	2	34.91	41.97
STL - St. Louis	34.04	2	34.91	41.97
JFK - N.Y. Kennedy	29.53	2	34.91	41.97
BOS - Boston	26.37	2	34.91	41.97
LAX - Los Angeles	24.13	3	30.35	36.50
ATL - Atlanta	23.88	3	30.35	36.50
DFW - Dallas-Ft. Worth	19.59	3	30.35	36.50
PHL - Philadelphia	17.95	3	30.35	36.50
IAH - Houston International	11.45	4	24.28	29.20
CVG - Cincinnati	10.38	4	24.28	29.20
MSP - Minneapolis	9.29	4	24.28	29.20
DTW - Detroit	9.10	4	24.28	29.20
PHX - Phoenix	7.25	4	24.28	29.20
IAD - Washington Dulles	6.81	4	24.28	29.20
MIA - Miami	6.79	4	24.28	29.20
MDW - Chicago Midway	6.70	4	24.28	29.20
PIT - Pittsburgh	6.60	4	24.28	29.20
CLT - Charlotte	6.55	4	24.28	29.20
DCA - Washington National	6.53	4	24.28	29.20
SEA - Seattle	6.37	4	24.28	29.20
CLE - Cleveland	4.68	5	18.21	21.90
MCO - Orlando	4.59	5	18.21	21.90
LAS - Las Vegas	3.68	5	18.21	21.90
BWI - Baltimore-Washington	3.67	5	18.21	21.90
SLC - Salt Lake City	3.53	5	18.21	21.90
SAN - San Diego	3.31	5	18.21	21.90
HOU - Houston Hobby	2.57	5	18.21	21.90
PDX - Portland	2.41	5	18.21	21.90
DEN - Denver	1.90	5	18.21	21.90
FLL - Ft. Lauderdale	1.53	5	18.21	21.90
BDL - Bradley	1.36	5	18.21	21.90
BNA - Nashville	0.73	5	18.21	21.90
MEM - Memphis	Not Available	5	18.21	21.90
OAK - Oakland	Not Available	5	18.21	21.90

Airport Throughput Benefits

Airport Throughput Benefits

- **Benefit Mechanism**

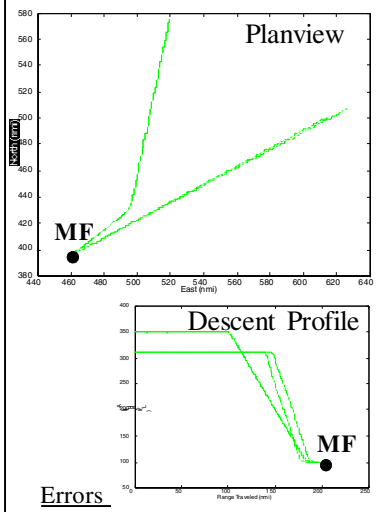
  Increase airport throughput (reduce delays) with improved arrival metering fix scheduling/delivery accuracy

- **Analysis Method**
  - Arrival Metering Fix Delivery Accuracy
  - Runway Spacing Buffers
  - Runway System Demand & Capacity Model Average Daily Delays
  - Extrapolate Daily Results to Annual/NAS-wide benefits

- **Study Cases**
  - **FFP1 Baseline**
  - **EDA** - Improved arrival trajectory prediction accuracy
  - **EDA + EDX** - Further arrival prediction improvements

Arrival Metering Fix Delivery Accuracy

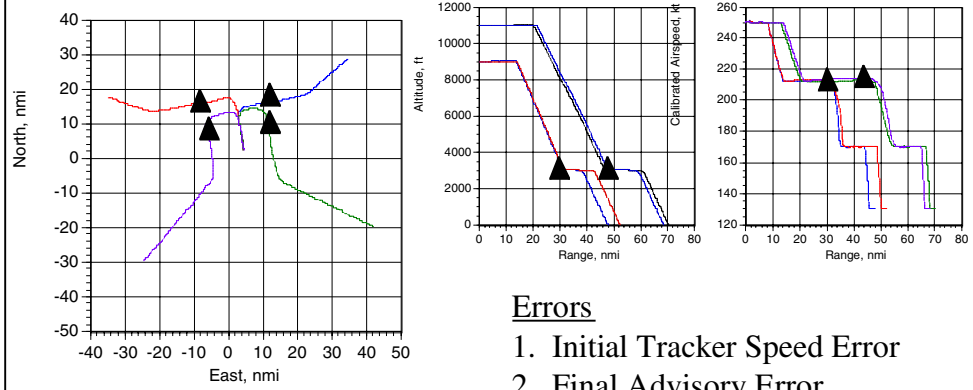
Center (Cruise to MF)



Errors

Performance - Weight, Drag
Actuation - TOD, Speed, Turns, Cross-Track, Navigation
Atmosphere - Winds, Temp
Surveillance

TRACON (MF to OM)

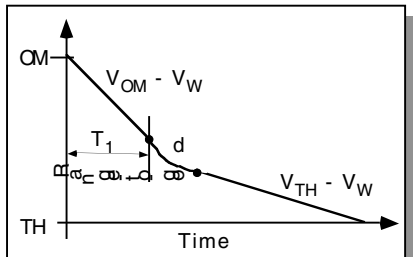


▲ Final ATM advisory point

Errors

1. Initial Tracker Speed Error
2. Final Advisory Error
3. Trajectory Error (final advisory point to OM)

Final Approach (OM to TH)



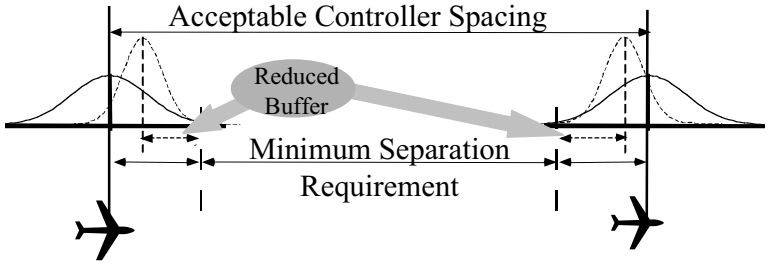
Errors

OM, TH Speed Variations
Wind Forecast Error
Deceleration Delay Time

Model OM to TH Time-to-Fly Error under each Scenario
EDA/EDX Improves Center(En Route) Trajectory Errors:

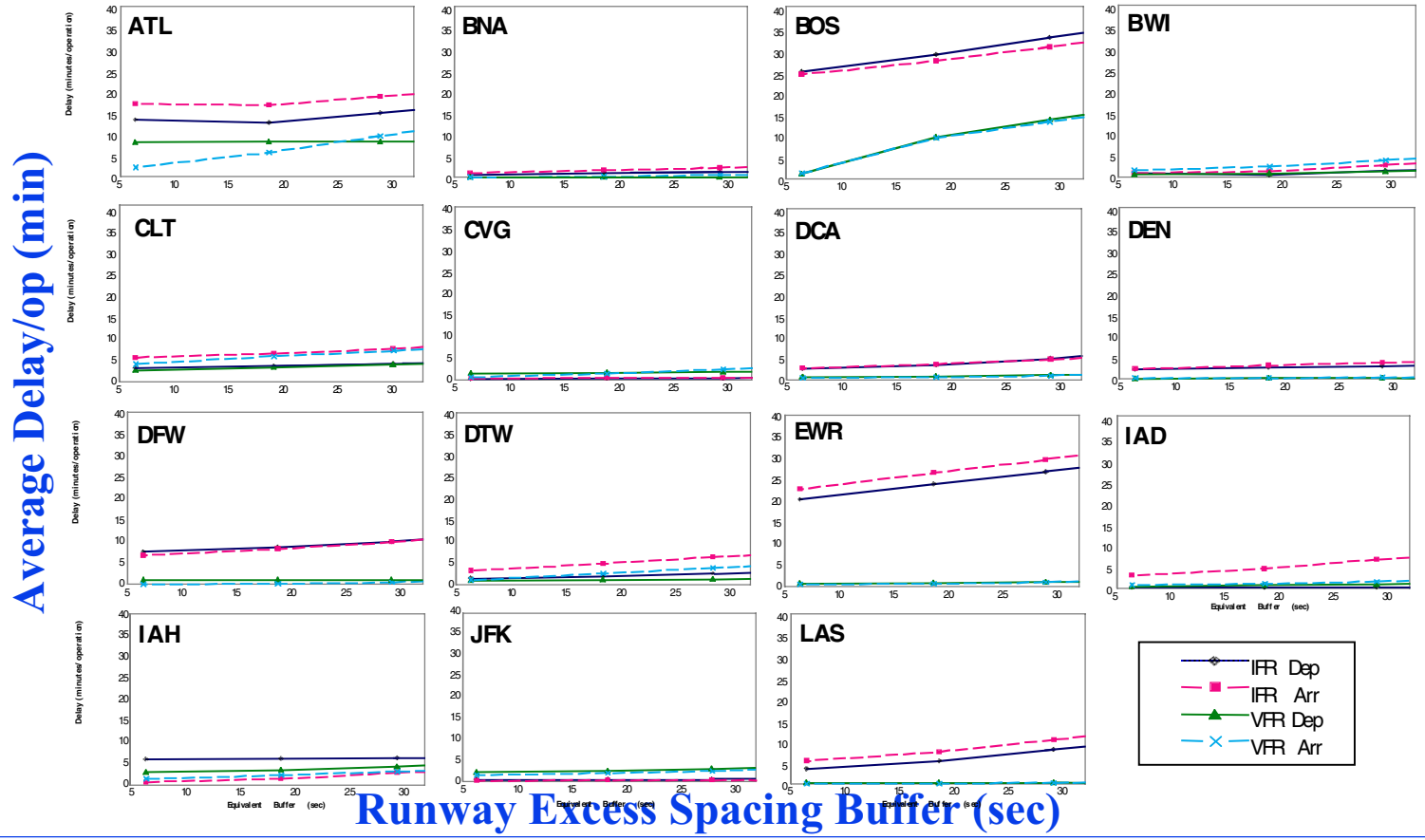
- **FFP1 Baseline**
- **EDA -** EDA advisory (common target) improves TOD placement and speed adherence error
- **EDA + EDX** - Improves wind speed/temperature forecast, aircraft weight, and drag errors

Runway Spacing & Associated Delays

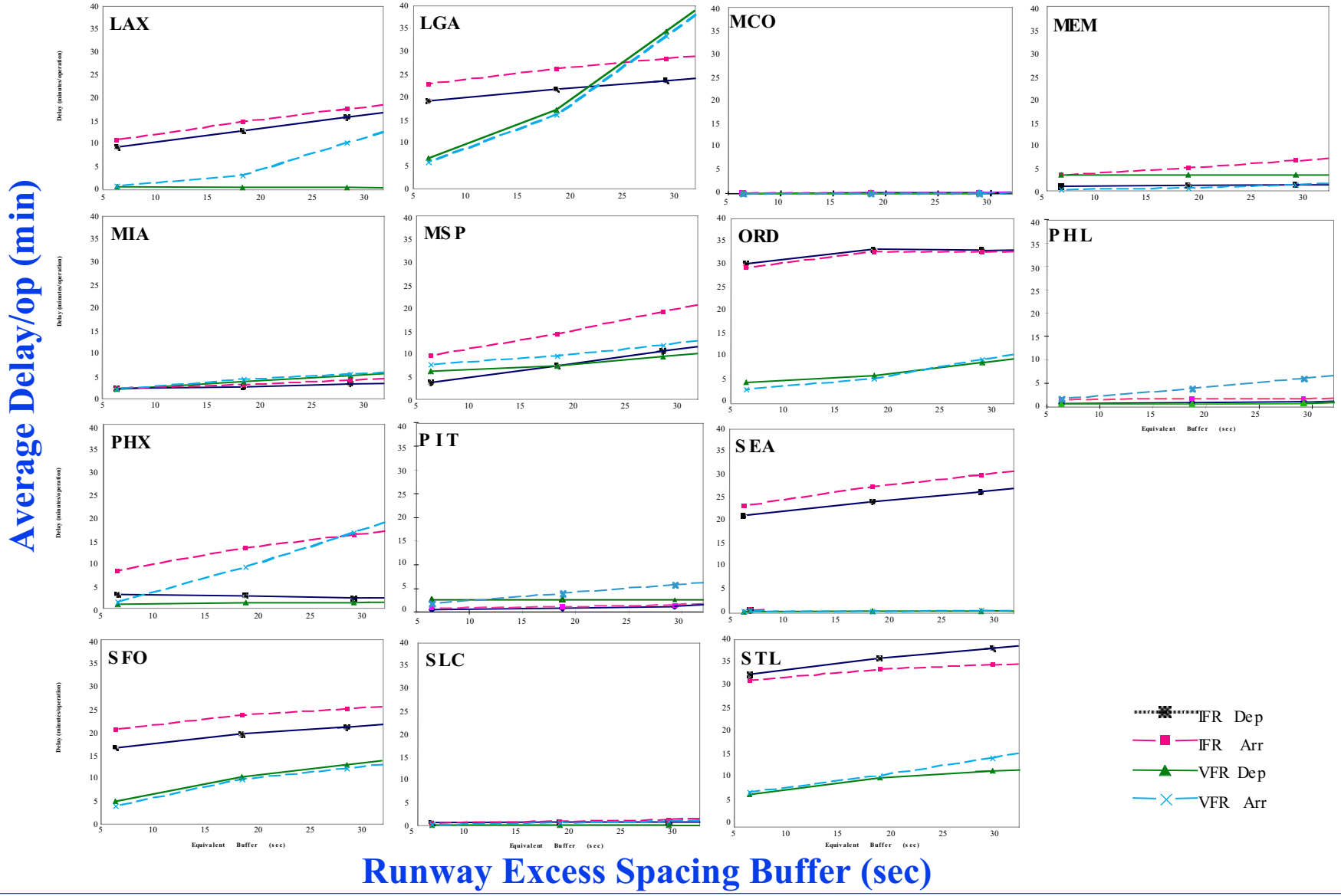


- **Estimate Excess Runway Spacing Buffer from simulated timing errors:**

FFP1 BL: 25.98 sec
EDA: 25.33 sec, improved 0.65 sec
EDA+EDX: 25.31 sec, improved 0.02 sec



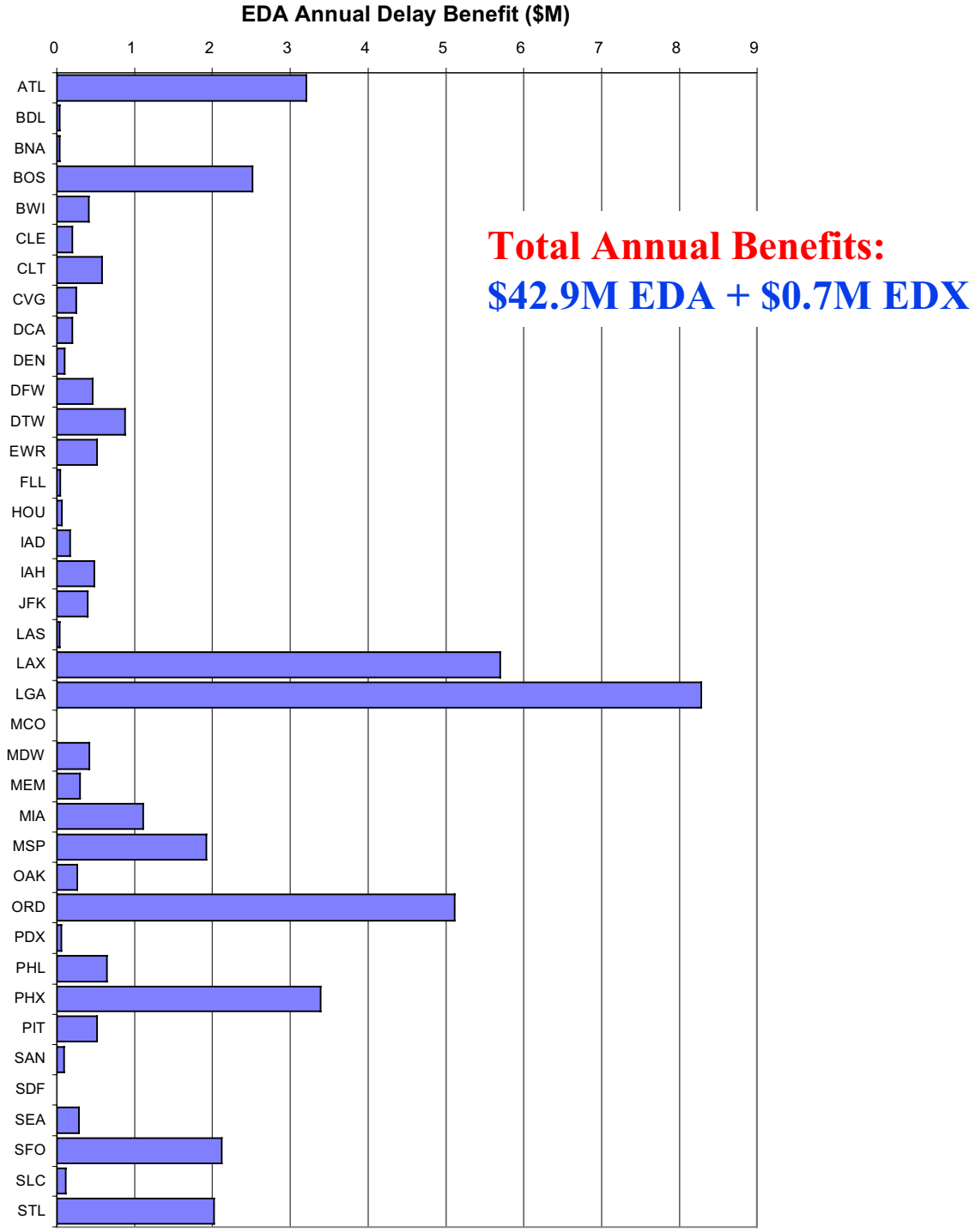
Runway Spacing & Associated Delays



Airport Throughput Benefits

Annual Savings = (***Annual Ops***) x (***Delay Savings/op***) x (***Cost***$_{\mathbf{Time}}$+***Cost***$_{\mathbf{Fuel}}$)

Evaluated for 4 operations types: IFR Arr, IFR Dep, VFR Arr, VFR Dep



Center/TRACON Delay Distribution Benefits

Center/TRACON Delay Distribution Benefits

- **Benefit Mechanism**

  Shift arrival delay from TRACON to Center airspace, saving fuel, with improved arrival metering fix delivery accuracy.

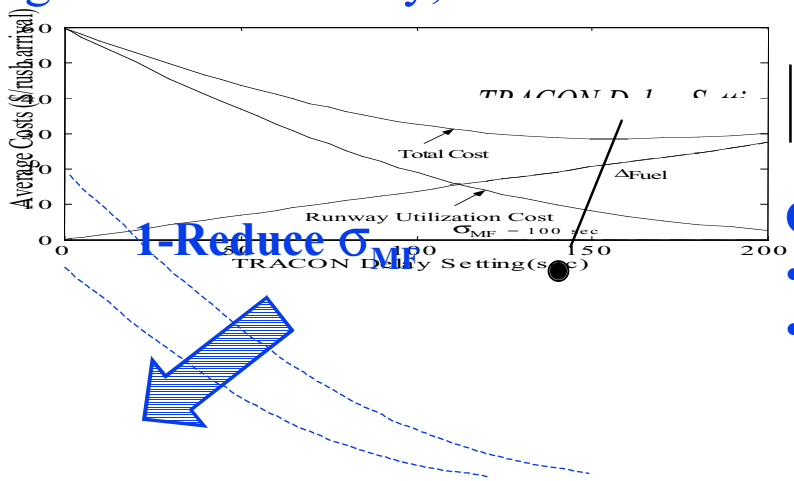
- **Analysis Method**
  - TRACON Delay Settings by rush and airport (ATL, DFW, LAX)
  - Calculate Rush and Daily Fuel Savings
  - Extrapolate Daily Results to Annual/NAS-wide benefits

- **Study Cases**
  - **FFP1 Baseline**
  - **EDA** - Improved arrival trajectory prediction accuracy
  - **EDA + EDX** - Further arrival prediction improvements

Center/TRACON Delay Distribution Concept

Improved MF Delivery or TRACON flight-time prediction leads to reduced need for TRACON flight-time flexibility, and allows TRACON delay to be pushed upstream

3-Reduce Fuel Cost

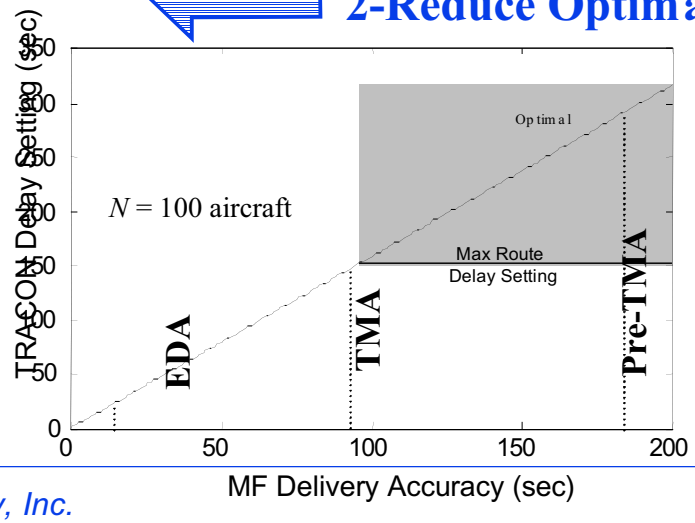


1-Reduce σ_{MF}

Optimal Setting minimizes combined:

- Runway Utilization (missed slots)
- TRACON Fuel penalty (ΔFuel) (1.5x ARTCC fuelburn rate)

2-Reduce Optimal TRACON Delay Setting

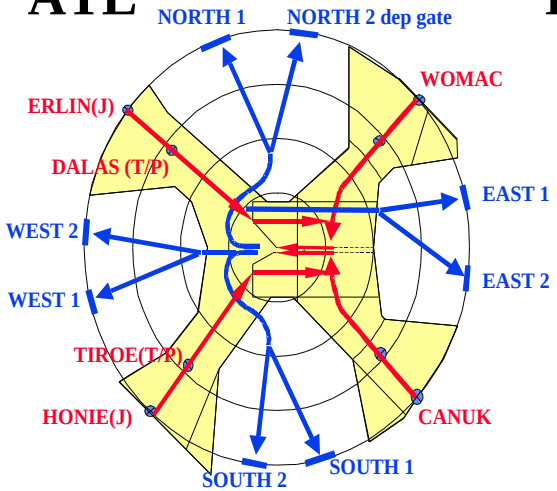


MF Accuracy σ_{MF}

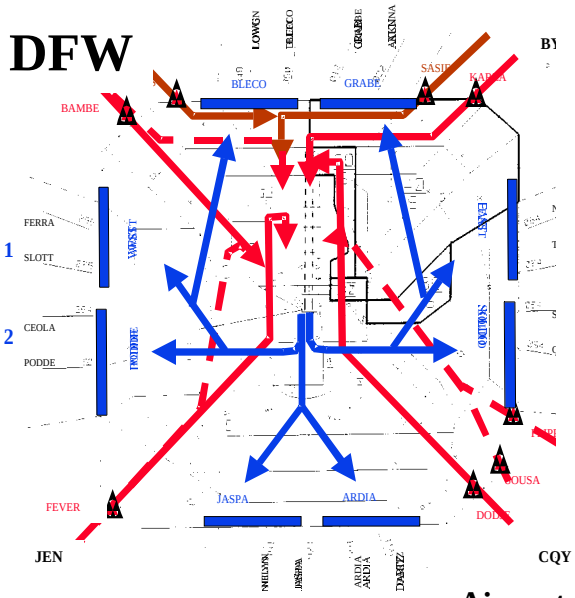
FFP1/TMA	EDA	EDX
86.1 sec	17.9	12.8

Airport Arrival Assumptions

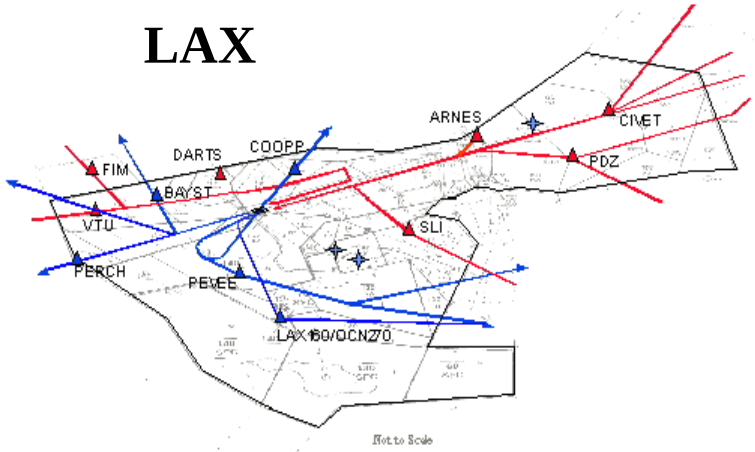
ATL



DFW



LAX



Arrival Routes
Departure Routes

	Approach Procedure	Max TRACON Delay (sec)	Airport Arrival Rushes Start Time, Duration, Operations Rush 1	Rush 2	Rush 3	Rush 4	Rush 5	Rush 6	Rush 7	Rush 8	Rush 9	Rush 10
ATL	Straight-In	150	07:20	08:43	10:38	12:14	14:10	15:41	17:35	19:36	21:47	
	Downwind	300	33 min	51 min	55 min	63 min	67 min	94 min	79 min	89 min	55 min	
			40	62	64	79	77	116	99	109	63	
DFW	Straight-In	180	06:48	08:19	09:41	11:34	13:11	14:28	15:54	17:34	18:48	20:26
	Downwind	360	13 min	24 min	25 min	46 min	26 min	47 min	31 min	52 min	63 min	53 min
			17	27	35	78	47	75	53	85	107	64
LAX	Straight-In	100	09:17	10:40	13:53	16:50	18:45					
	Downwind	300	29 min	102 min	71in	71 min	193 min					
	PropHolding	360	31	122	80	83	216					

Note: LAX Prop Holding Fixes are DARTS and SLI

Sources: ATM Facility contacts & ETMS-based (June 24,1996) airport simulation

TRACON Delay Setting Calculation

For each rush, at each airport (ATL, DFW, LAX)….

DFW

	Approach Procedure	Rush Ops	Optimal TRACON Delay Setting (sec) FFP1 Baseline	EDA	EDA Fuel burn Savings ($)	
Rush 1	All	17	78	16	Per Arr	$4.75
					Per Rush	$81
Rush 2	All	27	115	24	Per Arr	$6.97
					Per Rush	$188
Rush 3	All	35	131	27	Per Arr	$7.96
					Per Rush	$279
Rush 4	All	78	171	36	Per Arr	$10.33
					Per Rush	$775

Etc…

Results Summary:

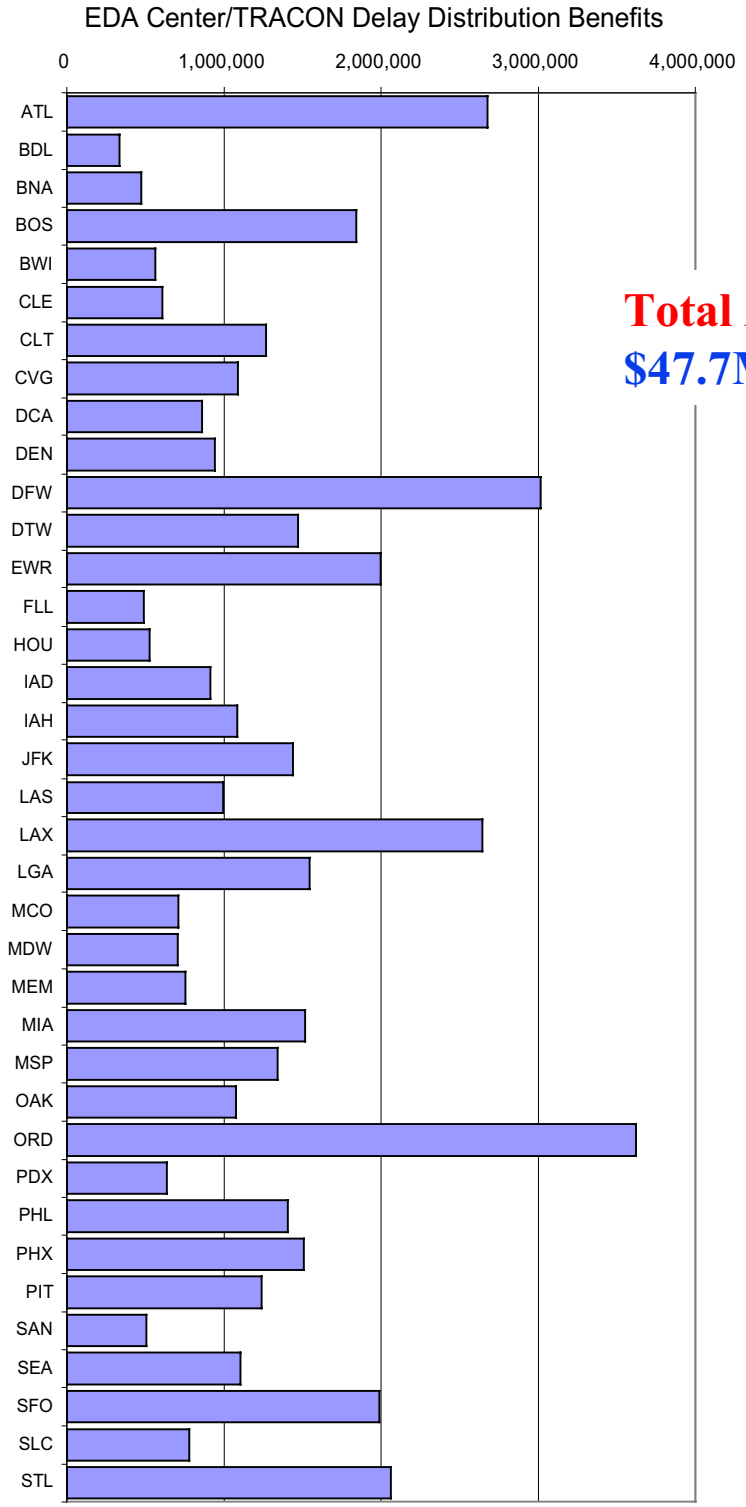
EDA Daily Center/TRACON Delay Distribution Benefits

	ATL	DFW	LAX	Airport Average
Rush Operations Rate (per 100 Airport ops)	35.7	27.0	27.0	30.4*
ARTCC Delay Shift (sec)	137 sec	128 sec	150 sec	138 sec
Average Fuel Savings ($)	$12.40/op	$9.82/op	$11.86/op	$11.42/op
	$977/rush	$577/rush	$1,262/rush	$939/rush
	$8,794/day	$5,772/day	$6,311/day	$6,959/day

*** 3-airport average used in annual/NAS extrapolation**

Delay Distribution Benefits

$$Annual\ Savings = (Annual\ Ops) \times (Rush\ Arrivals_{DFW}) \times (Apt\ Factor) \times (Savings\ Per\ Interrupt)$$



Total Annual Benefits:
$47.7M EDA + $6.0M EDX

Metering Conformance Efficiency Benefits

Metering Conformance Benefit

- **Benefit Mechanism**

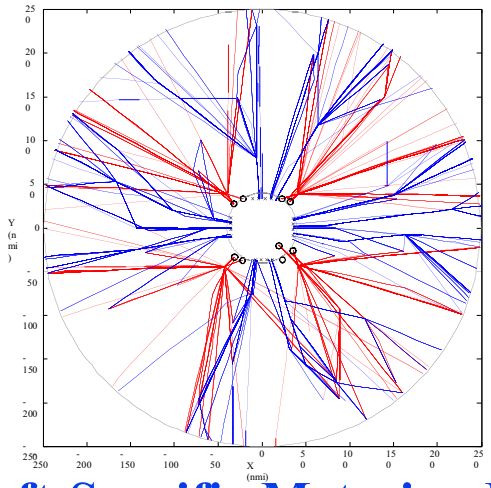
  Improve metered arrival flight efficiency with EDA delay strategy/advisory and longer time horizon

- **Analysis Method**
  - DFW Trajectory Database & Metering Delay
  - Metering Conformance Interruptions
    - Overview
    - Modeled methods
    - FFP1 and EDA Strategies
  - DFW Daily & Annual/NAS-wide benefits

- **Study Cases**
  - **FFP1 Baseline** - cognitively developed metering clearance
  - **EDA** - EDA-generated strategy and maneuver advisory
  - **EDA+ EDX** - EDA accommodation of downlinked FMS speed strategy to meet arrival metering fix RTA

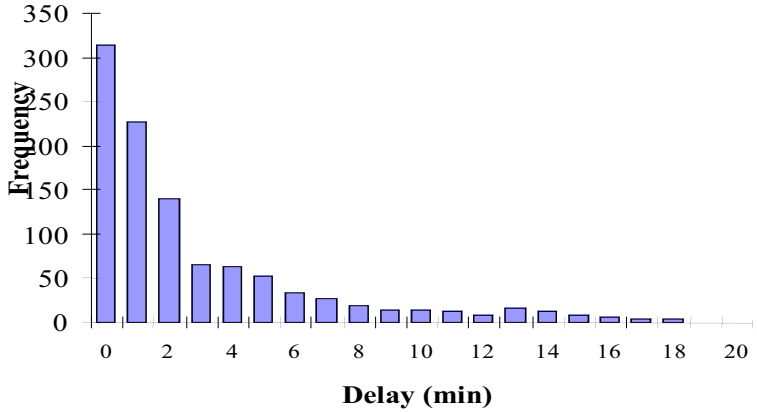
Trajectories and Metering Delay

- **DFW Daily Traffic Scenario (June 24, 1996 ETMS-based)**



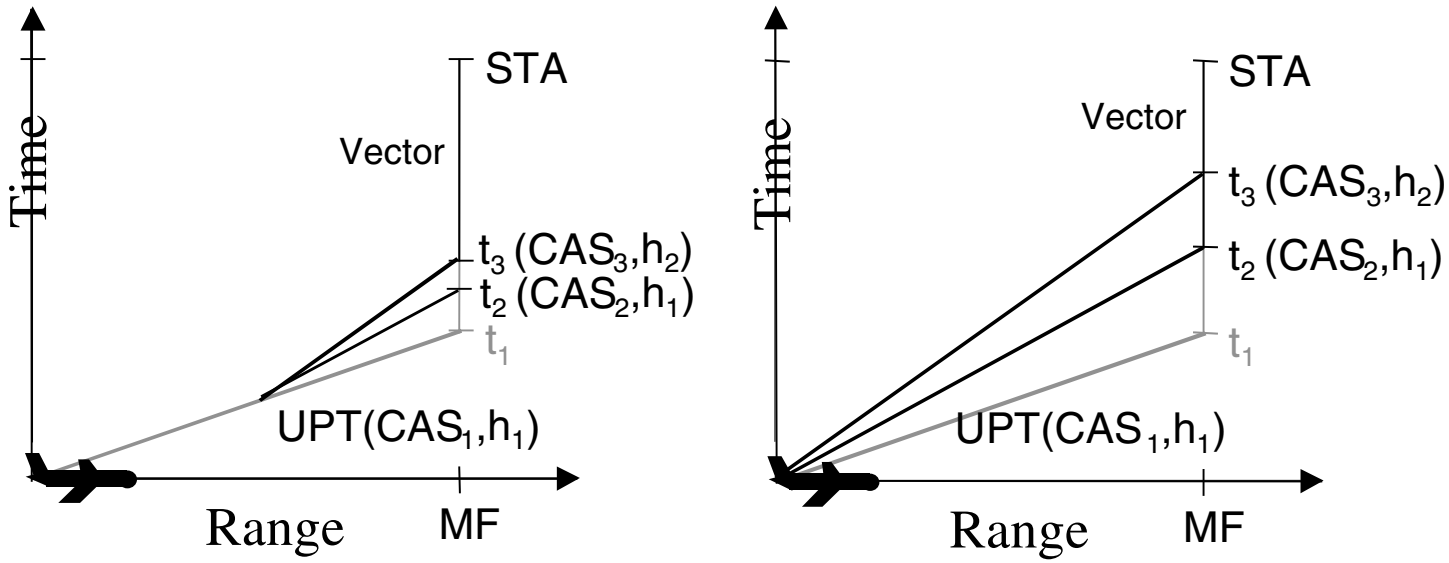
DFW

- **Aircraft-Specific Metering Delay from application of Airport/Airspace Flow-Rate Restrictions**



Scheduling Criteria	Assumed Value
Minimum Arrival Meter-Fix Separation	5.50 nm
Maximum TRACON Arrival Rate (4 Arrival Runways)	150 ac/hr

Metering Conformance Objective

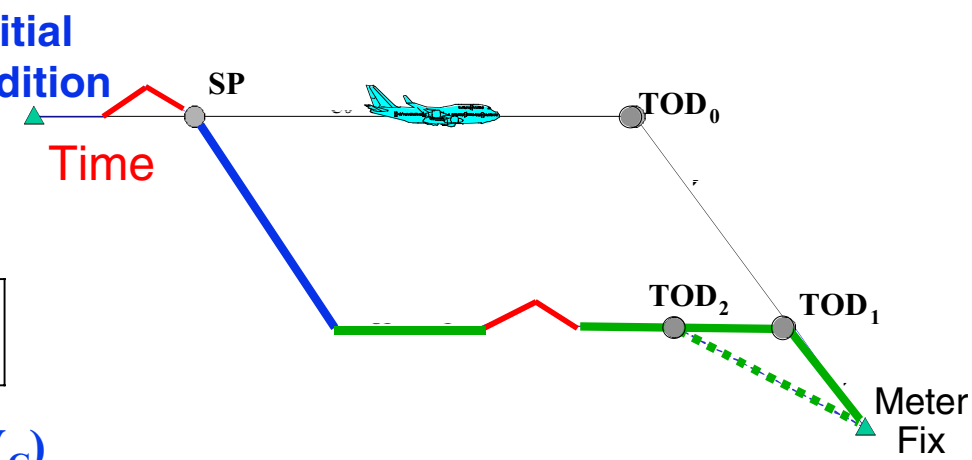


t_1 = User Preferred Trajectory (UPT) = Undelayed Metering Fix (MF) crossing time (CAS_1, h_1)
t_2 = Crossing time if cleared to minimum speed (CAS_2)
t_3 = Crossing time if cleared to minimum speed at a lower altitude (h_2)
STA = crossing time if cleared to minimum speed, lower altitude, and vectored

Modeled Metering Conformance Methods

Delay Methods

- Speed Control ← 1st w/EDA
  - Cruise (V_C)
  - Descent (V_D)
- Altitude Change ← 1st w/FFP1
- Vectoring (at V_C)
- Time Shift (excessive vectoring at V_C)



Fuel Cost

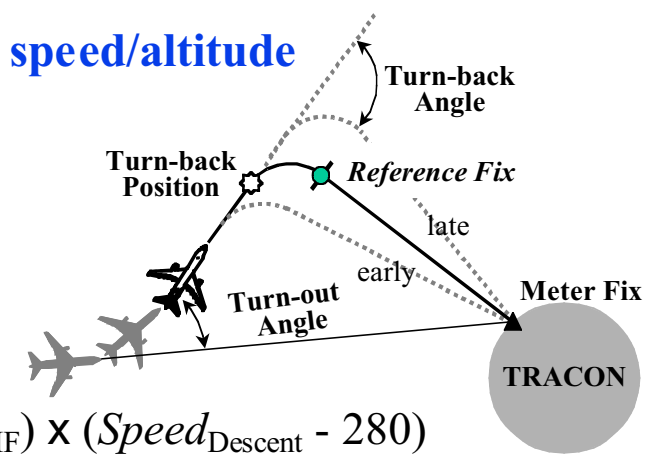
$$FuelCost = Fuelburn\ Rate \times Distance_{Cruise}/Speed_{Cruise}$$

- B737 High-fidelity fuelburn rates, sensitive to speed/altitude
- Fleet-wide extrapolation using BADA data

Cost Adjustments

- Vectoring Turnback Error
- TOD Shift with Speed Change

$$TOD\ Shift = 0.00001 \times (Altitude_{Cruise} - Altitude_{MF}) \times (Speed_{Descent} - 280)$$



Baseline and EDA Metering Strategies

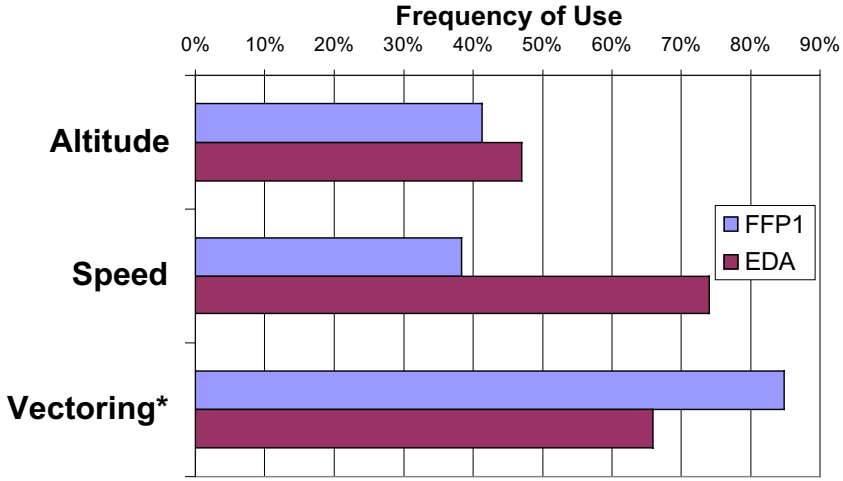
	FFP1	CTAS EDA
General		
Strategy Order	Altitude Speed Vectoring Time Shift	Speed Altitude/Speed Vectoring Time Shift
Time Horizon	16 min	18 min
Speed		
Speed Increments	10 kt	5 kt
Speed Error	+ 10 kt	None
Min Cruise Speed Min Descent Speed	BADA BADA	BADA – 10 kts BADA – 20 kts
Altitude (Jets only)		
Permitted Altitudes	Min Altitude	FAR Altitudes
Min Altitude	FL230/FL240	FL230/FL240
Vectoring		
Heading Increment	1°	1°
Max Vector Angle	60°	60°
Turn back Error	± 60 seconds	± 30 seconds

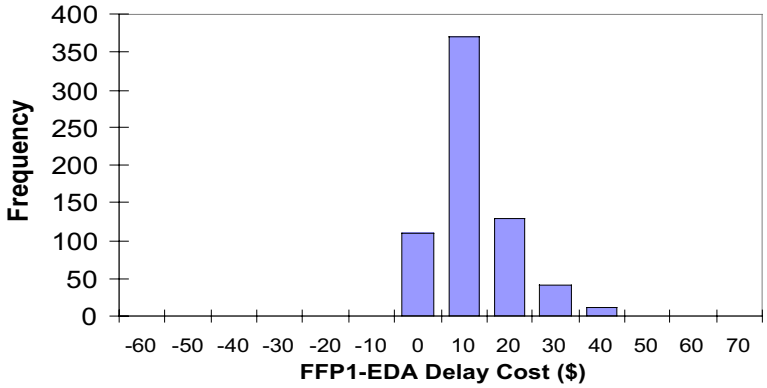
Note:

FFP1 Min speeds - No automation to help controllers identify efficient speeds; used Eurocontrol BADA model "low" cruise speeds (e.g. 250 kts for jets).

EDA min speeds - EDA advisories allow speeds closer to best endurance; used 10 kts (20 kts in descent) lower than FFP1/BADA.

EDA Metering Conformance Interruptions





* Vectoring includes Time Shift method.

	FFP1 Baseline			CTAS EDA-STAR			CTAS EDA-DIR		
	Fuel (lbs)								
	Range	Ave	Total	Range	Ave	Total	Range	Ave	Total
Altitude/Speed	(168)-579	14	9,502	(533)-590	17	11,494	(753)-483	13	8,645
Vectoring*	0-2,659	244	161,422	0-2,440	182	120,205	0-2440	183	120,866
Total	(133)-2,793	258	170,924	(533)-2,773	199	131,700	(533)-1,870	196	129,511
	Total Fuel Cost ($) **								
Total	$(13)-279	$25.82	$17,092	$(53)-277	$19.89	$13,170	$(53)-187	$19.56	$12,951

* Vectoring includes Time Shift method.

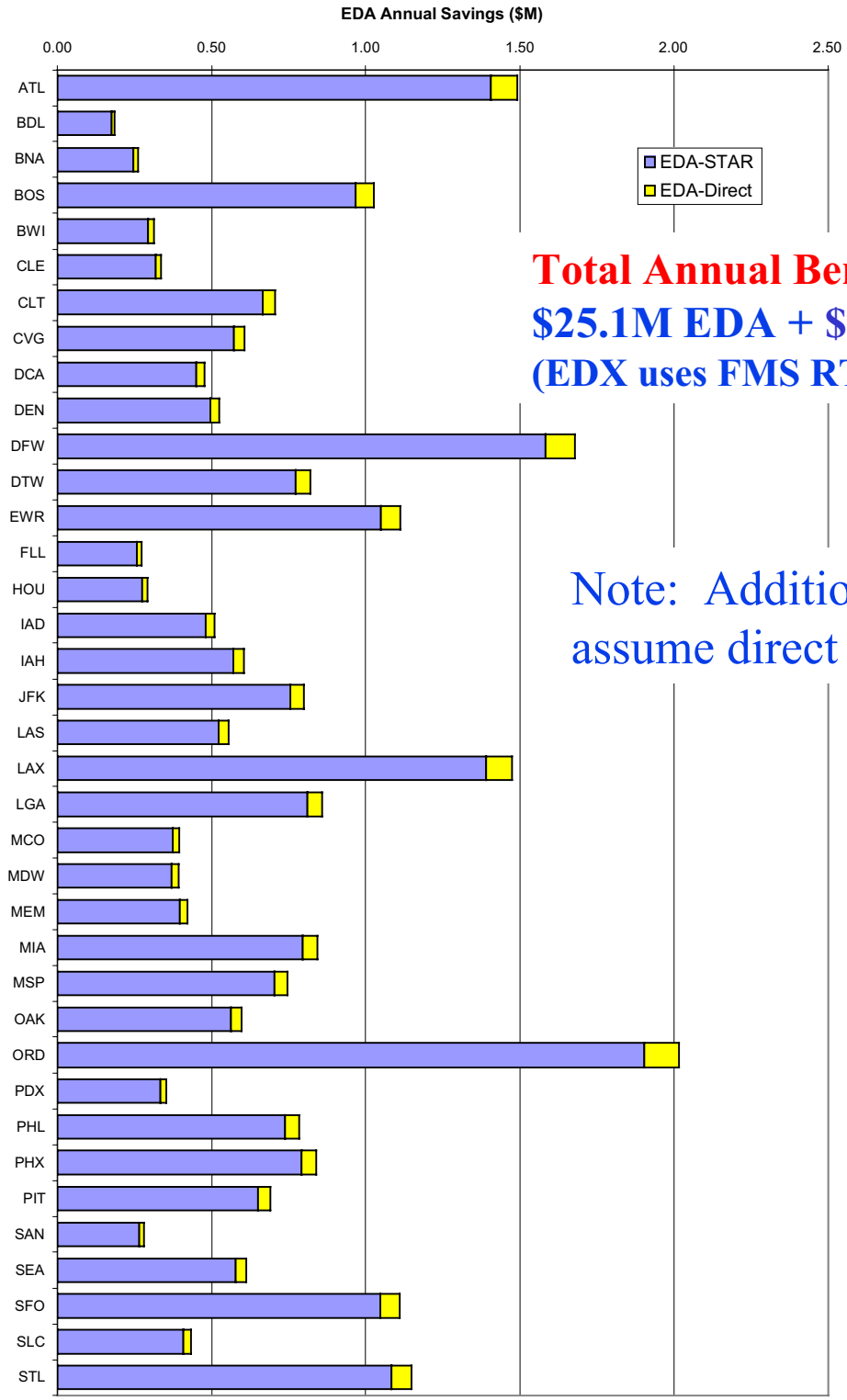
Interrupt Rates/Costs:

	FFP1 Baseline	EDA-STAR	EDA- Direct
Metered Arrival Rate (per 100 ops)	30.4	30.4	30.4
Cost Per Interrupt ($/op)*	$104.66	$97.86	$97.50

* Includes fuel and time

Metering Conformance Benefits

Annual Cost = (*Annual Ops*) x (*Rush Arrivals*$_{DFW}$) x (*Apt Factor*) x (*Cost Per Interrupt*)
Annual Savings = *Annual Cost* $_{FFP1}$ – *Annual Cost* $_{EDA}$



Total Annual Benefits:
$25.1M EDA + $1.1M EDX
(EDX uses FMS RTA-Speed Profile)

Note: Additional benefit when assume direct arrival routing

Separation Assurance
ATM Interruption Benefits

ATM Interruptions Benefits

- **Benefit Mechanism**

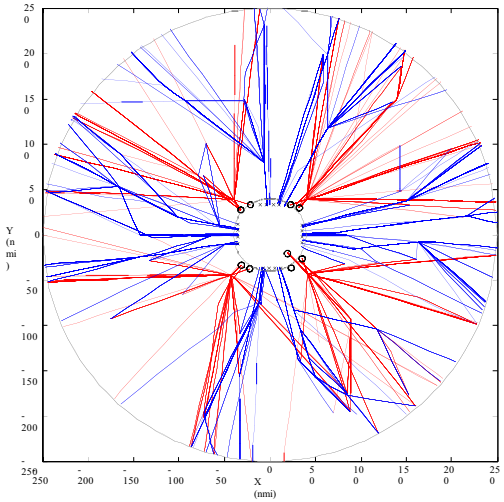
  Reduce Missed/False alerts and conflict resolution fuelburn with more accurate ATM perception(ac state & intent)

- **Analysis Method**
  - DFW Conflict Detection - Potential Incident Database
  - ATM Perception
    - Trajectory Prediction Accuracy by flight mode
    - Acceptable Controller Spacing
    - Perceived Miss Distance
  - DFW Daily & Annual/NAS-wide benefits

- **Study Cases**
  - FFP1 Baseline
  - **EDA** - Integrated metering and conflict probe and improved arrival prediction
  - **EDA + EDX** - Improved arrival, departure and overflight prediction, including intent (next two waypoints)

Potential Incident Database

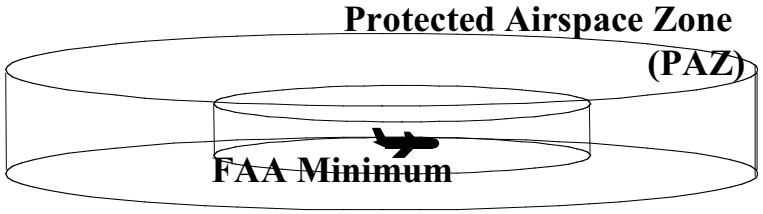
- **DFW Daily Traffic Scenario (June 24, 1996 ETMS-based)**



DFW

- **Incident Database** - Set of all conflicts/near-conflicts from DFW daily en route traffic scenario

PAZ = Min Sep. Requirement + Buffer

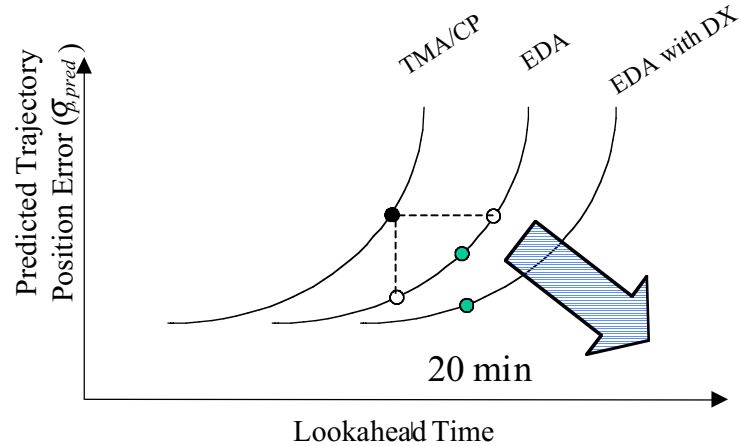


  - Violate PAZ (less than 12 nm horizontally & up to 3000'/2000' vertically)
  - Unique 2-aircraft incidents
  - Record incident attributes (Miss distance, ops types, flight modes, etc.)

ATM Perception

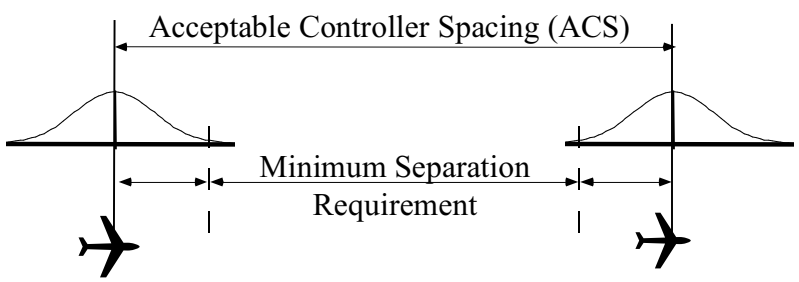
Tool Accuracy...

$$\sigma_{p.pred}$$



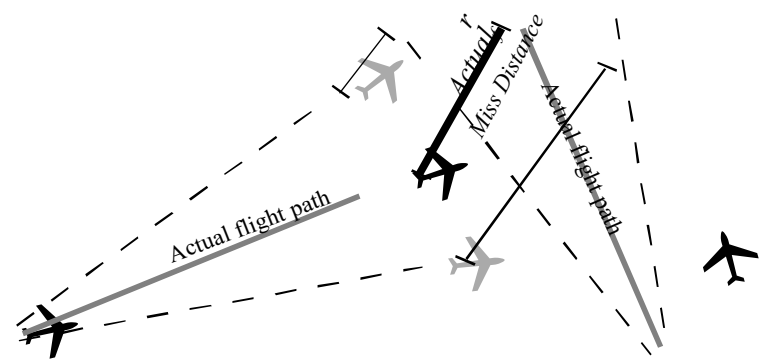
Acceptable Controller Spacing (*ACS*)

$$ACS = n\sigma_{p.pred} + Min\ Sep\ Reqmn't$$



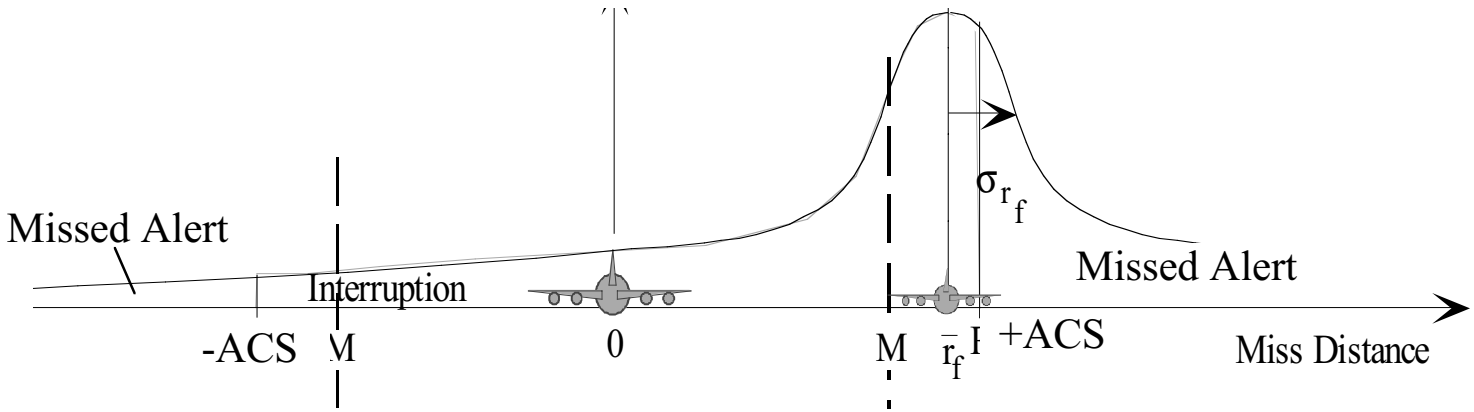
Perceived Miss Distance ~N(r_f, σ_{rf})

$$\sigma_{r_f} = \sqrt{\sigma^2_{p,pred,acj} + \sigma^2_{p,pred,acj}}$$



Perceived ATM Interruptions (1 of 2)

- **For Each Incident…**



- **Incident, Miss Distance (r_f)**
- **Perception**
  - Distribution of Perceived Miss Distance ~N(r_f, σ_{rf})
  - Acceptable Controller Spacing (± ACS)
    (Min Sep Reqmn't, ± M + buffer)
- **Intervene when Perceive Miss Distance < ±ACS**
  (shaded area)

$$P(conflict) = \frac{1}{2} erf\left(\frac{R + r_f}{\sqrt{2}\sigma_{r_f}}\right) + \frac{1}{2} erf\left(\frac{R - r_f}{\sqrt{2}\sigma_{r_f}}\right)$$

Perceived ATM Interruptions (2 of 2)

For each incident, at a given tool accuracy... Identify weighted interrupt cost.

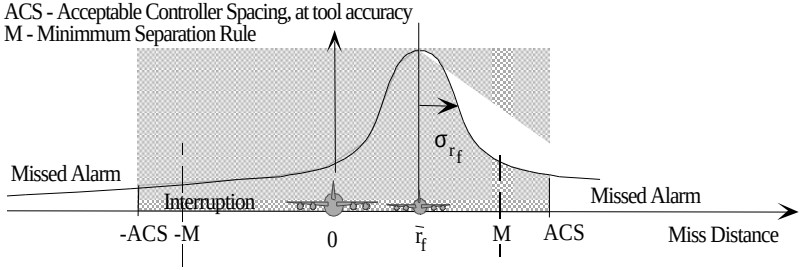
Compare
Incident Minimum Distance ($\bar{r}_f$)
with Perception (σ_{r_f},ACS)

Probability of Interruption

Resolution Cost

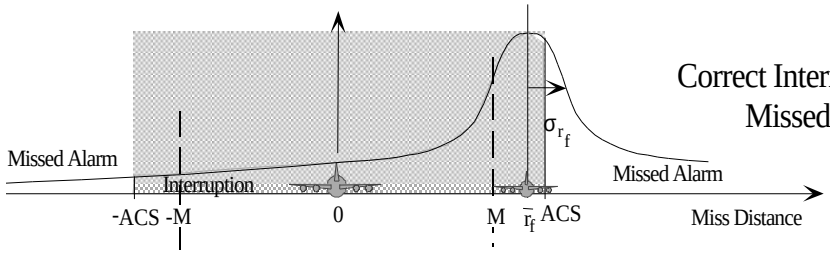
Violate Minimums

ACS - Acceptable Controller Spacing, at tool accuracy
M - Minimmum Separation Rule



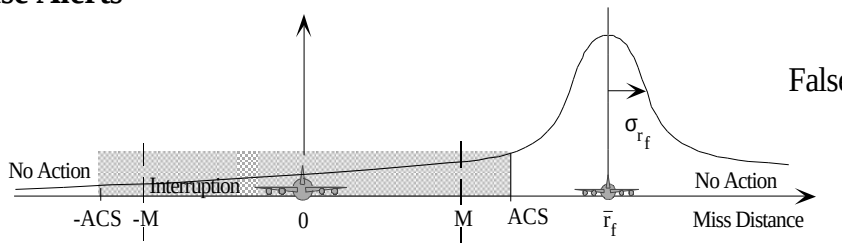
Correct Interruption — $ C, strategic
Missed Alarm — $ C^+, tactical
100%

Violate Acceptable Controller Spacing



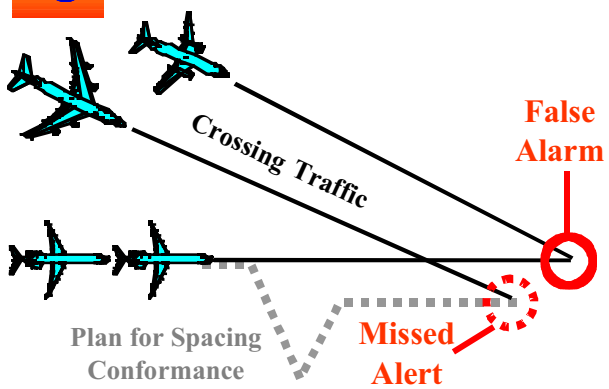
Correct Interruption at tool accuracy — $ C, strategic
Missed Alarm at tool accuracy — $ C^+, tactical
100%

False Alerts



False Alert Interruption — $ C^-, strategic
No Action — $ 0
100%

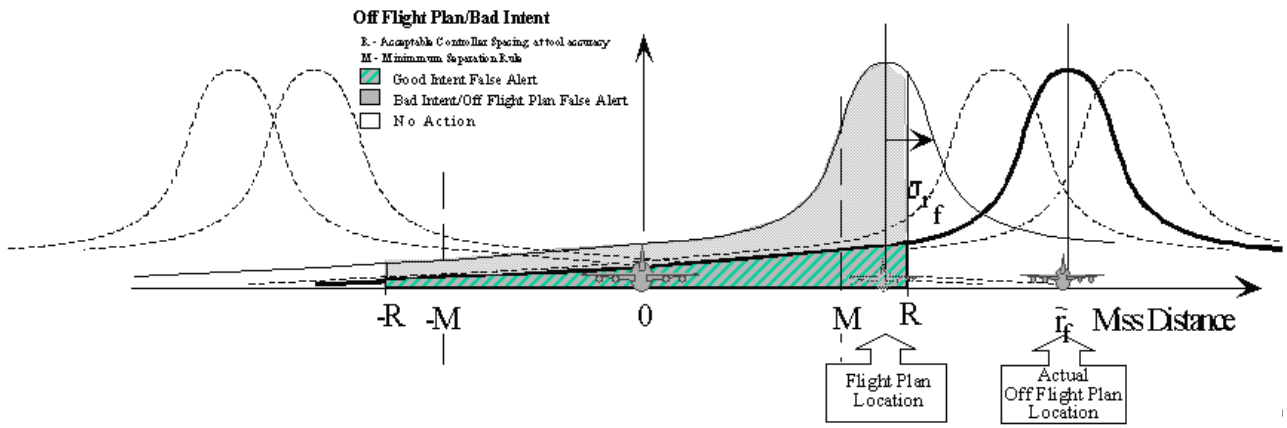
Erroneous Intent



Bad Intent Results from:

1. Undocumented Off-Flight Plan routing
2. Lack of integration with Metering Conformance Flight Changes - EDA Benefit

Undocumented Off-Flight Plan routing



- **FFP1 assumes 15% of all conflicts Undocumented Off-Flight Plan (Bad Intent)**
- **EDA facilitates arrival documentation - 0% bad intent for metered arrival aircraft**
- **EDX downlink of Next 2 Waypoints - 0% bad intent for all flights**

Trajectory Prediction Accuracy Modeling

A_i

Maneuver Error Partial Derivatives			
Parameter	Units	Climb	Descent
Initial Weight	sec/%	24.2	0.88
(Thrust – Drag)	sec/%	4.08*	1.39
TOD Placement	sec/nm	N/A	4.08
Speed. Adherence	sec/kt	11.1*	1.46
X-Track Wander	sec/nm	1.77**	1.77
Aircraft Navi Bias	sec/deg	1.94**	1.94
Turn Dynamics	sec/sec	1.11**	1.11
Wind Forecast	sec/kt	3.7*	0.95
Temperature Forecast	sec/°C	8.7*	4.62
Surveillance	sec/kt	0.26**	0.26

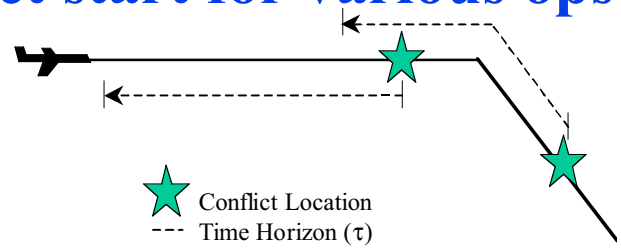
* Path distance errors at TOC converted to time error based on speed of 415 kts at TOC

** Climb coefficients set equal to descent coefficients, due to lack of climb data.

σ_i

		Prediction Error (1-sigma, Jet with FMS)					
		FFP1 Baseline			EDA		
Parameter	Units	Cl	Cr	D	Cl	Cr	D
Initial Weight	%	9.2	N/A	7.8	9.2	N/A	7.8
(Thrust – Drag)	%	5.9	N/A	5.9	5.9	N/A	5.9
TOD Placement	nm	N/A	N/A	20	N/A	N/A	0.25
Speed Adherence ($\sigma_{V,FTE}$)	kt	15	15	15	15	15	4.0
X-Track Wander	nm	0.14	N/A	0.14	0.14	N/A	0.14
AC Navigation Bias	deg.	0.15	N/A	0.15	0.15	N/A	0.15
Turn Dynamics	Sec	2.3	N/A	2.3	2.3	N/A	2.3
Wind Forecast ($\sigma_{V,W}$)	kt	12.0	13.4	12.0	12.0	13.4	12.0
Temperature Forecast	°C	1.0	N/A	1.0	1.0	N/A	1.0
Surveillance-Speed ($\sigma_{V,S}$)	kt	13.1	12.5	13.1	13.1	12.5	13.1
Surveillance-Position	nm	N/A	0.87	N/A	N/A	0.87	N/A

Identify Trajectory Accuracy at conflict start for various ops



Assume:
- 12-minute time horizon (conflict at climb/descent midpoint)
- Maneuver Error Coefficients (A_i)
- Contributing Errors by case (σ_i)

where:

$$\sigma_{P,Pred}(\tau) = \sqrt{\sigma_P^2 + \tau^2 \sigma_V^2}$$

$$\sigma_v = \sqrt{\sigma_{V,S}^2 + \sigma_{V,W}^2 + \sigma_{V,FTE}^2}$$

And for climb/descent altitude maneuvers:

$$\sigma_P = \sqrt{\sigma_{t,M}^2 V_M^2}$$

$$\sigma_{t,M} = \sqrt{\sum_{\forall i} A_i^2 \sigma_i^2}$$

Assumed ATM Perception

		FFP1 Baseline					EDA					EDX				
		DEP		OVR	ARR		DEP		OVR	ARR*		DEP		OVR	ARR*	
		CL	CR	CR	CR	D	CL	CR	CR	CR	D	CL	CR	CR	CR	D
12-minute Trajectory Prediction Error																
Predicted Position Error	nm	13.8	4.7	4.7	4.7	4.5	13.8	4.7	4.7	3.7	1.6	9.4	3.6	3.6	3.6	1.4
Horizontal ACS																
En Route	nm	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	7.37	6.07	7.04	7.26	7.26	7.26	5.91
Vertical ACS																
>FL290	Ft	3000	2000	2000	2000	3000	3000	2000	2000	2000	2357	2680	2000	2000	2000	2303
<=FL290	Ft	2000	1000	1000	1000	2000	2000	1000	1000	1000	1357	1680	1000	1000	1000	1303
Off-Flight Plan Frequency																
Off-FP	%	15%	15%	15%	15%	15%	15%	15%	15%	0%	0%	0%	0%	0%	0%	0%

* Applies to metered arrivals only.

EDA - Improves metered arrival (cruise and descent flight segments) ACS and Off-flight plan intent

EDA + EDX - Improves ACS and Off-flight plan intent of all flights.

Note: FFP1 Baseline ACS calibrated to CTAS Conflict Probe-Trial Planner settings

Separation Assurance Conflicts

	Number of ATM Resolutions						Metrics	
	PCA<Rule		Rule<PCA<ACS		PCA >ACS			
	CA	MA	CA	MA	FA	Total	R_{MA}	R_{FA}
FFP1 Baseline								
OVR-OVR	122	86	170	180	291	848	48%	52%
OVR-ARR	39	44	62	119	185	449	62%	70%
OVR-DEP	26	56	47	142	227	498	73%	84%
ARR-DEP	4	9	7	34	55	110	80%	102%
DEP-DEP	13	24	NA	NA	NA	37	NA	NA
ARR-ARR	58	87	NA	NA	NA	145	NA	NA
Total	263	307	286	474	758	2,087	59%	67%
EDA – STAR Arrivals								
OVR-OVR	131	77	156	159	259	782	45%	50%
OVR-ARR	64	27	93	72	124	380	39%	48%
OVR-DEP	48	35	79	93	161	416	50%	63%
ARR-DEP	7	8	18	23	54	110	56%	98%
DEP-DEP	18	20	NA	NA	NA	37	NA	NA
ARR-ARR	173	32	NA	NA	NA	205	NA	NA
Total	440	198	346	347	599	1,930	46%	56%
EDA – Direct Arrivals								
OVR-OVR	131	77	156	159	259	782	45%	50%
OVR-ARR	67	30	94	82	120	392	41%	44%
OVR-DEP	48	35	79	93	161	416	50%	63%
ARR-DEP	15	19	34	50	76	195	58%	65%
DEP-DEP	18	20	NA	NA	NA	37	NA	NA
ARR-ARR	142	25	NA	NA	NA	167	NA	NA
Total	421	205	364	383	617	1,989	47%	53%

PCA = Point of Closest Approach distance, Rule = FAAminima, ACS = Acceptable Controller Spacing
ARR = DFW Arrival, DEP = DFW Departure, OVR =Overflight/Satellite

Interrupt Rates/Costs:

	Interrupts		Resolution Cost	
	Number	Rate/100 ops	($/op)	($/day)
FFP1 Baseline	2,087	26.1	$1.98	$4,123
EDA - STAR	1,930	24.1	$1.90	$3,660
EDA - Direct	1,989	24.9	$1.79	$3,552

Arrival Conflict Improvement

	Number of ATM Resolutions						Metrics	
	PCA<Rule		PCA<ACS		PCA >ACS			
	CA	MA	CA	MA	FA	Total	R_{MA}	R_{FA}
FFP1 Baseline								
OVR-ARR	39	44	62	119	185	449	62%	70%
ARR-DEP	4	9	7	34	55	110	80%	102%
ARR-ARR	58	87	86	124	172	527	59%	48%
Total	101	140	156	277	412	1,086	62%	61%
EDA – STAR Arrivals								
OVR-ARR	64	27	93	72	124	380	39%	48%
ARR-DEP	7	8	18	23	54	110	59%	98%
ARR-ARR	173	32	143	57	90	494	22%	22%
Total	244	67	254	152	268	984	31%	37%

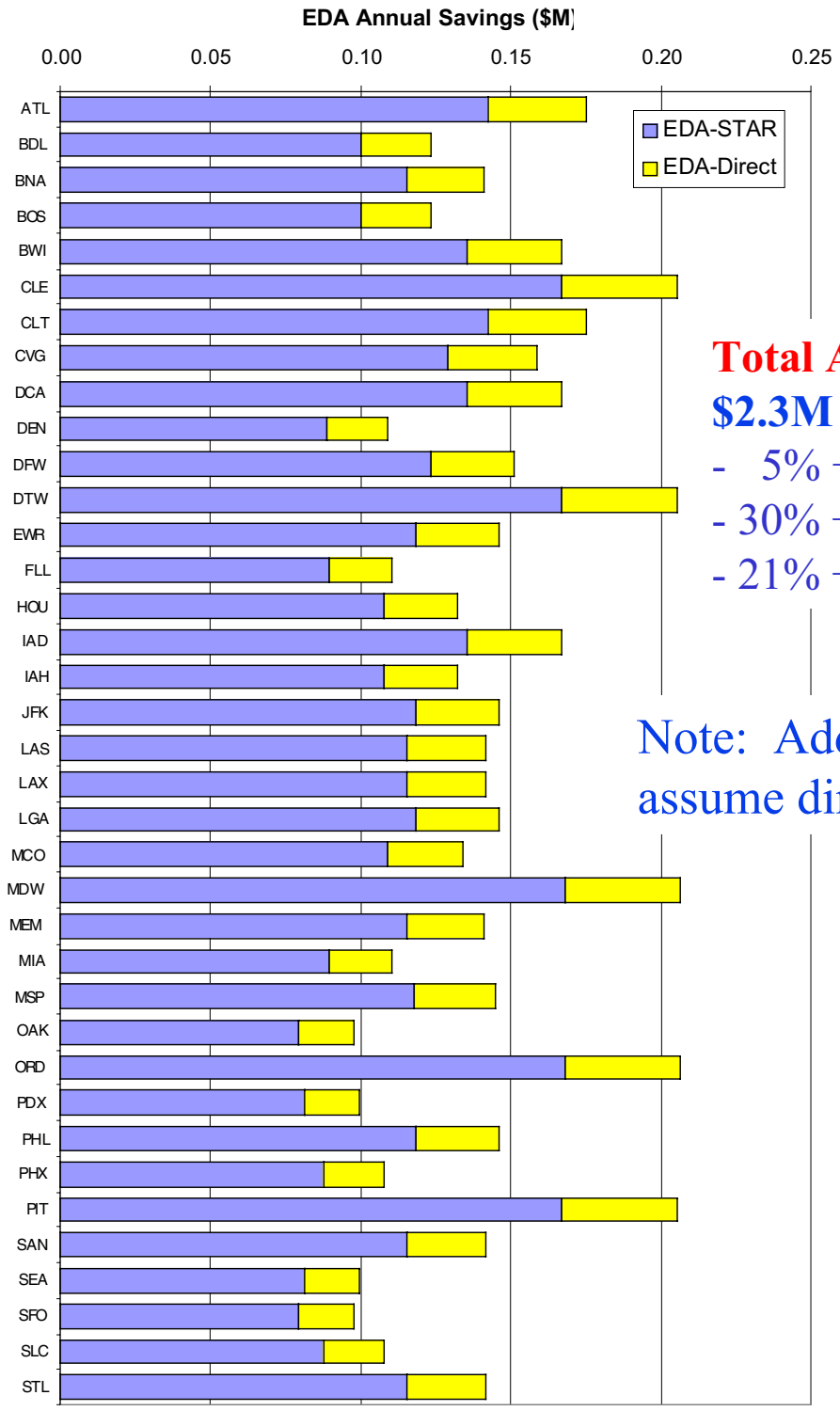
- **Changes Reflect many factors:**
  - FFP1-EDA difference in metering conformance flight changes
  - EDA integrates metering flight changes with conflict probe
  - EDA allows reduced Acceptable Controller Spacing (ACS)
- **Reduced conflict alerts:**
  - **EDA Arrival**: 9% overall, 62% missed, 35% false alerts
  - **EDA All**: 5% overall, 30% missed, 21% false alerts
  - **EDA+EDX**: additional 10% overall, 25% missed, 7% false alerts

Note: EDA arrivals metering conformance trajectories were not modeled as conflict-free

Separation Assurance Benefits

Annual Cost = (*Annual Ops*) x (*Interrupt Rate*) x (*Cost Per Interrupt*)

Annual Savings = *Annual Cost* $_{FFP1}$ – *Annual Cost* $_{EDA}$



Total Annual Benefits:

$2.3M EDA + $3.6M EDX

- 5% + 10% overall conflicts
- 30% + 25% missed alerts
- 21% + 7% false alerts

Note: Additional benefit when assume direct arrival routing

Arrival Trajectory Optimization Benefits

Arrival Trajectory Optimization Benefits

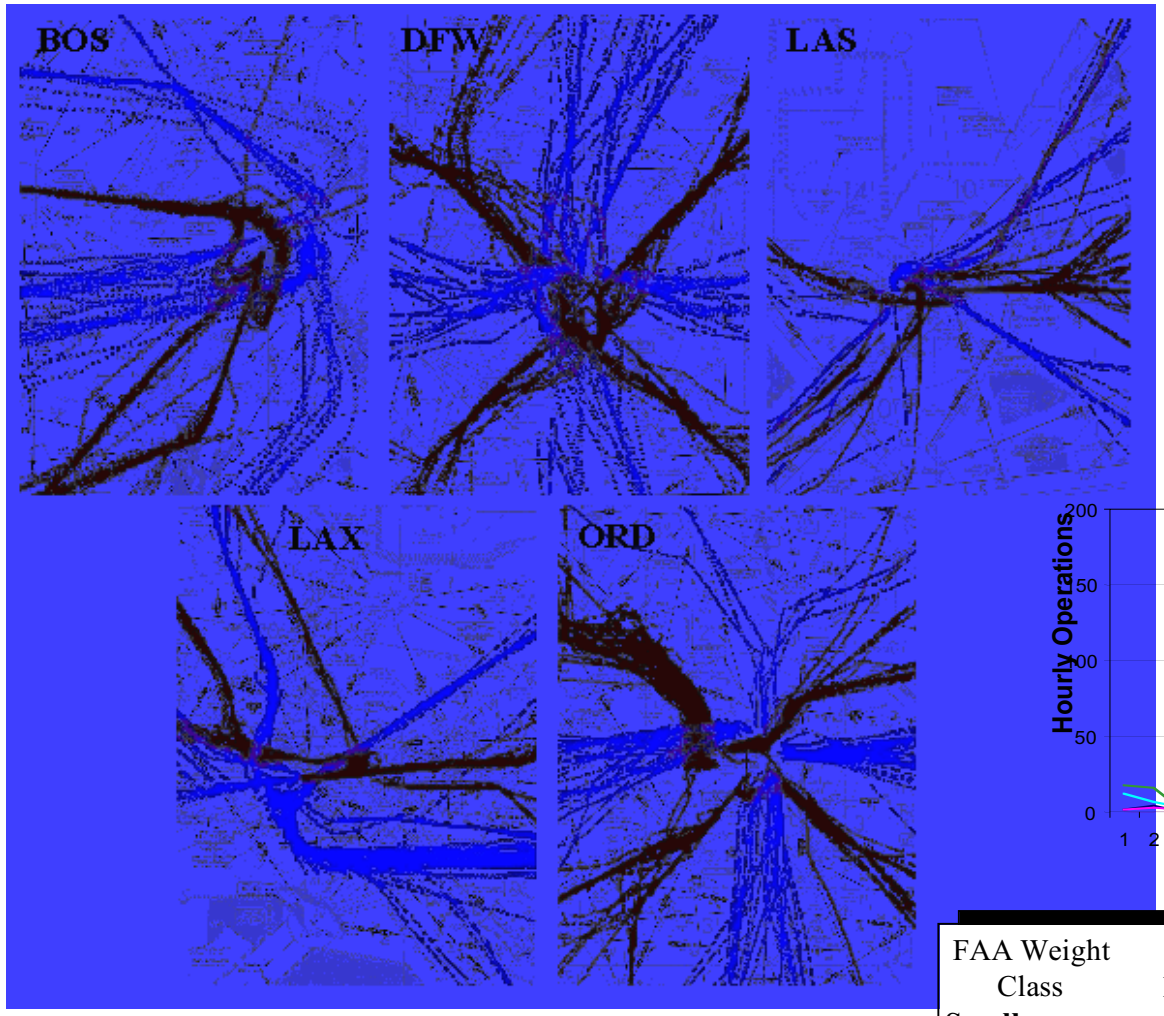
- **Benefit Mechanism**

  Improve arrival fuel efficiency by minimizing early descents and indirect routes to metering/merge point, under existing and relaxed metering fix restrictions

- **Analysis Method**
  - Baseline Conditions (ATL, DFW, LAS, LAX radar data)
  - Near-Term (existing MF restrictions)
    - TOD Optimization
    - Direct Routing
  - Far-Term Anchor Point Concepts (relaxed MF restrictions)
    - Vertical - Move BOD into TRACON
    - Horizontal - Direct Route to TRACON merge point
  - DFW Daily & Annual/NAS-wide benefits

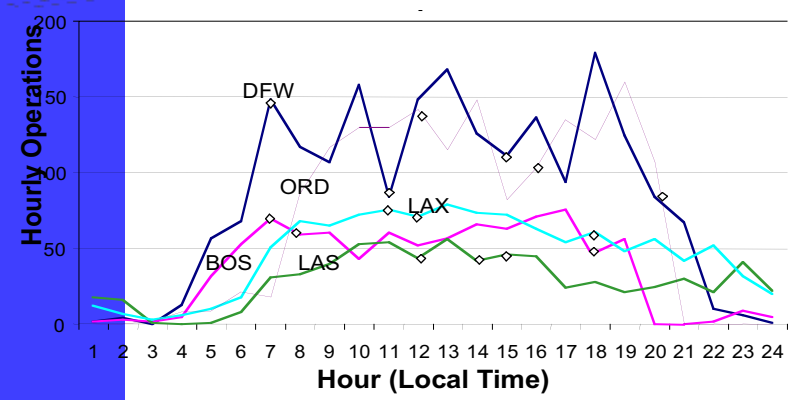
- **Study Cases**
  - FFP1 Baseline
  - EDA, existing MF restrictions
  - EDA, relaxed Anchor Point metering restrictions

Five-Airport Baseline Radar Data



- **Boston Logan (BOS)**
- **Dallas/ Ft. Worth (DFW)**
- **Las Vegas (LAS)**
- **Los Angeles (LAX)**
- **Chicago O'Hare (ORD)**

3-hours analyzed per airport (pre-rush, rush, post-rush)

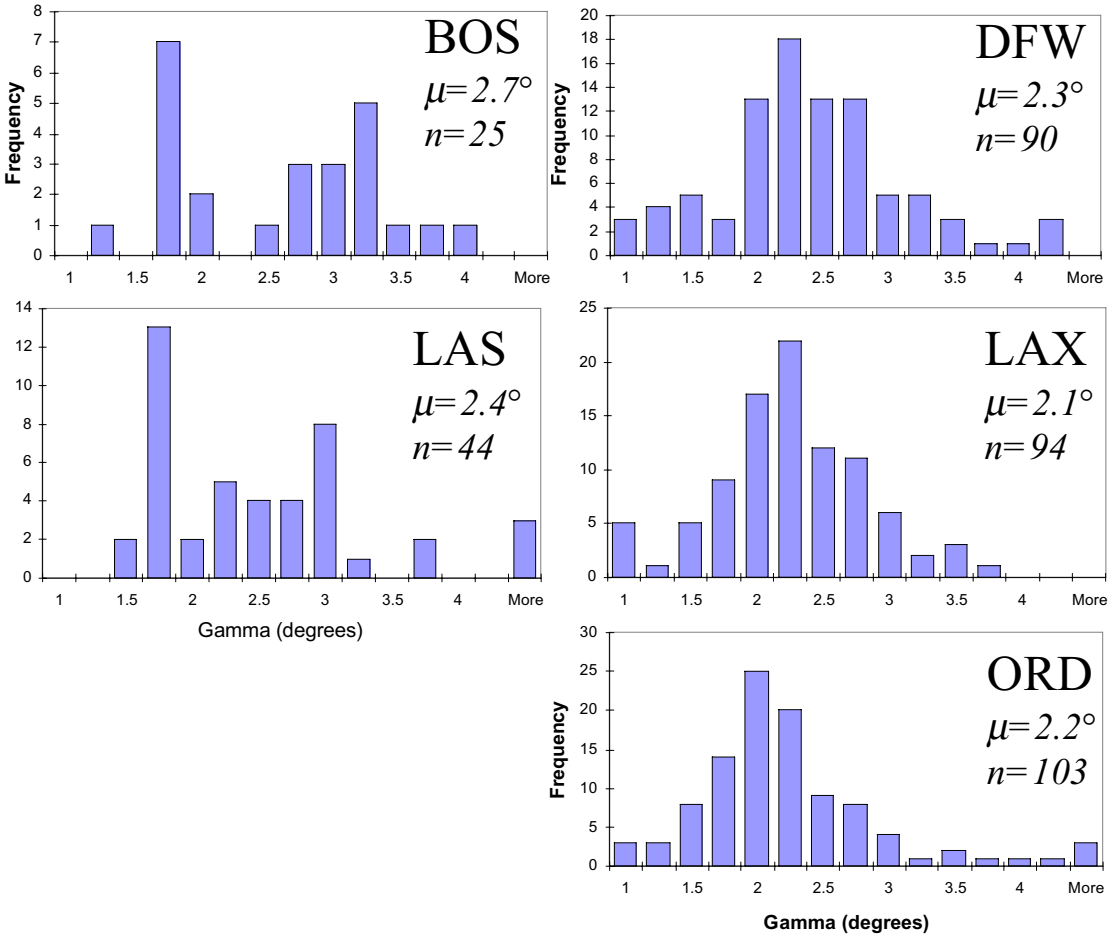


FAA Weight Class	Airport Fleet mix				
	BOS	**DFW**	**LAS**	**LAX**	**ORD**
Small	3%	2%	2%	5%	5%
Large	83%	84%	59%	42%	85%
Heavy	15%	13%	39%	53%	10%
Total	100%	100%	100%	100%	100%

Existing MF - **TOD Optimization**

- **Current TOD location relative to Idle Thrust**
- **Approximate using equivalent constant flight path angle (baseline from radar data range & altitude)**

Flight Path Angles by Airport:

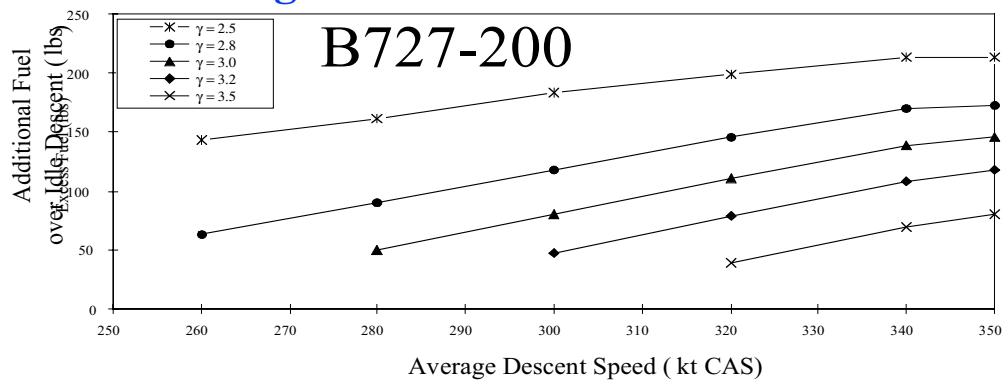


TOD Optimization Fuel Savings

- Estimated B727-200 fuel savings relative to Idle Thrust, with high-fidelity simulations at various descent speeds and flight path angles (nominal weight)

- Savings extrapolated fleet-wide:
  - Apply B727 fuel savings, assuming nominal aircraft descent speed at nominal weight (BADA) (baseline limited to ≥ 2°)
  - Apply BADA-based fuel scale factors

Fuel Savings Relative to Idle Thrust Descent:

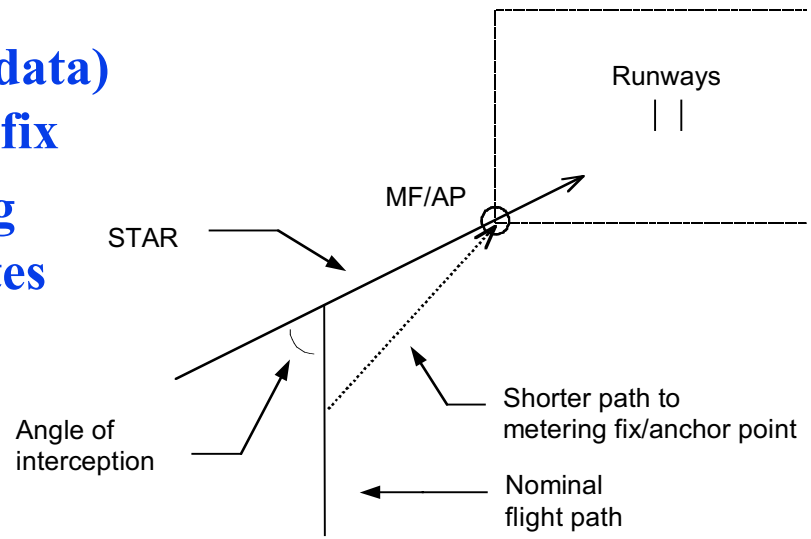


Per Operation Savings:

	Baseline Conditions		Per Operation Savings		
Airport	TOD to MF Distance (nm)	Average Flight Path Angle (degrees)	Fuel Range (lbs/op)	Savings Average (lbs/op)	Fuel Cost Savings* ($/op)
BOS	82.81	2.7	0-433	107.16	$10.72
DFW	92.36	2.3	0-236	142.38	$14.24
LAS	89.72	2.4	0-621	188.82	$18.88
LAX	107.01	2.1	0-681	270.00	$27.00
ORD	97.89	2.1	0-298	199.84	$19.98
Average	93.96	2.3	--	181.64	$18.16**

Existing MF - **Direct Arrival Routing**

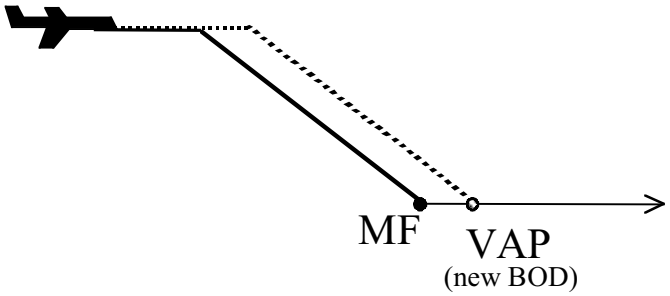
- **Current horizontal routing (radar data) vs. direct route to arrival metering fix**
- **Path savings converted to fuel using aircraft-specific cruise fuelburn rates**



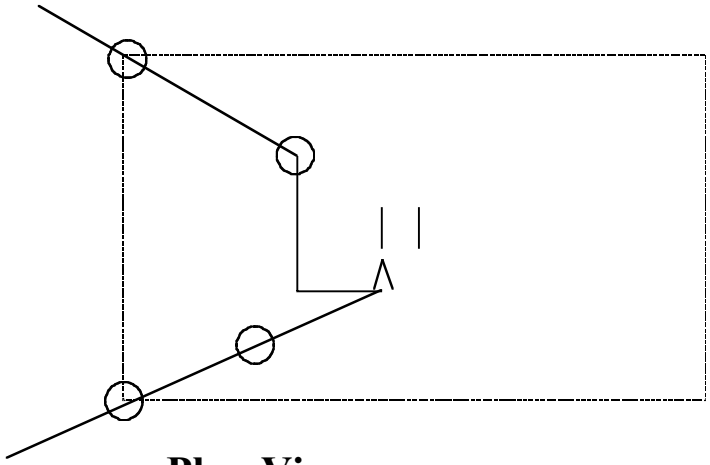
Per Operation Savings:

	Savings Per Arrival Operation		
Airport	Distance Savings (nm/op)	Fuel Savings (lbs/op)	Fuel Cost Savings* ($/op)
BOS	0.89	10.54	$1.05
DFW	2.17	23.05	$2.31
LAS	1.80	22.93	$2.29
LAX	2.54	36.67	$3.67
ORD	3.06	11.83	$1.18
Average	2.09	21.00	$2.10**

Relaxed MF - **Vertical Anchor Point**



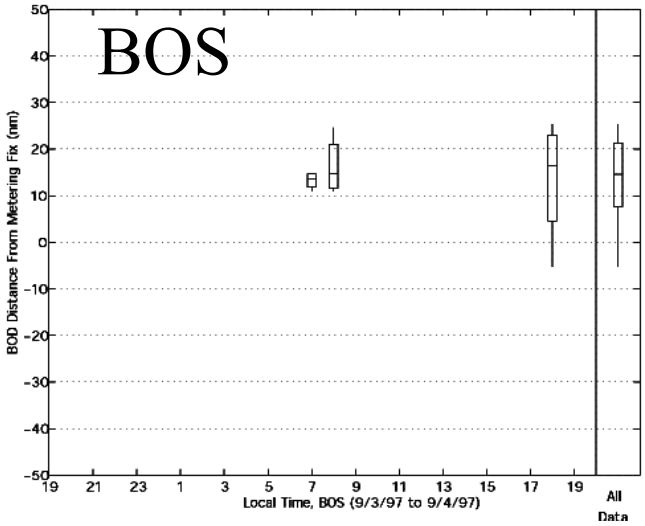
Profile View

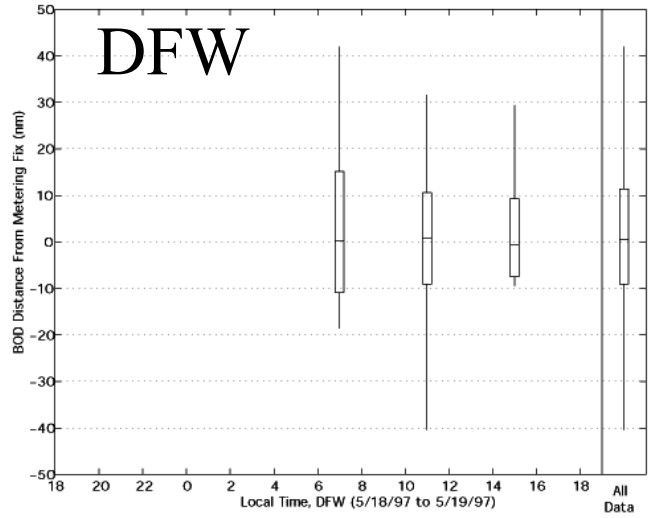


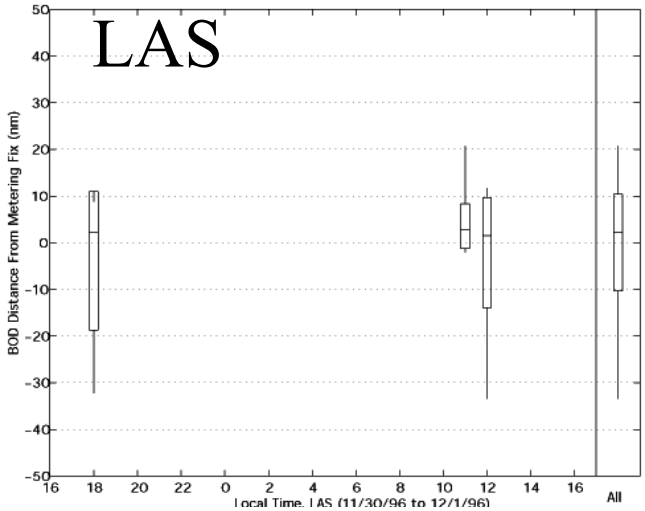
Plan View

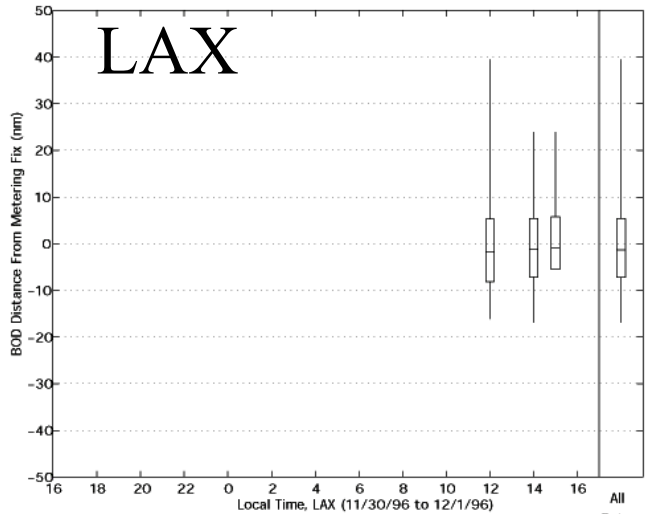
- **Vertical Anchor Point (VAP) shifts aircraft Bottom of Descent (BOD) into TRACON, for longer time at fuel-efficient cruise altitude**
- **Allowable VAP downstream shift will vary by approach route (short side vs. long-side), airport route structure, and aircraft performance**
- **Compared current BOD location (radar data) to a set VAP shift distance (existing MF, +5, +10, +15 nm)**
- **Applied aircraft-specific fuelburn rates at MF and Cruise altitudes**

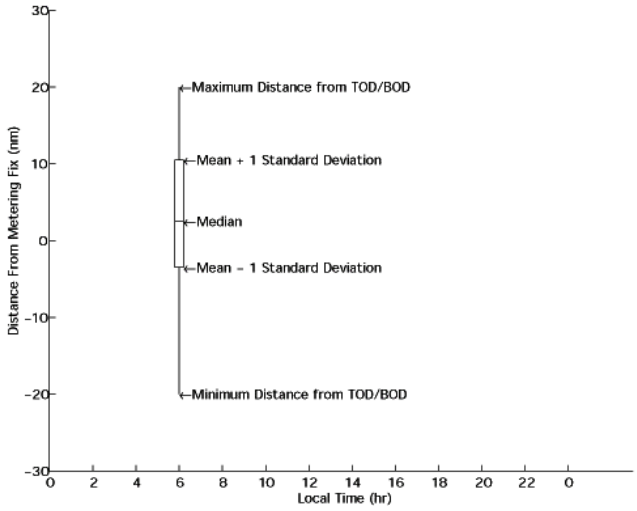
Baseline BOD Variation

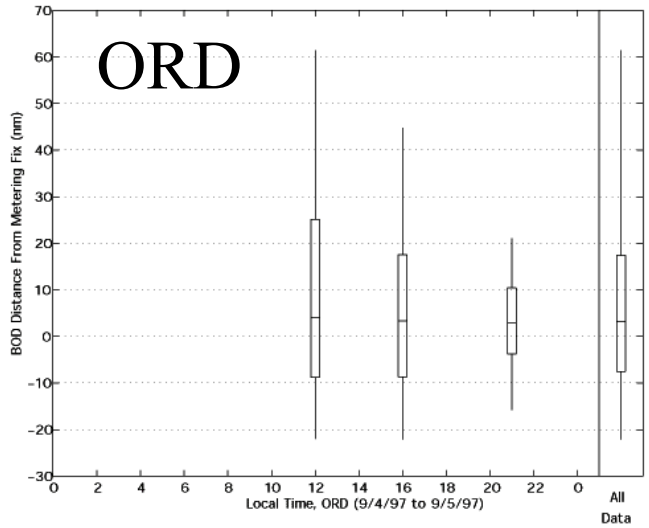












Vertical Anchor Point Savings

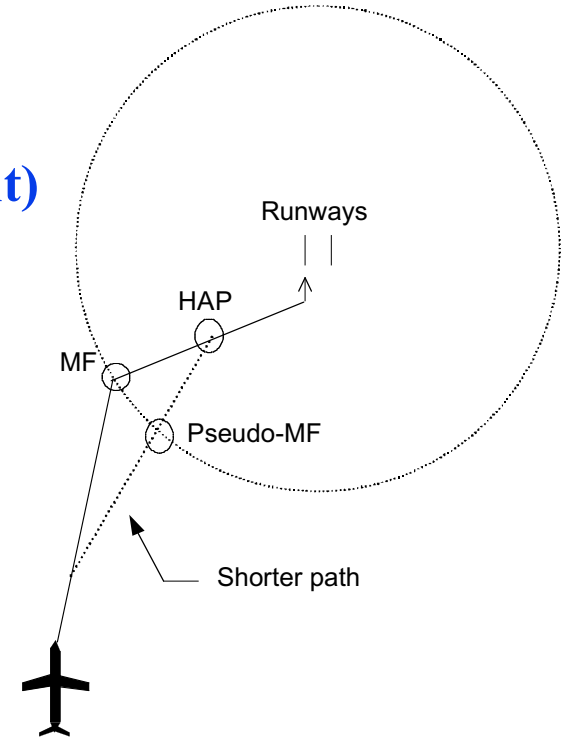
- **Static MF reflects current MF location relative to 35 nm ring**
- **Pushed VAP 5, 10, 15 nm into TRACON, (5 nm used in annual/NAS extrapolation)**

		Average Per Operation Savings		
Airport	Scenario	Distance Savings (nm/op)	Fuel Savings (lbs/op)	Fuel Cost Savings* ($/op)
BOS	Static MF	14.48	132.55	$13.26
	5nmVAP	19.48	178.34	$17.83
	10nmVAP	24.48	224.12	$22.41
	15nmVAP	29.48	269.90	$26.99
DFW	Static MF	1.16	10.03	$1.00
	5nmVAP	6.16	53.37	$5.33
	10nmVAP	11.16	96.71	$9.67
	15nmVAP	16.16	140.05	$14.01
LAS	Static MF	0.02 (1)	0.22 (1)	$0 (1)
	5nmVAP	5.02	52.47	$5.25
	10nmVAP	10.02	104.72	$10.47
	15nmVAP	15.02	156.97	$15.70
LAX	Static MF	(0.91) (1)	0 (1)	$0 (1)
	5nmVAP	4.09	46.66	$4.67
	10nmVAP	9.09	103.63	$10.36
	15nmVAP	14.09	160.61	$16.06
ORD	Static MF	4.94	43.94	$4.39
	5nmVAP	9.94	88.44	$8.84
	10nmVAP	14.94	132.94	$13.29
	15nmVAP	19.94	177.45	$17.75
Average**	5nmVAP	8.94	74.96	$7.50

(1) Negligible savings due to current BOD optimization at LAS and LAX.

Relaxed MF - **Horizontal Anchor Point**

- **Horizontal Anchor Point (HAP) allows aircraft-specific shifting of arrival metering fix (MF) along Center/TRACON boundary, shortening path length**
- **Compared current route (radar data from 140 nm out) vs. direct route to a point 15 nm downstream of MF**
- **HAP savings may be attenuated by conflicting airspace and aircraft (not evaluated)**
- **Path savings converted to fuel using aircraft-specific fuel burn rates**



Per Operation Savings:

	Per Operation Savings		
Airport	Distance Savings (nm/op)	Fuel Savings (lbs/op)	Fuel Cost Savings* ($/op)
BOS	2.60	32.58	$3.26
DFW	4.19	45.88	$4.59
LAS	3.15	44.40	$4.44
LAX	3.82	51.99	$5.20
ORD	1.49	6.12	$0.61
Average	3.05	36.20	$3.62**

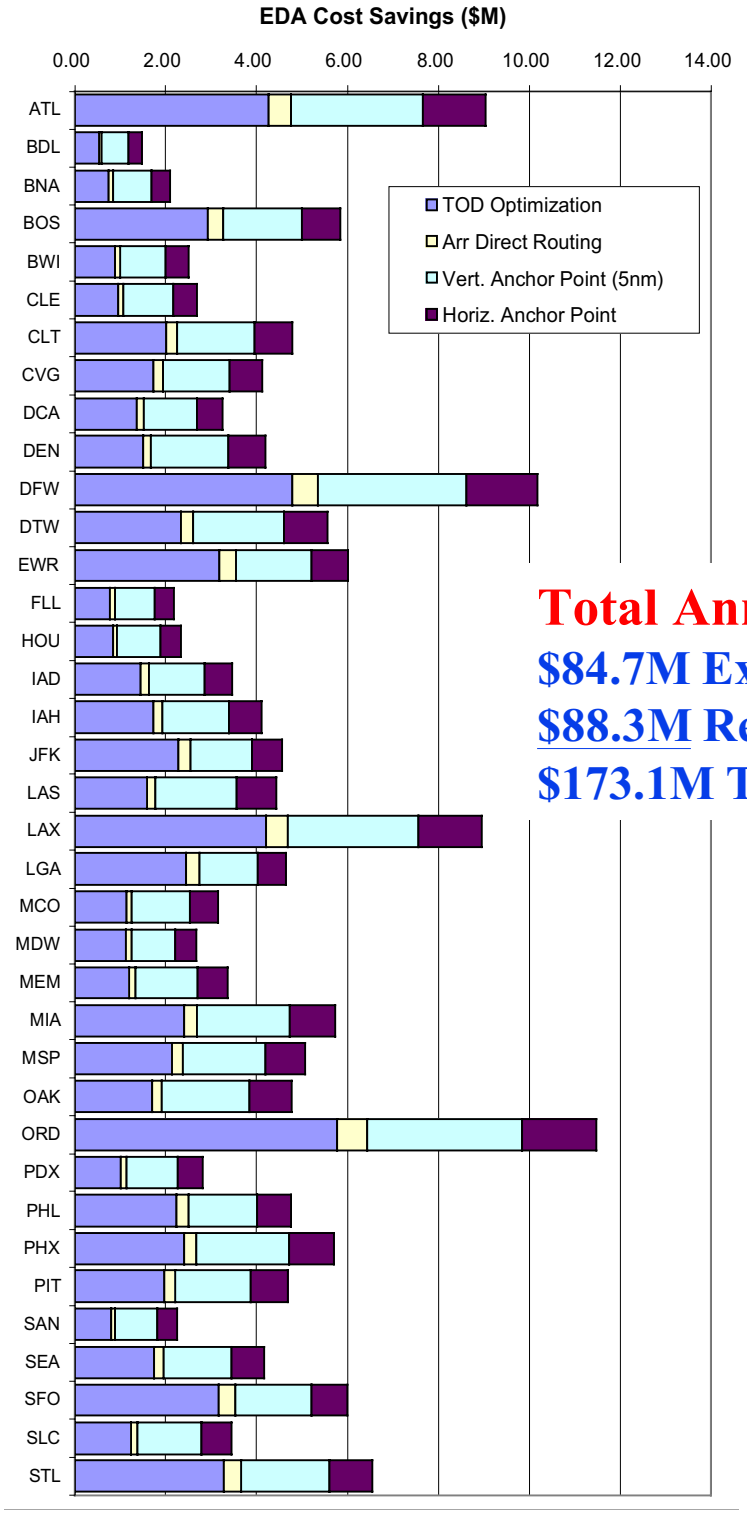
Per Operation Savings

Parameter	Existing MF		Relaxed MF	
	TOD Optimization	Arrival Direct Routing	Vertical * Anchor Point	Horizontal Anchor Point
ATL – Atlanta Hartsfield International Airport	$10.72	$1.05	$17.83	$3.26
DFW – Dallas Ft. Worth International Airport	$14.24	$2.31	$5.33	$4.59
LAS – Las Vegas McCarren International Airport	$18.88	$2.29	$5.25	$4.44
LAX – Los Angeles International Airport	$27.00	$3.67	$4.67	$5.20
ORD – Chicago O'Hare International Airport	$19.98	$1.18	$8.84	$0.61
Average Savings Per Applicable Operation	$18.16	$2.10	$7.50	$3.62
Applicable Operations Rate (per 100 Airport ops)	30.4**	30.4**	50.0	50.0

- **Results reflect airport/airspace configuration at each site during 3 study hours, 5-airport average used in NAS/Annual extrapolation**
- **Existing MF mechanisms applied only to rush arrivals, assuming controllers currently optimize under low workload conditions**
- **Relaxed MF/anchor point concept applied to all arrival operations**

Trajectory Optimization Benefits

Annual Savings = (*Annual Ops*) x (*Frequency*) x (*Savings Per Interrupt*)



Total Annual Benefits:

$84.7M Existing MF (90%TOD)

$88.3M Relaxed MF (67%VAP)

$173.1M Total

Key Recommendations to Enhance Benefits Estimates

- Enhance Existing Models & Inputs
  - Expand Modeling Conditions and Calibrate Baseline with Field Data
  - Continue to Develop and Employ Higher-Fidelity Scheduling Models (e.g. IAT)
  - Combine Center/TRACON Delay Distribution and Metering Conformance Analyses
  - Enhance ATM Interruptions Model
  - Improve Trajectory Optimization Analyses
  - Upgrade Trajectory Prediction Accuracy Parameters and Models
  - Analyze other Traffic Scenarios
  - Sensitivity Analysis
- New Models/Analyses
  - Controller Benefits
  - Enhance EDA Spacing Tool Benefits