AATT RTO 26 Final Briefing

En Route Descent Advisor (EDA) and En Route Data Exchange (EDX) ATM Interruptions Benefits

Potential Benefits of User-Preferred Descent Speed Profile

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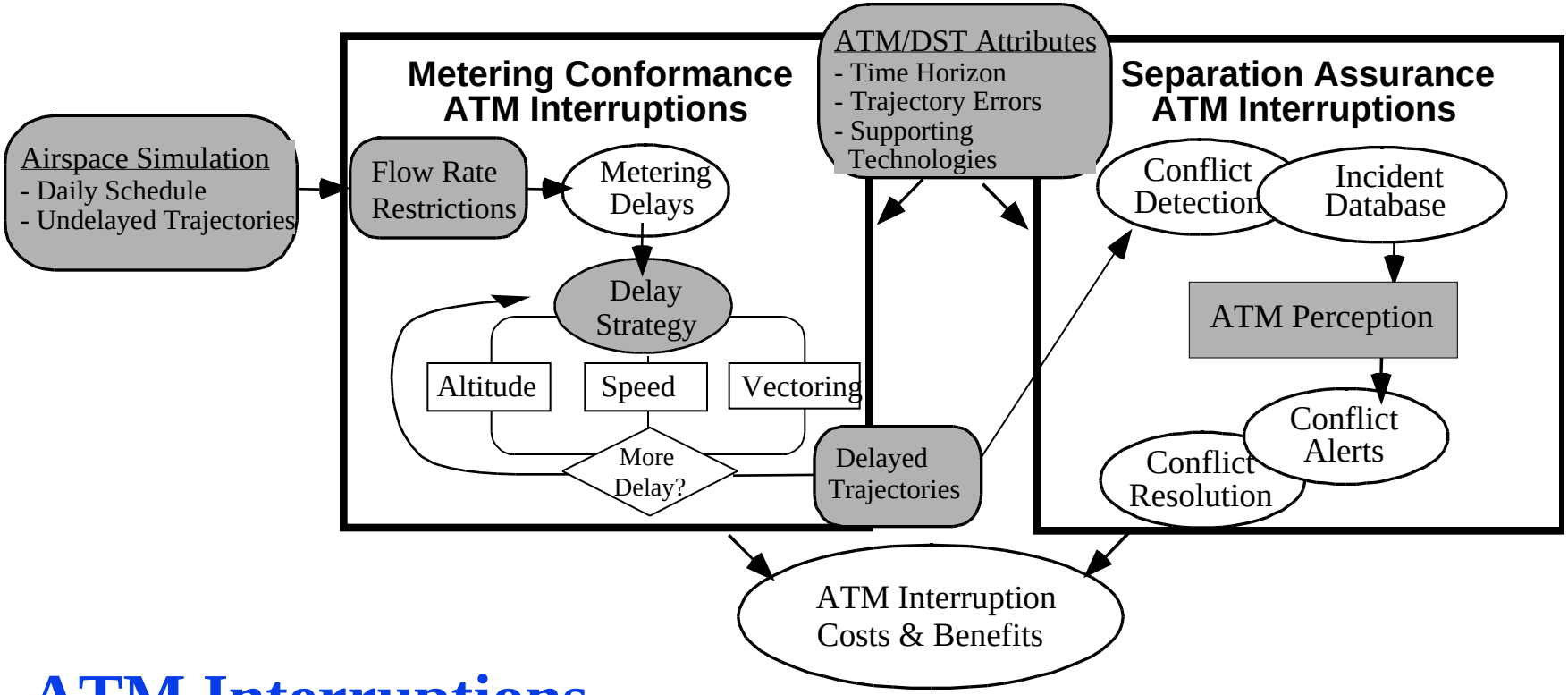
Outline

- **ATM Interruptions Benefits Estimates**
  (Part of RTO52 EDA and RTO27 EDX Benefits Compilations)
  - Common RTO 6/RTO 9 Methodology
    - Overview
    - Model Components
  - Parameters/Results - EDA
  - Parameters/Results - EDX
  - Recommendations
- **EDX User-Preferred Descent Speed Profile Benefits**
  (Part of RTO27 EDX Benefits Compilations)
  - Operational Scenario
  - Analysis Methodology
  - Parameters/Results - EDX
  - Recommendations

ATM Interruptions Methodology

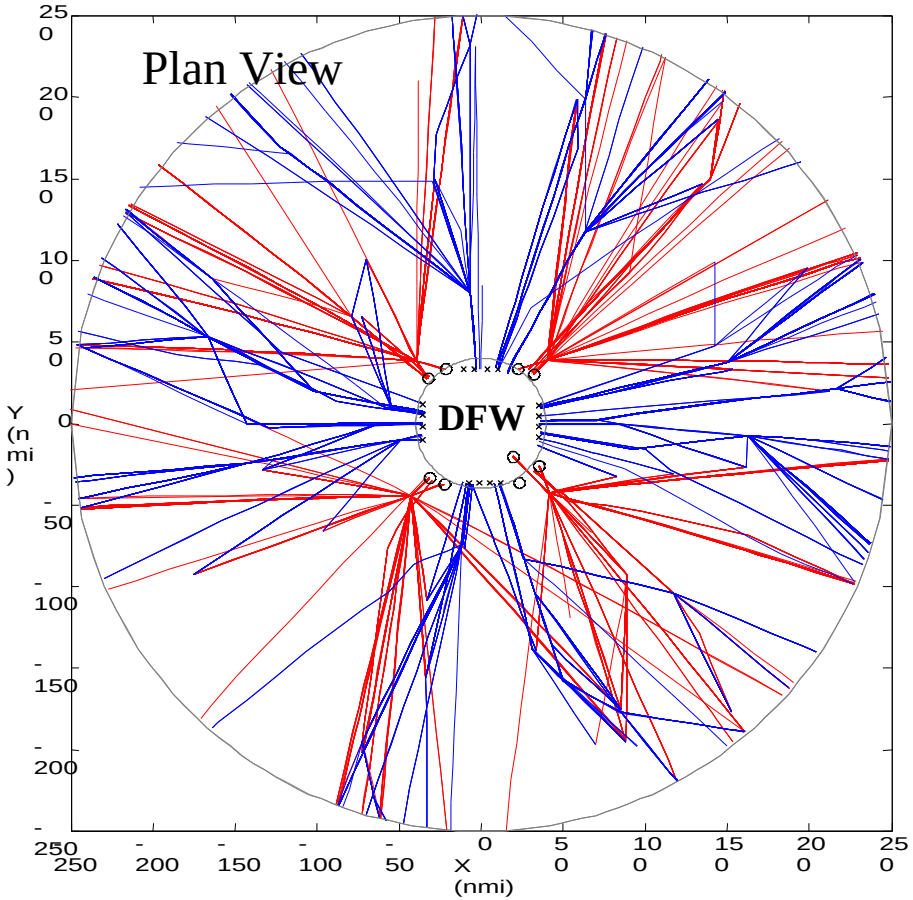


ATM Interruptions

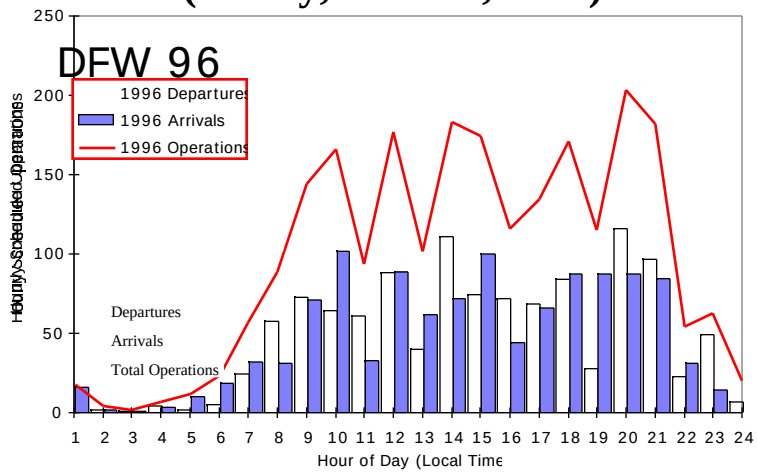
- Metering Conformance (Metering Delay Absorption)
- Separation Assurance (Conflict Probe)

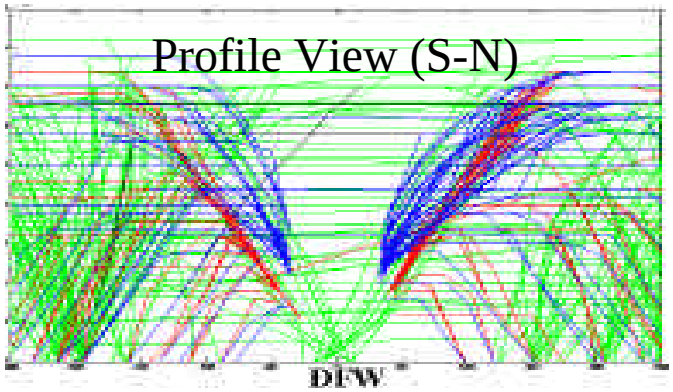
En Route Traffic Scenario

Analyzed all operations (above FL100) within 40-250 nm of DFW



ETMS flight plans (Friday, June 14, 1996)





Arrivals (direct route with EDA)

Departures

Satellite Airport/Overflight Trajectories

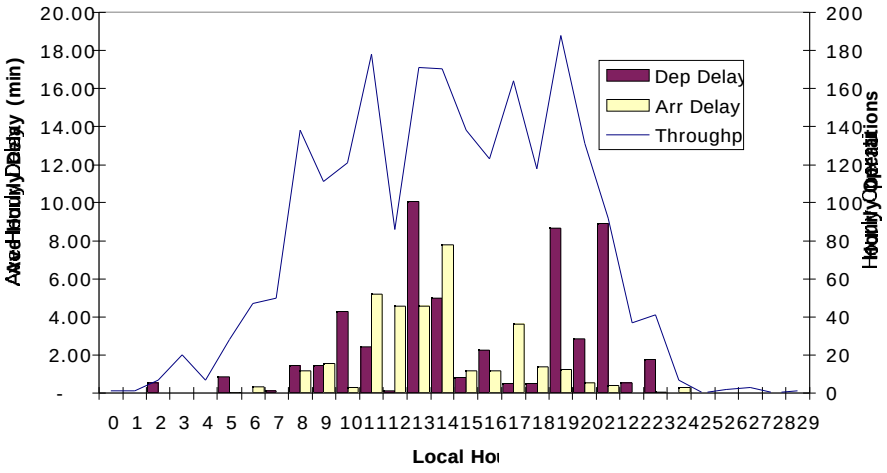
Profile View (S-N)

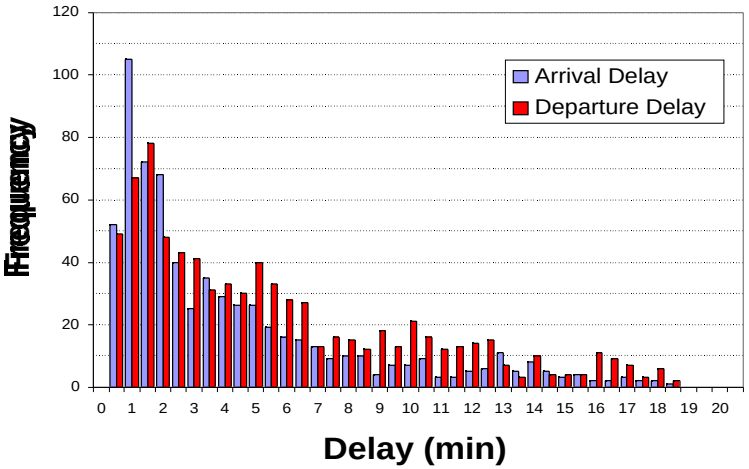
	DFW Satellite Airport	Daily Ops
IAH	Houston Apt	1,043
HOU	William Hobby Apt	497
DAL	Dallas Love Field Apt	468
SAT	San Antonio Intl Apt	432
AUS	Robert Mueller Muni Apt	377
OKC	Will Rogers World Apt	276
TUL	Tulsa Intl Apt	261
SPS	Wichita Falls Muni Apt	156
SHV	Shreveport Regional Apt	136
LBB	Lubbock Intl Apt	128
	Top 10 DFW Satellite	3,774 (83%)
	DFW Satellite Ops	4,005
	DFW Overflight Ops	527

Plan View

Metering Delays

- **Airport flow-rate restrictions impose delays on DFW arrivals and departures**
- **Flights delayed to reflect realistic flight trajectories for conflict probe DST evaluation**
- **CTAS-like scheduling model calculates metering fix crossing schedule and associated delays**





DFW Scheduling Criteria	Parameter Value
Arr/Dep Fix Separations	5.50 nm
TRACON Acceptance Rates	
Arrivals (4 rwys)	150 ac/hr
Departure (3 rwys)	115 ac/hr

Arrival Metering Conformance Strategy

Delay Methods

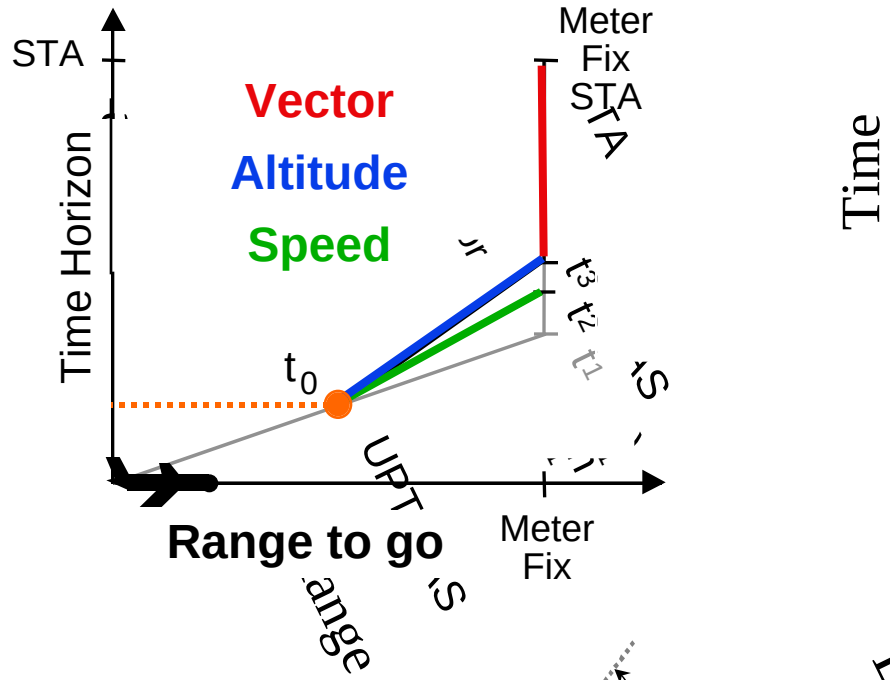
- Speed — 1st w/EDA
  - Cruise
  - Descent
- Altitude — 1st w/FFP1
- Vectoring
- "Time Shift"

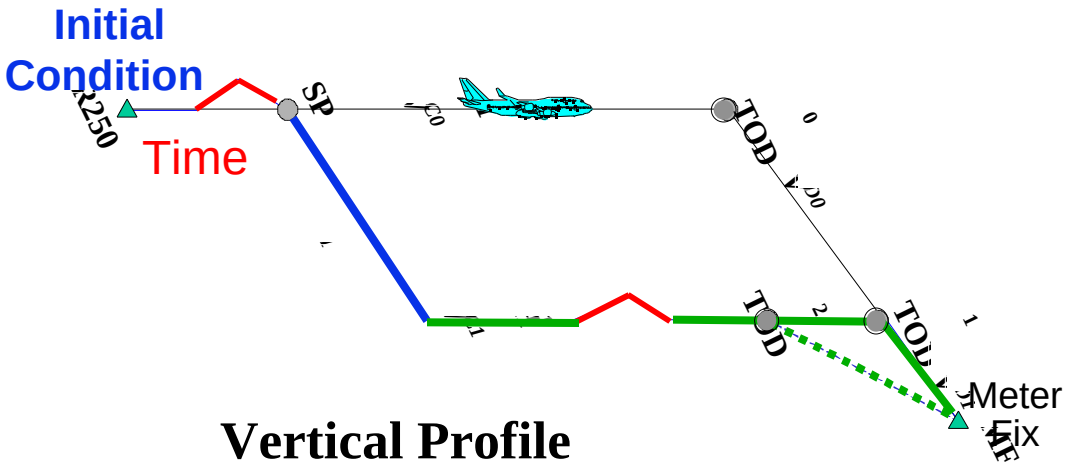
Time Horizon

(TMA delay advisory at 19 minutes)

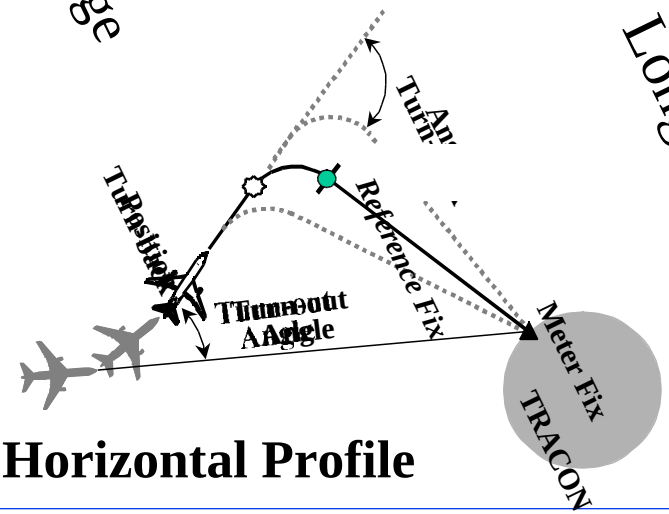
FFP1: 16 minutes

EDA: 18 minutes





Vertical Profile



Horizontal Profile

Metering Conformance Interruption Cost

Time

- FAA time cost rates by aircraft type

Fuel

- $0.10 per pound of fuel
- Departures - FAA ground hold fuel cost rate by aircraft type
- Arrivals - B737 high-fidelity simulation cruise fuelburn rates (by CAS speed & altitude), fleet extrapolation using FAA airborne fuel cost rates

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

- Cruise speed/altitude fuelburn rate
- Vectoring Turnback Error (fuel & time)
- TOD location Shift with speed change

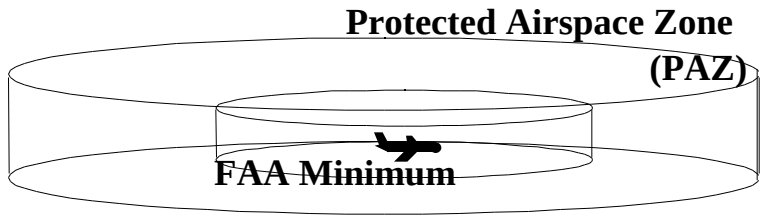
$$TOD\ Shift = 0.00001 \times (Altitude_{Cruise} - Altitude_{MF}) \times (Speed_{Descent} - 280)$$

Incident Database

Objective:

Create database of all conflicts/near-conflicts from DFW Airspace Model trajectories (x,y,z,t)

- Filter to identify unique 2-aircraft incidents
  (less than 12 nm horizontally & up to 3000'/2000' vertically)



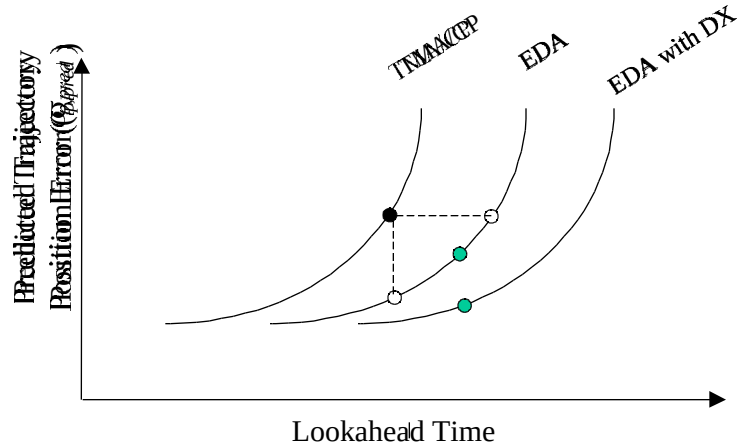
Min Sep. Requirement + Buffer

- Calculate incident attributes
  - Miss distance (horiz/vert distance, time, location)
  - Operations Type (arrival, departure, overflight)
  - Flight mode (climb, descent, cruise)
  - Other as needed to categorize incident or ATM perception accuracy (arr/dep fix, relative speeds and headings)

ATM Perception

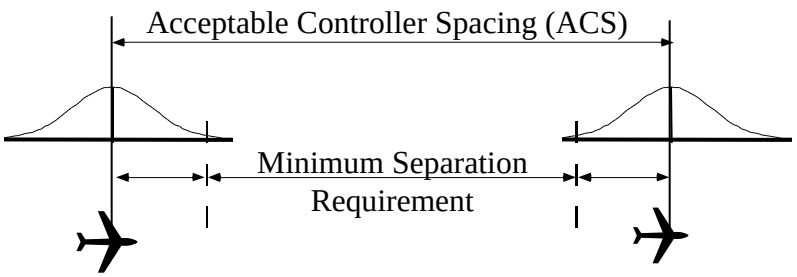
Tool Accuracy...

$$\sigma_{p.pred}$$



Acceptable Controller Spacing (*ACS*)

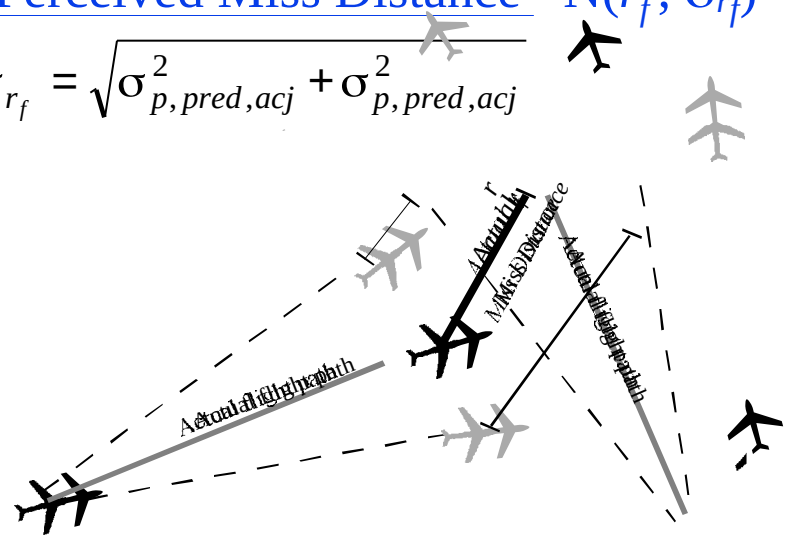
$$ACS = n\sigma_{p.pred} + Min\ Sep\ Reqmn't$$



Note: *n* values estimated for vertical and horizontal cases using observed (CTAS CPTP) ACS values and FFP1 estimated 12-min prediction error

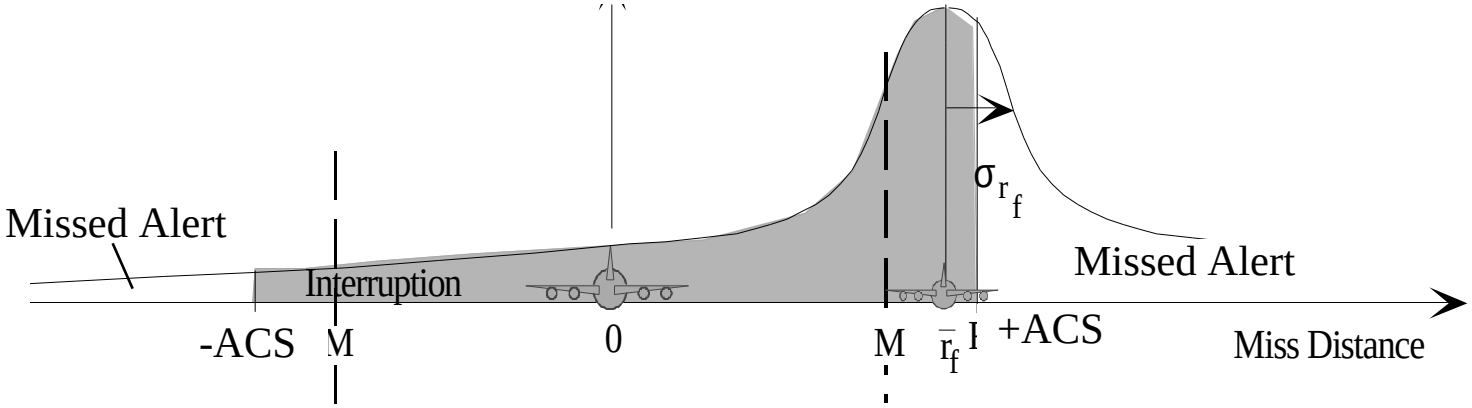
Perceived Miss Distance ~N(r_f, σ_{r_f})

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



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...

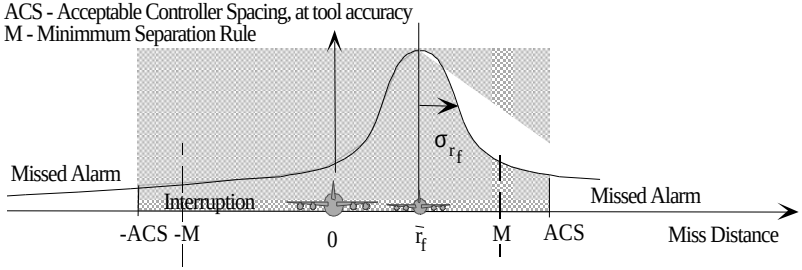
Compare
Incident Minimum Distance ($\bar{r}_f$)
with Perception (σ_{r_f},ACS)

Probability of Interruption

Resolution Cost

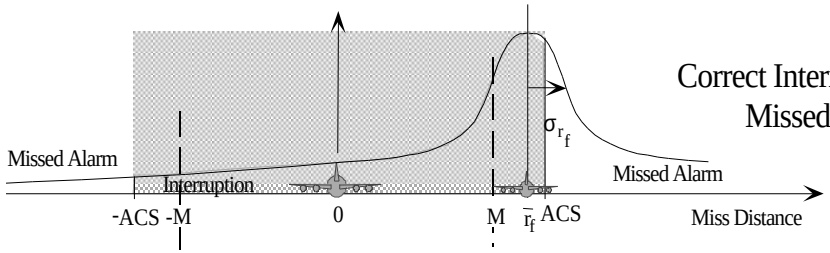
Violate Minimums

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



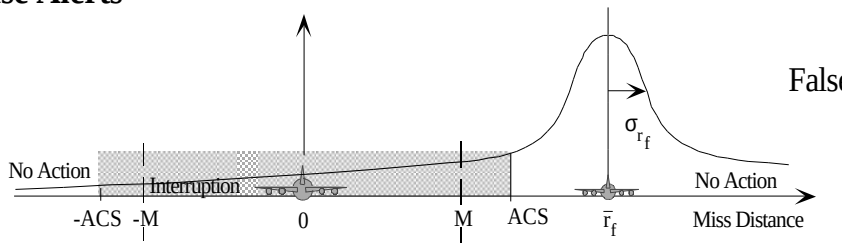
Correct Interruption	■	$ C, strategic
Missed Alarm	□	$ C^+, tactical
	100%	

Violate Acceptable Controller Spacing



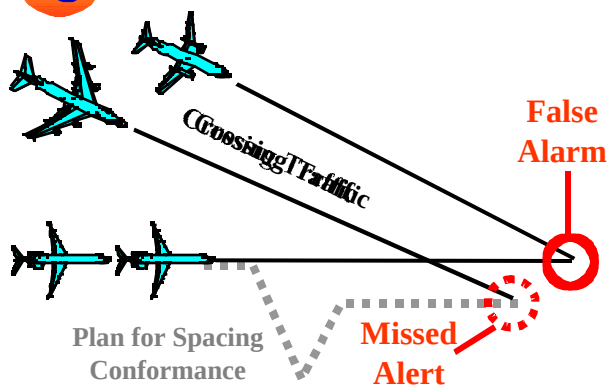
Correct Interruption at tool accuracy	■	$ C, strategic
Missed Alarm at tool accuracy	□	$ C^+, tactical
	100%	

False Alerts



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

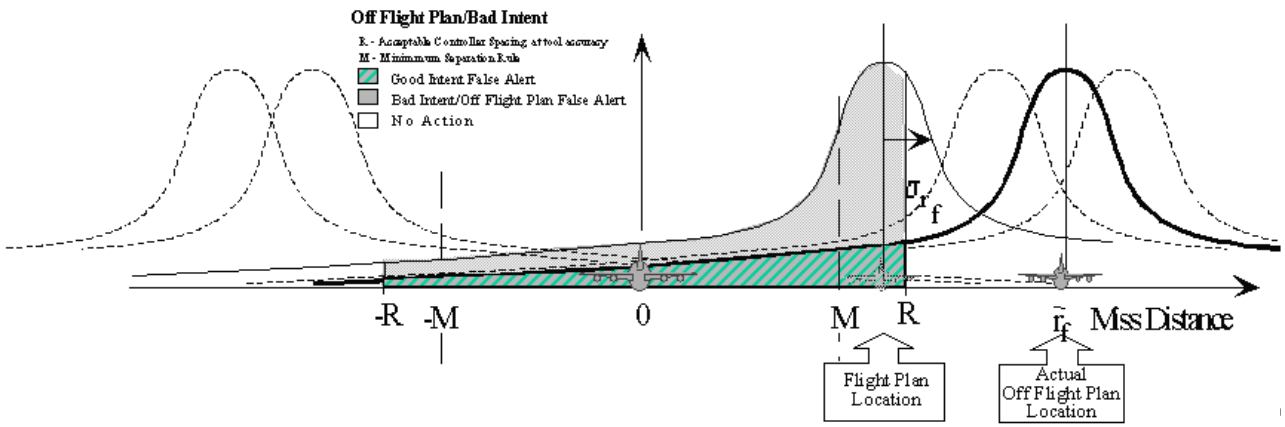
Erroneous Intent (1 of 2)



Bad Intent Results from:

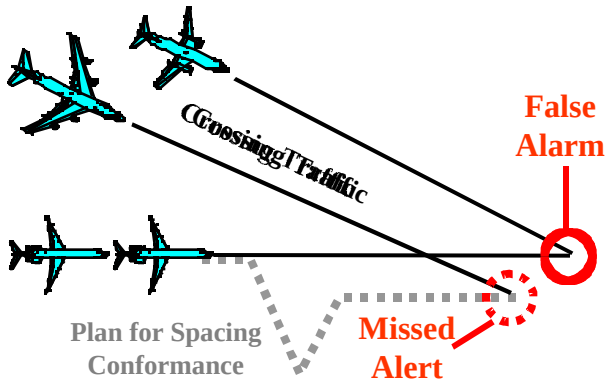
1. Undocumented Off-Flight Plan routing
2. Lack of integration with Metering Conformance Flight Changes

1. 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**

Erroneous Intent (2 of 2)



2. Lack of integration with Metering Conformance Flight Changes

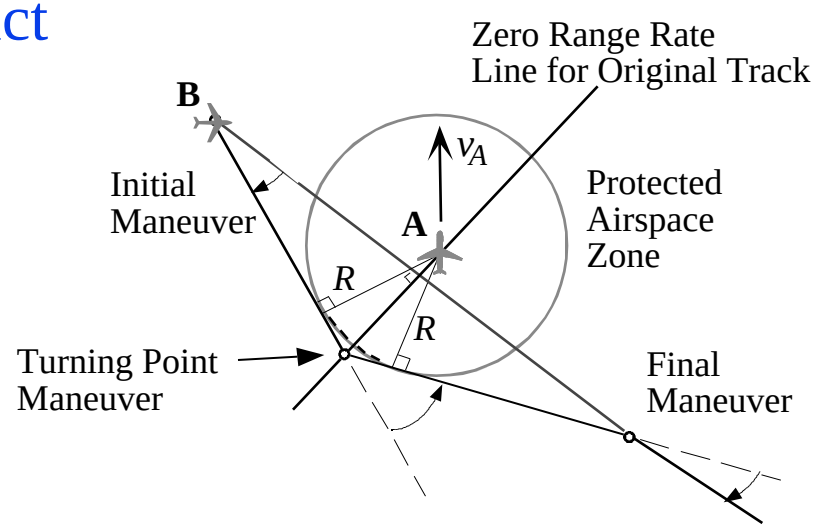
Degraded FFP1 by comparing Delayed and Flight Plan (undelayed) ATM perception and conflict attributes:

- **Incidents appearing in ONLY the Delayed Incident Database** –Missed Alert
- **Incidents appearing in ONLY the Flight Plan Incident Database** – False Alerts
- **Incidents appearing in BOTH Incident Databases** – FFP1 misperception of correct, missed, false alert, based on true (delayed database) conflict attributes.

EDA metering-conflict probe integration removes misperceptions thereafter.

Traffic Avoidance Resolution Costs

- **Resolution Maneuver**
  - Vectoring resolutions ONLY (backside/frontside depending on geometry)
  - Maneuvering by both aircraft (co-operative)
  - Trajectories not altered
  - Strategic, 12 min time-to conflict
  - Tactical, 5 min time-to-conflict



- **Resolution Fuel Penalty**
  - Fuel Cost $0.10/lb
  - BADA fuelburn rates

$$TC = (\Delta S / V_{initial}) \times \begin{matrix} Fuelburn \\ Rate \end{matrix} \times C_{fuel}$$

- **Notes**
  - Dep-Dep, resolutions very large (~$6/conflict)
  - False Alerts ≤ Correct Alerts
  - Others (average costs of relevant category)

EDA Study Cases

- **Free Flight Phase 1 (FFP1) Baseline**
  - SID/STAR Routing
  - CTAS TMA Scheduling/Arrival Metering
  - Initial conflict probe & Trial Planner (URET CCLD)
  - FMS flight control (sets cross-track, navigation bias, and turn dynamics errors)
- **CTAS EDA**
  - TMA/EDA Arrival Metering and Automated Advisories
  - Integrated Metering Conformance Advisories/Conflict Probe
- **CTAS EDA - Arrival Direct Routing**
  - EDA-enabled Arrival Direct Routes

EDX Study Cases

- **CTAS EDA - Arrival Direct Routing Baseline**
- **EDA Enhanced with En Route DX**
  - EDX1 + Weather (wind/temperature) DX
  - EDX2 + Wx + AC Weight, Thrust/Drag Coefficients DX
  - EDX3 + Wx + Weight + Speed Intent DX
  - EDX5 + Wx + Weight + Speed Intent + Next 2 Waypoints DX

Note: EDX not assumed to improve Metering Conformance ATM Interruptions

Baseline and EDA Delay 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:

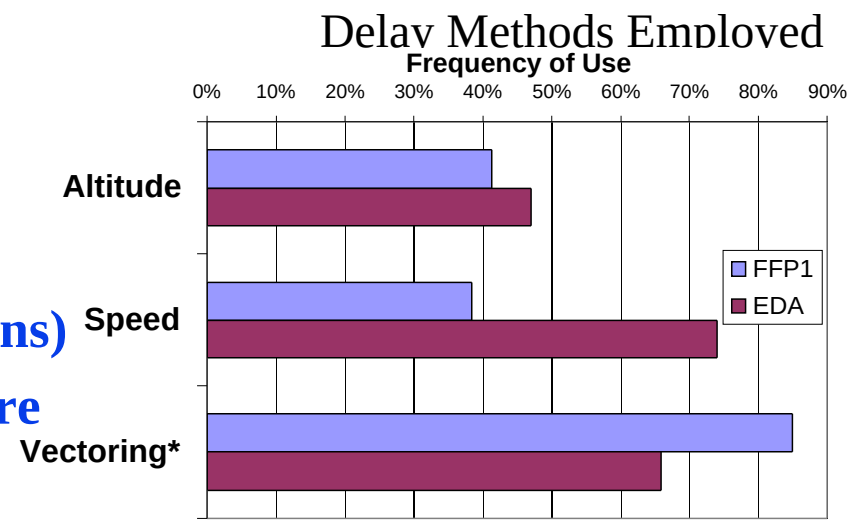
FFP1 Min speeds - No automation to help controllers identify efficient speeds; used Eurocontrol BADA model "low" cruise speeds (e.g. 250 kts for jets).

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

Metering Conformance Operational Impact

EDA Differences in Delay Absorption

- **Speed and altitude replace vectoring**
- **Optimal speed/altitude combinations (difficult without DST data/calculations)**
- **Reduced minimum speed leads to more fuel-efficient vectoring**



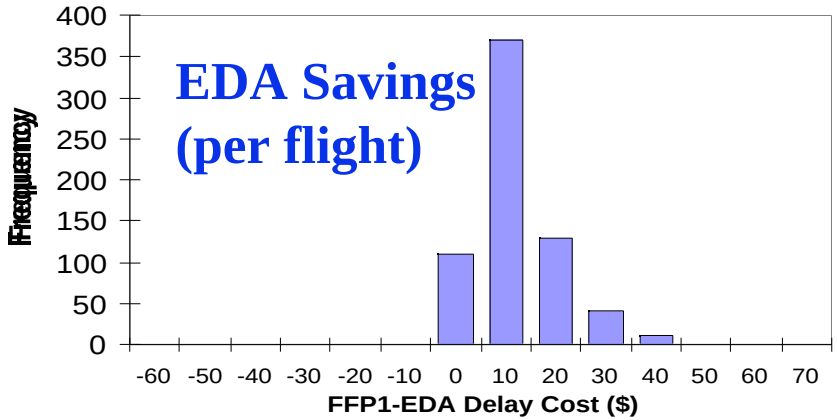
Delay (minutes)

	FFP1 Baseline			EDA – SID/STAR**			EDA – Direct Routing**		
	Range	Ave	Total	Range	Ave	Total	Range	Ave	Total
Altitude	0-2.5	0.2	160	0-10.2	1.3	845	0-10.2	1.3	845
Speed	0-4.6	0.4	275						
Vectoring*	0-18.1	3.4	2,247	2.8-17.9	2.7	1,808	2.8-17.9	2.7	1,808

* Vectoring includes Time Shift method.
** CTAS EDA cases combine speed and altitude methods.

EDA Metering Conformance Savings

CTAS EDA Daily Savings of $4500 ($4000 fuel + $500 time)



Fuel:

	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.
** Assumes $0.10 per lb of fuel.

Time: Vectoring Error, 1 % time savings with EDA

Climb/Descent Maneuver Error

Altitude Maneuver Error: $\sigma_{t,M} = \sqrt{\sum_i A_i^2 \sigma_i^2}$

Source of model coefficients (A_i):

- **Descent** - Monte Carlo high-fidelity simulation of time-to-fly errors
- **Climb** - limited sensitivity data, assumed descent values in some cases

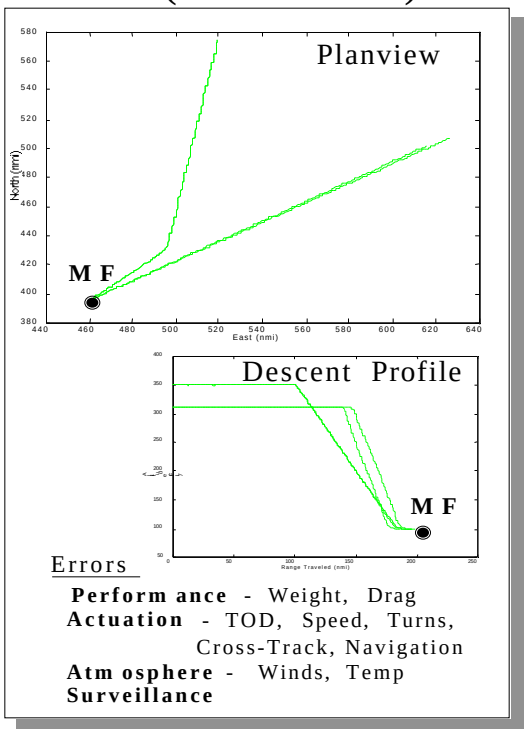
A_i

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/^{o}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.

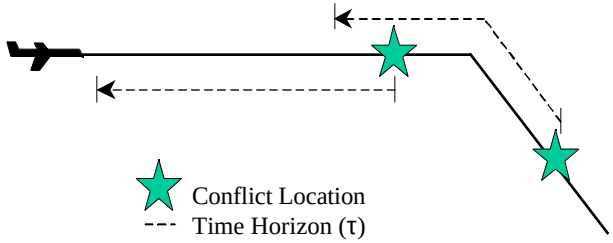
Descent (Cruise to MF)



Trajectory Prediction Accuracy Modeling

Position Error & Velocity Propagation Error

- Assume contributing errors by case (σ_i)
- Position error replaced by altitude maneuver error, (conflict assumed to occur at maneuver midpoint)



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

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

And for climb/descent maneuvers:

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

σ_i

		Passive Baseline			Active Baseline											
Error		**FFP1**			**EDA**			**EDX1** (Wx)			**EDX2** (Wt,Thr/Dg)			**EDX3** (Spd Intent)		
Parameter	Units	Cl	Cr	D	Cl	Cr	D	Cl	Cr	D	Cl	Cr	D	Cl	Cr	D
Initial Weight	%	9.2	N/A	7.8	9.2	N/A	7.8	9.2	N/A	7.8	7.6	N/A	5.6	7.6	N/A	5.6
(Thrust – Drag)	%	5.9	N/A	5.9	5.9	N/A	5.9	5.9	N/A	5.9	2.1	N/A	2.1	2.1	N/A	2.1
TOD Placement	nm	N/A	N/A	20	N/A	N/A	0.25	N/A	N/A	0.25	N/A	N/A	0.25	N/A	N/A	0.25
Speed Adherence(1) ($\sigma_{V,FTE}$)	kt	15	15	15	15	15	4.0	15	15	4.0	15	15	4.0	4.0	15	4.0
X-Track Wander	nm	0.14	N/A	0.14	0.14	N/A	0.14	0.14	N/A	0.14	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	0.15	N/A	0.15	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	2.3	N/A	2.3	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	8.9	10.5	8.9	8.9	10.5	8.9	8.9	10.5	8.9
Temperature Forecast	°C	1.0	N/A	1.0	1.0	N/A	1.0	0.5	N/A	0.5	0.5	N/A	0.5	0.5	N/A	0.5
Surveillance-Speed ($\sigma_{V,S}$)	kt	13.1	12.5	13.1	13.1	12.5	13.1	13.1	12.5	13.1	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	N/A	0.87	N/A	N/A	0.87	N/A	N/A	0.87	N/A

(1) Includes components of mismatched CTAS-FMS speed targets and aircraft Flight technical error.

Assumed ATM Perception

		FFP1 Baseline					EDA				
		DEP		OVR	ARR		DEP		OVR	ARR*	
		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
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
Vertical ACS											
>FL290	Ft	3000	2000	2000	2000	3000	3000	2000	2000	2000	2357
<=FL290	Ft	2000	1000	1000	1000	2000	2000	1000	1000	1000	1357
Off-Flight Plan Frequency											
Off-FP	%	15%	15%	15%	15%	15%	15%	15%	15%	0%	0%

- **Predicted Position Error** (assuming 12-min time horizon)
- **Acceptable Controller Spacing** (Horizontal/Vertical)
- **Off-Flight Plan Error Frequency**

		EDX1 (Weather)					EDX2 (Aircraft Weight)					EDX3 (Speed Intent)					EDX5 (Next 2 Waypoints)				
		DEP		OVR	ARR		DEP		OVR	ARR		DEP		OVR	ARR*		DEP		OVR	ARR	
		CL	CR	CR	CR	D	CL	CR	CR	CR	D	CL	CR	CR	CR	D	CL	CR	CR	CR	D
12-minute Trajectory Prediction Error																					
Predicted Position Error	nm	13.7	4.7	4.6	3.6	1.37	12.2	4.7	4.6	3.6	1.44	9.4	3.6	3.6	3.6	1.4	9.4	3.6	3.6	3.6	1.4
Horizontal ACS																					
En Route	nm	7.98	7.91	7.91	7.26	5.95	7.66	7.91	7.91	7.26	5.91	7.04	7.26	7.26	7.26	5.91	7.04	7.26	7.26	7.26	5.91
Vertical ACS																					
>FL290	Ft	2994	2000	2000	2000	2318	2886	2000	2000	2000	2303	2680	2000	2000	2000	2303	2680	2000	2000	2000	2303
<=FL290	Ft	1994	1000	1000	1000	1318	1886	1000	1000	1000	1303	1680	1000	1000	1000	1303	1680	1000	1000	1000	1303
Off-Flight Plan Frequency																					
Off-FP	%	15%	15%	15%	0%	0%	15%	15%	15%	0%	0%	15%	15%	15%	0%	0%	0%	0%	0%	0%	0%

* Applies to metered arrivals only.

- **FFP1 Baseline** - Calibrated to CTAS conflict probe ACS and TMA prototype operations
- **EDA** - EDA improves metered arrival ATM perception and metering conformance intent
- **EDA + EDX** - Improves all flight ATM perception and near-term intent

EDA ATM Interruptions

EDA-STAR: -7% overall, -30% Missed, -21% False alerts

	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 = FAA minima, ACS = Acceptable Controller Spacing
ARR = DFW Arrival, DEP = DFW Departure, OVR = Overflight/Satellite

Arrival Conflict Detail:

	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%

EDX ATM Interruptions

EDX: -10% overall, -25% Missed, -7% False alerts

	Number of ATM Resolutions						Metrics	
	PCA< Rule		Rule<PCA<ACS		PCA>ACS			
	CA	MA	CA	MA	FA	Total	R_{MA}	R_{FA}
Active Baseline								
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%
EDX1 (Weather)								
OVR-OVR	132	76	152	154	259	773	45%	50%
OVR-ARR	67	29	92	80	117	386	41%	44%
OVR-DEP	48	34	79	92	161	414	50%	63%
ARR-DEP	15	19	34	49	76	193	58%	66%
DEP-DEP	18	19	NA	NA	NA	37	NA	NA
ARR-ARR	144	23	NA	NA	NA	167	NA	NA
Total	425	200	357	375	613	1,971	46%	54%
EDX2 (Weight, Thrust/Drag Coefficients, Weather)								
OVR-OVR	135	73	150	139	259	756	43%	52%
OVR-ARR	68	28	91	74	117	379	39%	45%
OVR-DEP	50	33	79	86	161	409	48%	65%
ARR-DEP	16	18	33	42	76	185	55%	70%
DEP-DEP	19	19	NA	NA	NA	37	NA	NA
ARR-ARR	144	23	NA	NA	NA	167	NA	NA
Total	432	194	353	342	613	1,934	45%	55%
EDX3 (Speed Intent, Weight, Thrust/Drag Coefficients, Weather)								
OVR-OVR	145	64	141	110	253	713	38%	55%
OVR-ARR	71	25	82	58	117	354	35%	50%
OVR-DEP	54	29	75	67	157	382	43%	70%
ARR-DEP	18	16	32	34	76	175	50%	76%
DEP-DEP	21	16	NA	NA	NA	37	NA	NA
ARR-ARR	145	23	NA	NA	NA	167	NA	NA
Total	454	172	330	269	604	1,829	40%	60%
EDX5 (Next 2 Waypoints, Speed Intent, Weight, Thrust/Drag Coefficients, Weather)								
OVR-OVR	145	64	141	110	234	694	38%	51%
OVR-ARR	71	25	82	58	117	354	35%	50%
OVR-DEP	54	29	75	67	150	375	43%	67%
ARR-DEP	18	16	32	34	75	175	50%	76%
DEP-DEP	21	16	NA	NA	NA	37	NA	NA
ARR-ARR	145	23	NA	NA	NA	167	NA	NA
Total	454	172	330	269	577	1,802	40%	57%

Note: Number of false alerts was assumed to be equal or less than prior case.

PCA = Point of Closest Approach distance, Rule = FAA minima, ACS = Acceptable Controller Spacing

ARR = DFW Arrival, DEP = DFW Departure, OVR = Overflight/Satellite

DFW Daily Savings

- **EDA: $5000 daily at DFW**
  - $4500 from more efficient metering conformance interruptions (90%)
  - $500 from separation assurance interruptions
  - 5% more savings with EDA-Direct Routing

	EDA-SID/STAR		EDA-Direct Routing	
	Interrupts	Daily Cost	Interrupts	Daily Cost
Arrival Metering	0	$4,499	0	$4,740
Departure Metering	0	$0	0	$0
Separation assurance	157	$ 463	98	$ 571
Total	157	$4,962	98	$5,311

- **EDX: $400 daily at DFW**
  - 100% from separation assurance interruptions
  - Largest savings from EDX2 (aircraft weight) and EDX3 (speed intent)

	EDX1		EDX2		EDX3		EDX5	
	Interrupts	Daily Cost	Interrupts	Daily Cost	Interrupts	Daily Cost	Interrupts	Daily Cost
Arrival Metering	0	$0	0	$0	0	$0	0	$0
Departure Metering	0	$0	0	$0	0	$0	0	$0
Separation assurance	18	$ 22	55	$ 161	160	$ 293	187	$ 380
Total	18	$ 22	55	$ 161	160	$ 293	187	$ 380

1996 NAS/Annual Benefits Extrapolation

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

Annual Savings = *Annual Cost* $_{BL}$ – *Annual Cost* $_{EDA/X}$

- Assume EDA/EDX operable at 37 US airports
- 1996 Annual Operations - Airport & ARTCC
  - Airport Delay Categories scale rush arrivals according to FAA delay data

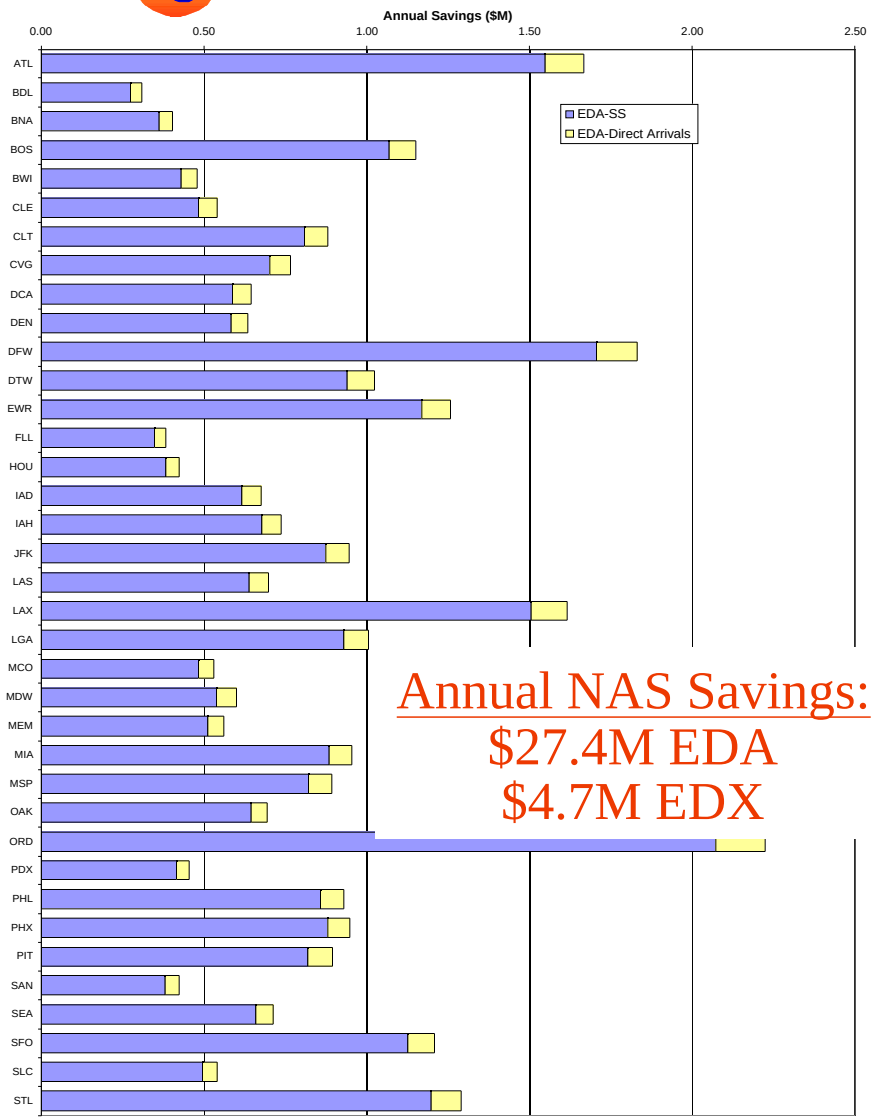
		1996 Ops (000s)		Apt Delay				1996 Ops (000s)		Apt Delay				1996 Ops (000s)	
	ARTCC	Airport	ARTCC	Class			ARTCC	Airport	ARTCC	Class			ARTCC	Airport	ARTCC
ATL	ZTL	773	2,453	3		FLL	ZMA	236	1,542	5		OAK	ZOA	516	1,368
BDL	ZBW	161	1,727	5		HOU	ZHU	252	1,853	5		ORD	ZAU	909	2,894
BNA	ZME	226	1,978	5		HPN	ZNY	193	2,040	5		PDX	ZSE	306	1,393
BOS	ZBW	463	1,727	2		IAD	ZDC	330	2,331	4		PHL	ZNY	406	2,040
BWI	ZDC	270	2,331	5		IAH	ZHU	392	1,853	4		PHX	ZAB	544	1,505
CLE	ZOB	291	2,870	5		JFK	ZNY	361	2,040	2		PIT	ZOB	447	2,870
CLT	ZTL	457	2,453	4		LAS	ZLA	480	1,981	5		SAN	ZLA	244	1,981
COS	ZDV	227	1,527	5		LAX	ZLA	764	1,981	3		SDF	ZID	173	2,222
CVG	ZID	394	2,222	4		LGA	ZNY	343	2,040	1		SEA	ZSE	398	1,393
DAB	ZJX	269	1,878	5		LGB	ZLA	482	1,981	5		SFO	ZOA	442	1,368
DCA	ZDC	310	2,331	4		MCO	ZJX	342	1,878	5		SLC	ZLC	374	1,509
DEN	ZDV	454	1,527	5		MDW	ZAU	254	2,894	4		STL	ZKC	517	1,986
DFW	ZFW	870	2,118	3		MEM	ZME	364	1,978	5		TEB	ZNY	193	2,040
DTW	ZOB	531	2,870	4		MIA	ZMA	546	1,542	4					
EWR	ZNY	443	2,040	1		MSP	ZMP	484	2,027	4					

- Interrupt Rates

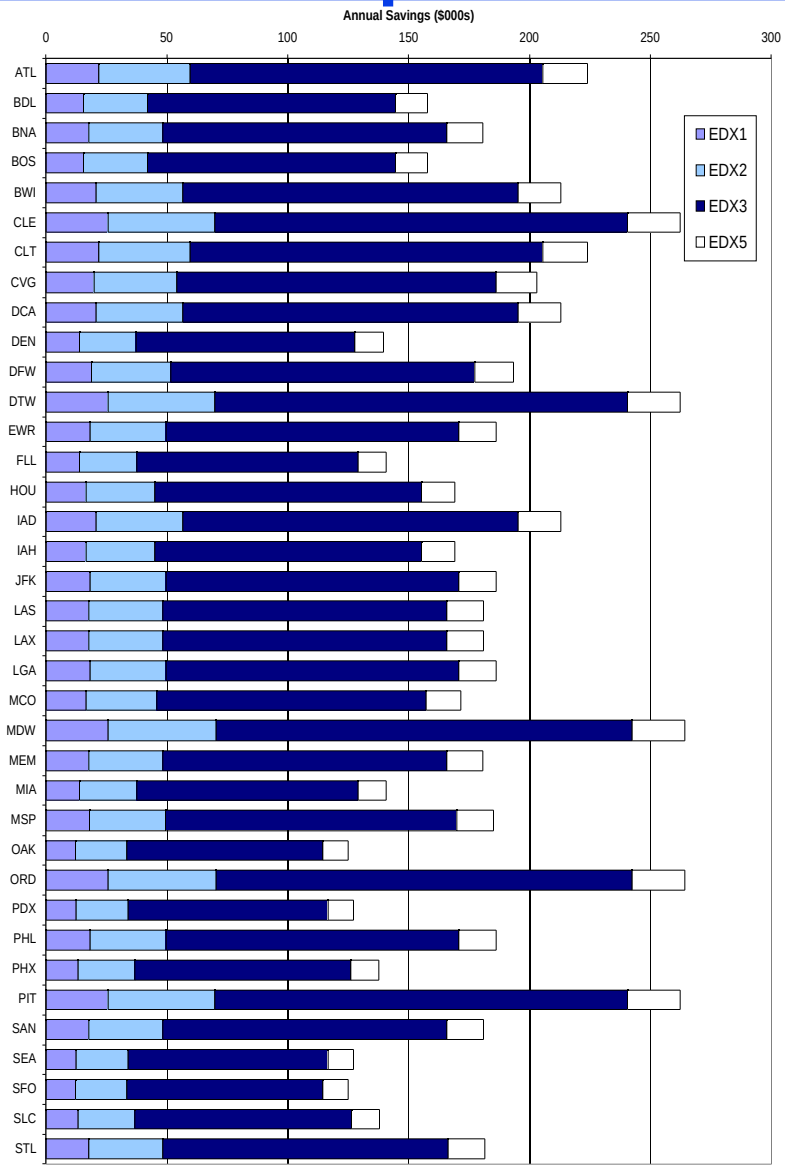
		FFP1	EDA-SS	EDA-DR	EDX1	EDX2	EDX3	EDX5
ATM Interruption Type	Ops Basis	Interrupt Rate (per 100 ops)						
Arrival Metering	Apt Arr/Dep	30.4	30.4	30.4	30.4	30.4	30.4	30.4
Departure Metering	Apt Arr/Dep	36.5	36.5	36.5	36.5	36.5	36.5	36.5
Separation assurance	ARTCC	26.1	24.1	24.9	24.6	24.2	22.9	22.5
		Cost Per Interrupt ($/op)						
Arrival Metering	Apt Arr/Dep	$104.66	$97.86	$97.50	$97.50	$97.50	$97.50	$97.50
Departure Metering	Apt Arr/Dep	$109.23	$109.23	$109.23	$109.23	$109.23	$109.23	$109.23
Separation assurance	ARTCC	$1.98	$1.90	$1.79	$1.77	$1.74	$1.58	$1.58*

* EDX3 cost rates applied to EDX5

1996 ATM Interruptions Benefits



Annual NAS Savings:
$27.4M EDA
$4.7M EDX



ATM Interruptions Recommendations

- **Improve Metering Conformance Interruptions Modeling**
  - Improve metering conformance strategy parameter assumptions
  - Model EDX metering conformance strategy improvement
  - Improved best endurance speed estimates
  - Allow non-jets to employ altitude delay method
  - Incorporate vectoring and TOD shift in delayed trajectories
  - Model ATM interruptions coupling
  - Improve rush arrival rate extrapolation
- **Improve Separation Assurance Resolution Strategies**
  - Enhance off-flight plan modeling
  - Improve conflict count method
  - Enhance resolution strategies (other methods, multiple aircraft conflicts)
- **General**
  - Evaluate multiple initial conditions
  - Evaluate additional en route ARTCCs in detail
  - Calibrate FFP1 baseline
  - Improve trajectory parameter accuracy values
  - Perform sensitivity analyses

EDX
Potential Benefits of
User-Preferred Descent Speed Profile

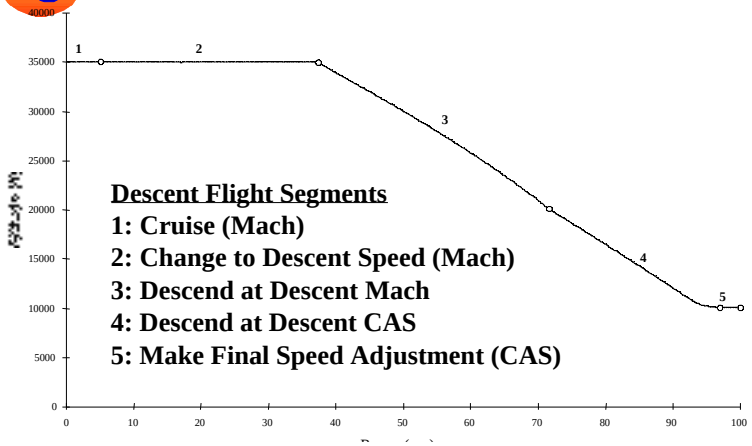
Operational Cases

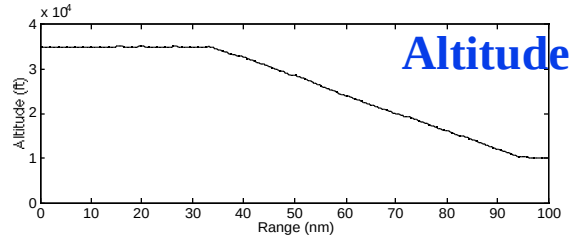
- **EDA Baseline**
  - CTAS TMA Arrival Scheduling/Metering
  - CTAS EDA-generated Descent Speed Advisories
  - Basic Weather and Aircraft Weight DX
- **EDA with Data Exchange**
  - CTAS TMA Arrival Metering Fix RTA uplink
  - FMS Optimum Descent Speed Profile downlink
  - Basic Weather and Aircraft Weight DX
  - Assumes 100% FMS-RTA Capability Equipage

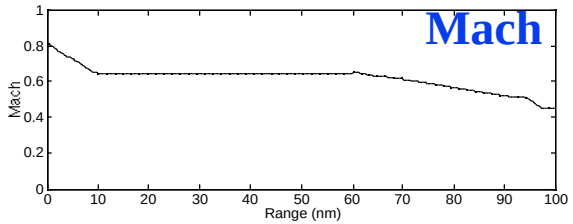
Analysis Methodology

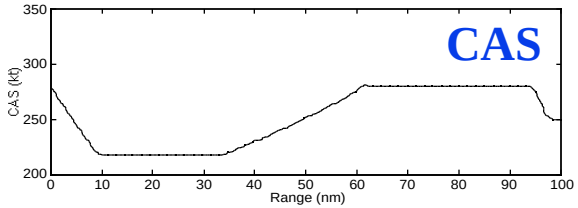
- **CTAS & FMS speed control strategies**
- **Fuelburn of speed control strategies**
- **DFW Arrival Metering Delay**
- **EDX FMS Speed Profile Fuel Benefits**
  - DFW Daily
  - Annual/NAS Extrapolation

Mach/CAS Descents

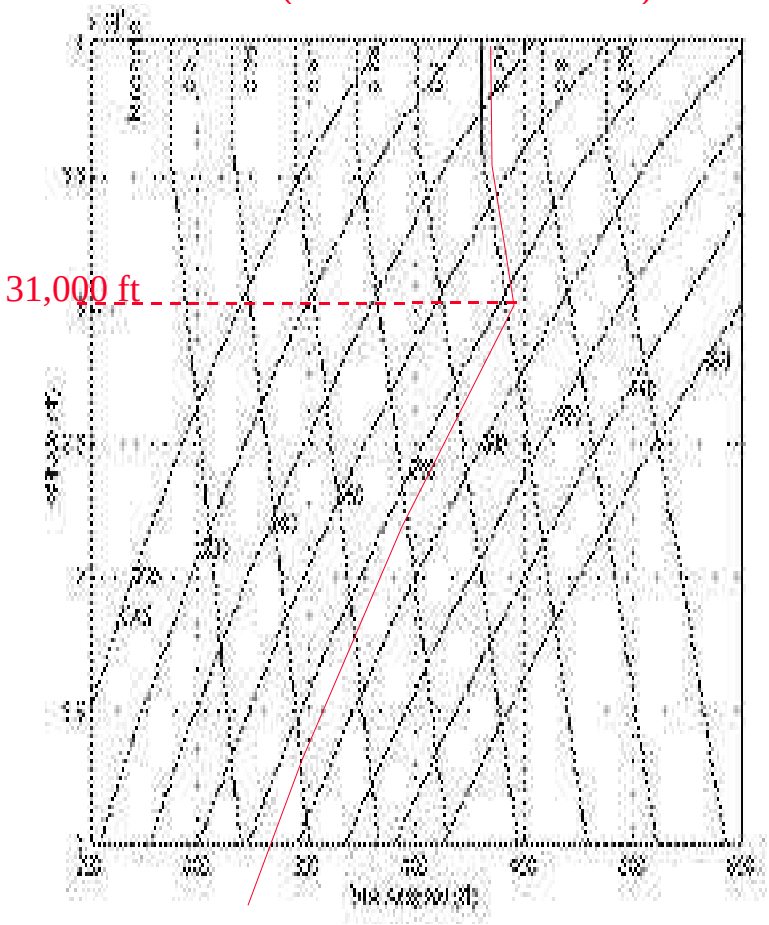




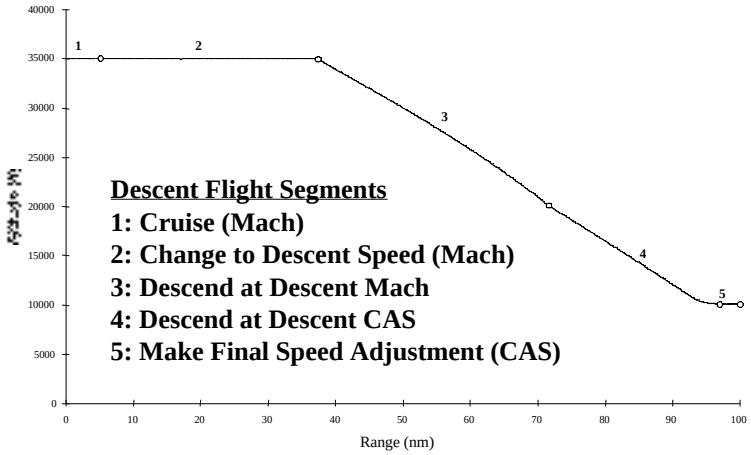




Nominal MD80 Profile
(0.76 Mach/280 kt CAS)

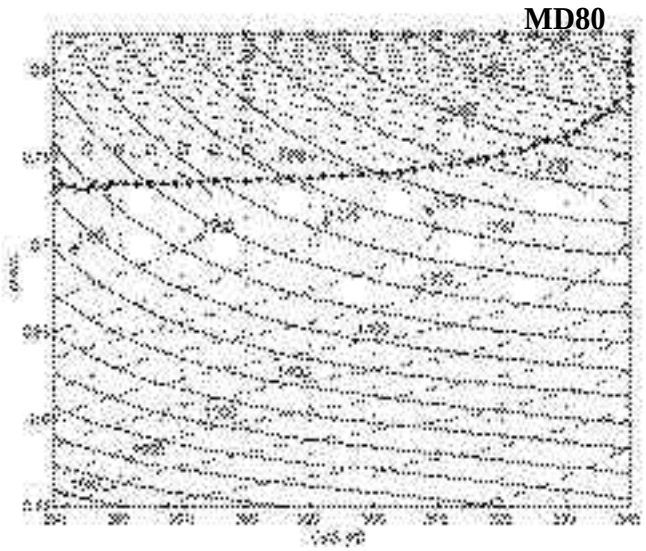


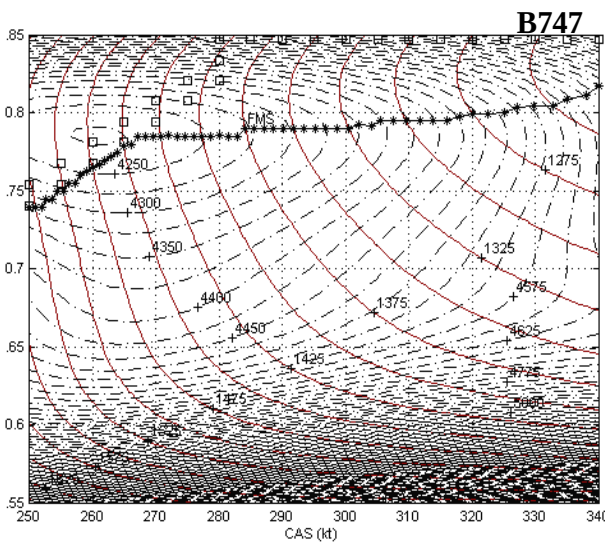
CTAS & FMS Speed Control Strategies



- **CTAS**
  - Nominal
    - Cruise Mach = Descent Mach, transition to Descent CAS
    - Use CTAS DB of nominal aircraft-specific Mach/CAS speeds
    - Characterize profile by Descent CAS
  - Delayed (C=D)
    - Balance Descent Mach (= Cruise Mach) & Descent CAS
    - Decrement larger until equal, then decrement alternately
- **FMS**
  - Fuel Optimal, assuming Cruise Mach = Descent Mach

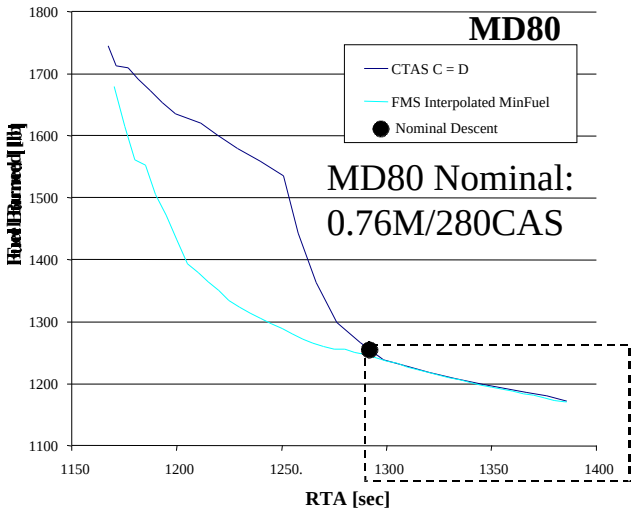
Fuelburn of Speed Strategies

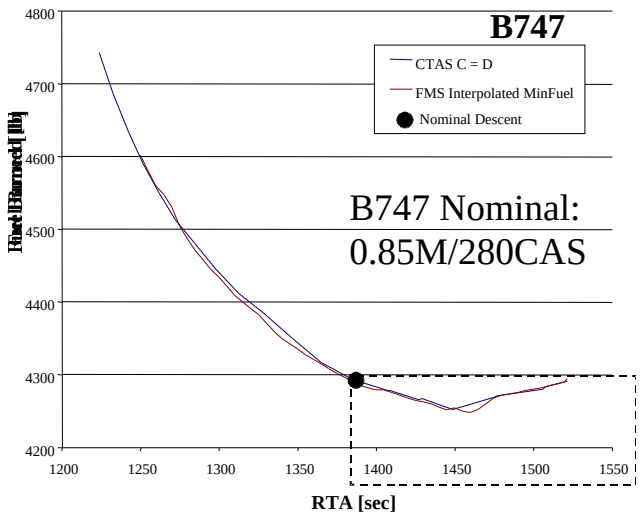


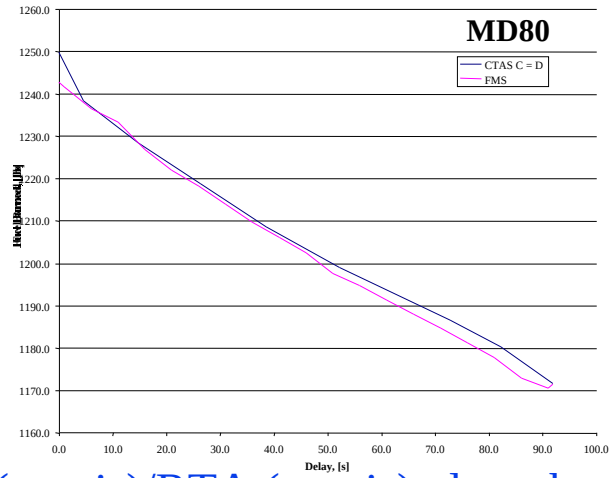


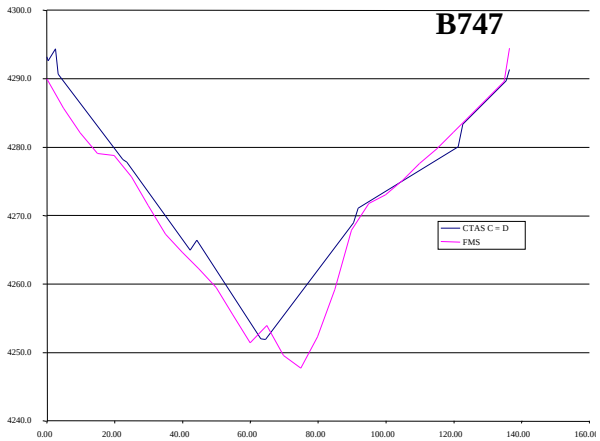
- High Fidelity fuelburn modeling of 2 Aircraft (Heavy-B747, Large-MD80)
- 1000’s of Runs over fixed range, variable Mach/CAS speeds, collected time/fuel
- Plots of Mach (y-axis)/CAS (x-axis) plot of strategies over fuel & time contours

Speed Control Strategy Fuelburn









- Fuel (y-axis)/RTA (x-axis) plots show FMS fuel savings
- Nominal/Undelayed Mach/CAS profiles per airline operations manuals
- Fuel (y-axis)/Delay (x-axis) plots show FMS fuel savings for a given delay

Fleet-wide Fuel Scale Factors

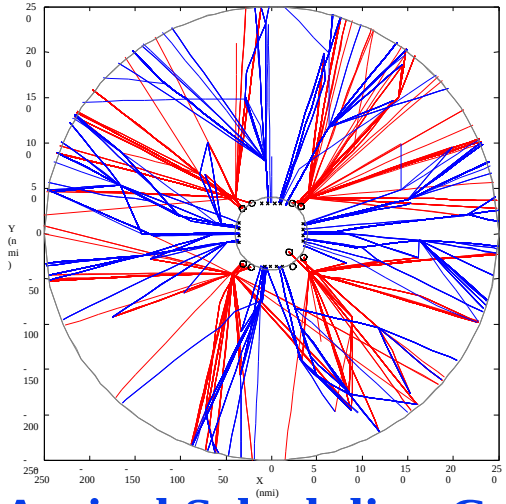
- BADA fuelburn relationships (nominal wt, cruise Mach, max altitude, 250 nm range)
- Heavy aircraft scaled to B747, Large/Small scaled to MD80 (94% operations w/FSF ≤ 1.0)

Aircraft Type (ICAO)	Initial Weight (lb)	Weight Class	Mach	Altitude (ft)	Fuel Scale Factor
A300	275575	H	0.78	38000	0.5140
A310	264552	H	0.80	41000	0.4025
A320	136685	L	0.78	39000	0.8303
A330	352736	H	0.80	41000	0.4596
A340	440920	H	0.80	40000	0.6303
ATP	44092	L	0.40	21000	0.3290
ATR	33069	S	0.45	25000	0.2688
B707	220460	H	0.80	42000	0.5297
B727	163140	L	0.82	33000	1.4941
B73A	101412	L	0.72	37000	0.8532
B73B	119048	L	0.74	37000	0.8649
B73C	136906	L	0.79	43000	1.1480
B74A	617288	H	0.82	36000	1
B74B	661380	H	0.85	39000	1.0615
B757	209437	H	0.78	39000	0.3290
B767	330690	H	0.80	39000	0.4508
B777	465171	H	0.84	43100	0.7198
BA11	69886	L	0.72	35000	0.5697
BA46	79366	L	0.70	31000	0.8093
BE20	11010	S	0.48	32000	0.0538
BE99	9039	S	0.35	15000	0.1417
BE9L	8025	S	0.40	31000	0.1076
C130	129983	L	0.50	30000	1.4601
C160	88184	L	0.38	30000	0.6522
C421	6261	S	0.33	18500	0.1217
C550	13228	S	0.63	38000	0.2382
C560	13977	S	0.73	45000	0.2011
CARJ	46297	L	0.74	38000	0.3569
CL60	34061	L	0.77	41000	0.2541
D228	12346	S	0.34	29600	0.3082
D328	26455	S	0.59	32800	0.2596
DC10	374782	H	0.82	39000	0.5640
DC8	242506	H	0.80	42000	0.3149

Aircraft Type (ICAO)	Initial Weight (lb)	Weight Class	Mach	Altitude (ft)	Fuel Scale Factor
DC9	100089	L	0.80	35000	0.9943
DHC8	37478	L	0.45	25000	0.2065
E120	22046	S	0.47	32000	0.1735
F100	83775	L	0.70	35000	0.6606
F27	37478	L	0.37	20000	0.3972
F28	52910	L	0.70	35000	0.4969
F50	39683	L	0.44	25000	0.3261
F70	74956	L	0.70	37000	0.6218
F900	33951	L	0.80	44000	0.2607
FA10	15983	S	0.75	45000	0.1510
FA20	22046	S	0.76	42000	0.3128
FA50	33069	S	0.75	49000	0.2540
H25B	18001	S	0.75	41000	0.3433
JSTA	13669	S	0.41	25000	0.1681
JSTB	19841	S	0.42	26000	0.1924
L101	340611	H	0.82	40000	0.5160
LJ35	14991	S	0.77	38000	0.1959
MD11	501106	H	0.83	37000	0.7604
MD80	134922	L	0.76	37000	1
MU2	8988	S	0.57	28000	0.1126
P31T	7981	S	0.44	29000	0.1146
PA27	4806	S	0.50	10000	0.0659
PA28	2326	S	0.18	10000	0.0157
PA31	5489	S	0.33	20000	0.1284
PA34	4564	S	0.34	15000	0.1268
PA42	9101	S	0.46	33000	0.1182
SB20	44092	L	0.62	31000	0.3745
SF34	22046	S	0.45	31000	0.3367
SH36	24912	S	0.33	20000	0.2323
SW3	10582	S	0.52	31000	0.1371
T134	92593	L	0.78	37000	0.7185
T154	187391	L	0.80	41000	1.5321
TRIN	2943	S	0.35	8000	0.0302

DFW Arrival Metering Delays

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



- **DFW Arrival Scheduling Criteria (4 arrival runways)**

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

- **DFW Delays per arrival**

Note: Speed absorbs only 1-2 minutes, remaining delay ignored in this analysis

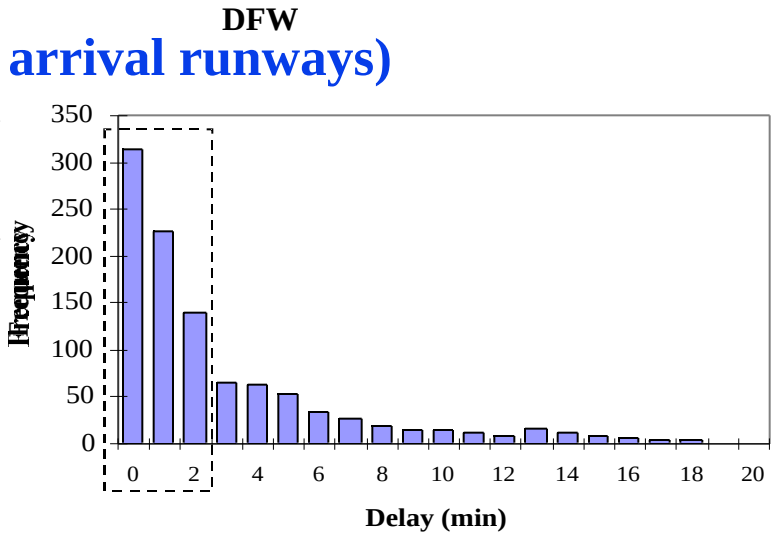
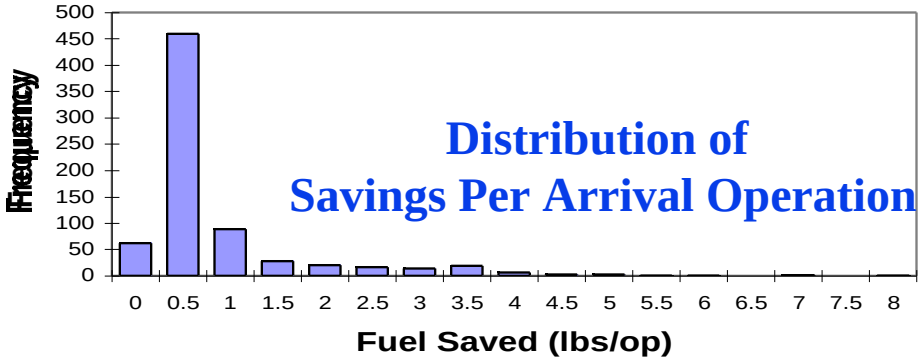


Figure 4. TMA Arrival Delays.

DFW Daily Fuel Savings



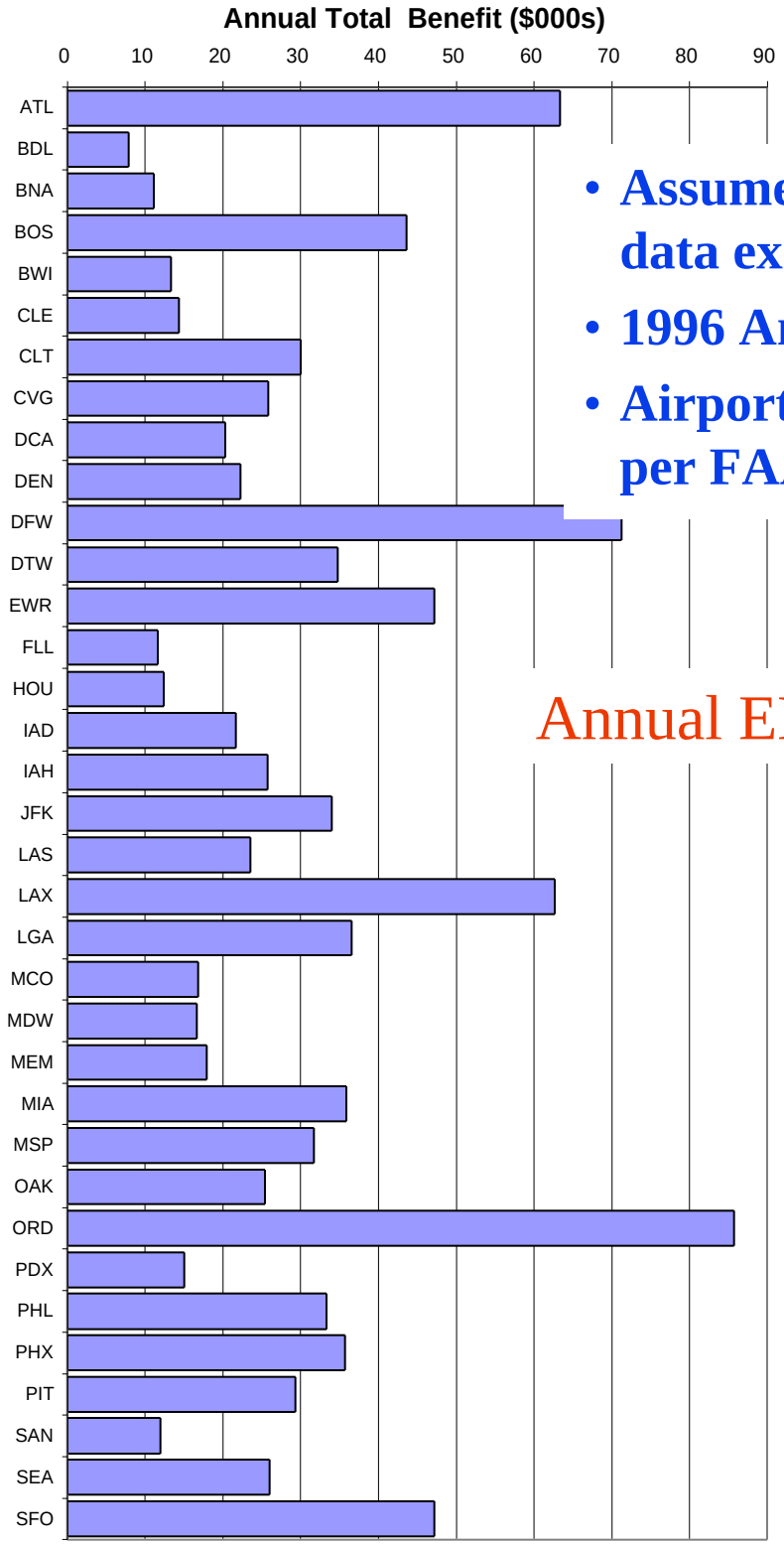
	Daily Delayed Arrivals	Average Savings Per Rush Arrival Operation
Daily Number of DFW Arrival Operations	732 (1)	NA
Daily TMA Delay	44.51 min	3.6 min/op
Daily Fuel Savings	1,991 lb	2.7 lbs/op
Daily Cost Savings (2)	$199	$0.27/op

(1) 70% of all modeled DFW arrivals were delayed.
(2) Assumes fuel cost of $0.10 per lb.

- DFW Rush Arrival Rate 30.4/100 airport operations
- DFW Interrupt Savings $0.27/interruption

1996 Annual/NAS Extrapolation

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

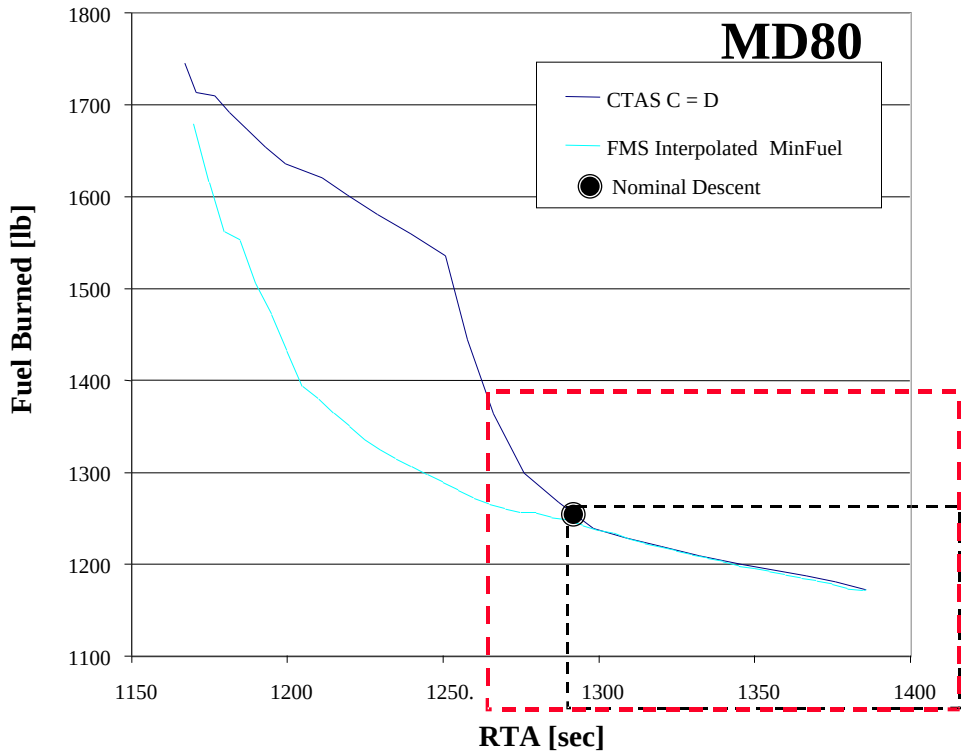


- **Assumes 100% equipage & data exchange participation**
- **1996 Annual Airport Ops**
- **Airport rush arrivals scaled per FAA delay data**

Annual EDX Savings: $1.1M

Sensitivity Analysis

Use MD80 nominal speed profile of 0.8M/280kt CAS



- Most aircraft fuel savings scaled from MD80 results
- Increases savings (up to 130 lbs per flight) from small delays (30 seconds or less)
- Savings increase from $350 to $550 per day, $150 if exclude delays less than 15 seconds

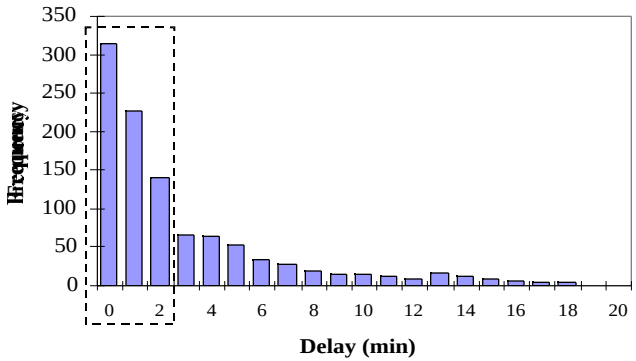
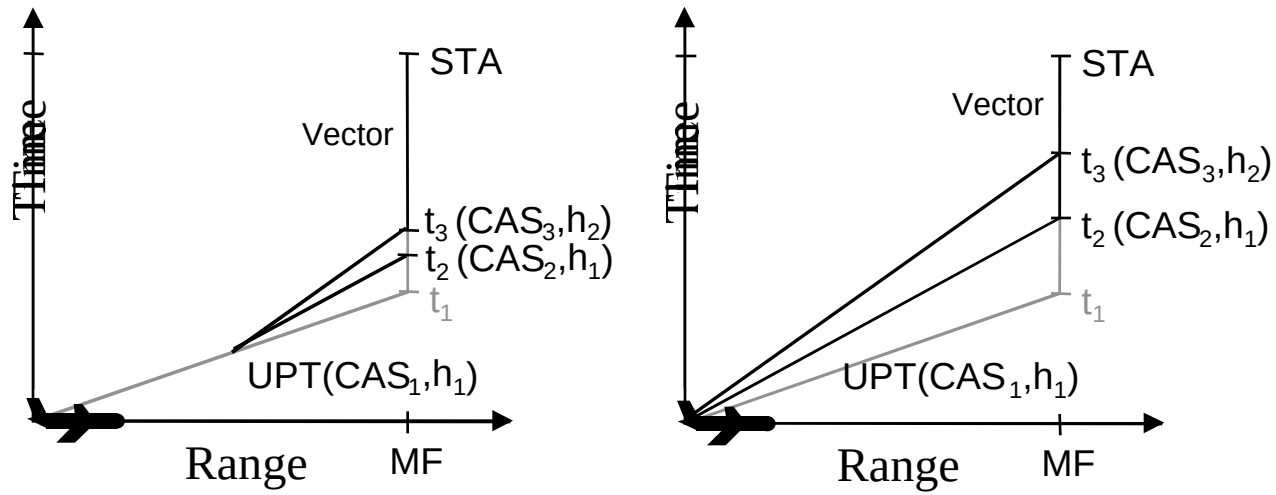


Figure 4. TMA Arrival Delays.

FMS Descent Speed Recommendations

- **Improve Fleet-wide fuelburn extrapolation**
- **Investigate sensitivity of assumed basic data exchange**
- **Improve FMS strategy modeling**

Arrival Metering Conformance



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)
t_4 = STA = crossing time if cleared to minimum speed, lower altitude, and vectored

Absorb arrival delay to meet airport capacity restrictions

- Speed Control (V_1>V_2)
- Altitude Change (V_1>V_2>V_3 and h_1>h_2)
- Vectoring (increase range at V_1)

Separation Assurance Resolution Costs

	Average Resolution Cost ($)		
	CA	MA	FA
OVR-OVR	$0.94-1.05	$1.74-2.15	$0.67-0.73
OVR-ARR	$0.59-1.23	$1.29-2.76	$0.69-0.88
OVR-DEP	$0.65-0.79	$1.36-1.66	$0.44-0.58
ARR-DEP	$0.16-0.24	$0.37-0.54	$0.20-0.24
DEP-DEP	$4.88-6.50	NA	NA
ARR-ARR	$0.79-1.75	NA	NA

- 2-conflict vectoring resolutions ONLY
- Vary by Operations types
- DEP-DEP large due to high fuel consumption rate in climb
- Costs improve with technology enhancements (EDA/EDX)