Estimating the True Extent of Air Traffic Delays

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Motivation

- Goal: assess congestion-related delays in the airspace/airport system and compare their evolution over time
- Most air traffic delay statistics report delays relative to schedule (RtS)
- Airlines adjust their schedules over time to absorb congestion in the system ⇒ RtS benchmark variable in time
- Cannot use RtS delay statistics to track evolution of congestion in ATC system

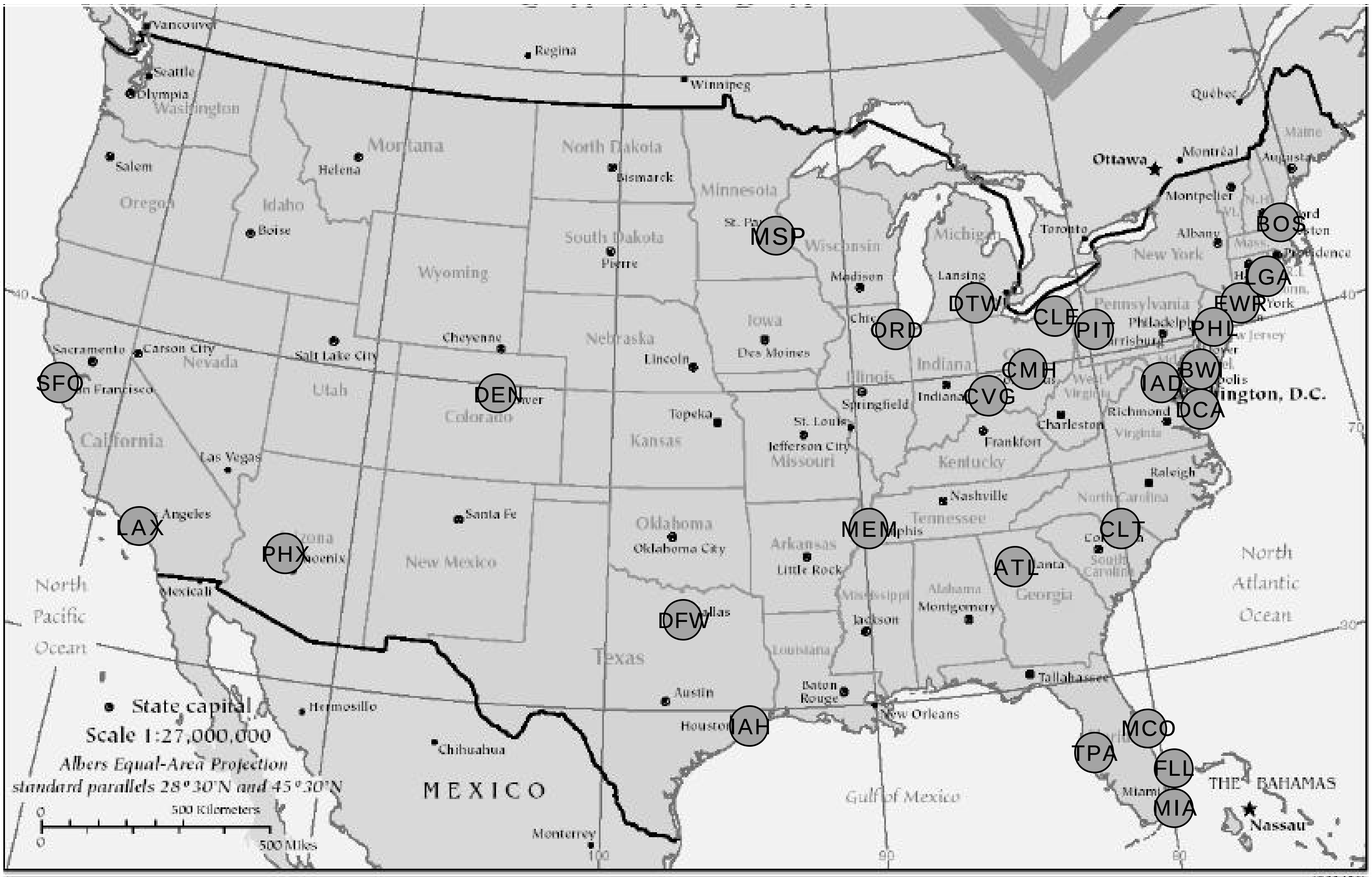
⇒ need for a new measure in order to assess delay-related performance

Research Goals

- Develop a measure that will provide a reasonable approximate “macroscopic” estimate of “true” delays, i.e., a measure not sensitive to schedule adjustments and useful for long-term tracking of congestion trends
- Estimate magnitude of “true” delays and examine their evolution over the 1995-2000 period
- Attribute O-D delays to airports of origin and destination and evaluate level of congestion at each airport [*not covered in detail in this talk*]
- Sample applications [*not covered in detail in this talk*]

Network

All calculations will be performed using a sub-network of 27 US airports (618 directional O-D pairs)



Properties of new delay metric

- Metric will measure delay as the difference between actual gate-to-gate time and a benchmark
- Benchmark should be a “baseline” which represents a standard estimated gate-to-gate time for completing a particular flight in the absence of congestion
- Benchmark should be consistent over time, independent of demand levels, characteristic of each O-D pair
- Note: Emphasis on long-term trends (e.g., year-to-year)

Factors affecting gate-to-gate times

Periodic Factors

- Seasonality
- Day of week
- Time of day

Stochastic Factors

- Weather/winds
- Runway and gate assignments
- Route/Flight path

Additional Factors

- Aircraft Type
- Direction of travel
- Congestion of en-route airspace
- Congestion of airport and terminal area airspace

⇒ All above factors cause variability in gate-to-gate times

⇒ Only concerned with variability due to airspace and airport congestion but existence of other factors greatly complicates the task

Factors taken into consideration

- Baselines would be used to monitor the approximate size of delays nationally, or at individual airports; assess whether airports and the ATM system are keeping up with traffic volume on aggregate

⇒ Need only to identify long-term trends and changes, not day-to-day fluctuations due to periodic variability or stochasticity in the system

Periodic Factors	Seasonality	**will usually cause only small fluctuations around annual averages**
	Day of week	
	Time of Day	
Stochastic Factors	Weather	
	Runway/gate assignment	
	Flight path	
	Aircraft Type	**impact may be significant in the long run, but relatively slow pace of change in airline fleets in 1995-2000**
	Directionality	**important => will treat each O-D pair as two distinct routes A-to-B and B-to-A**
	Airspace Congestion	**Focus of the research; hard to estimate how much of the increase is due to airspace congestion and how much to airport congestion**
	Airport Congestion	

Potential baseline estimates

- “True Delay”= actual gate-to-gate time minus Baseline.
- Baseline will approximate a congestion-free time while being conservative enough to account for inherent variability due to runway configurations in use, flight paths, and winds
- What historical statistic to choose for the baseline?
  - Average gate-to-gate time
  - Minimum gate-to-gate time
  - Percentile of gate-to-gate time
- Sample over which baseline is computed would cover a full year to ensure that periodic factors “average out” as much as possible
- Baseline would be the lowest value observed in any of the years under consideration

Average gate-to-gate time

- B_{ij}=Ave($G2G_{ij}$)
- Measure heavily influenced by delay on O-D pairs where congestion is present
- Unless a delay-free year can be identified for setting the baseline, using average gate-to-gate time as the baseline would almost certainly lead to serious underestimation of true delays

Minimum gate-to-gate time

- $B_{ij}=Min(G2G_{ij})$
- The shortest observed actual travel time on each O-D pair, for the data sample under consideration
- Similar measure suggested by Mayer and Sinai (2001) as an estimate of the congestion-free time
- Overly optimistic estimate that could result from unusually favorable combination of circumstances that might be very difficult to reproduce

Percentile of gate-to-gate time

- $B_{ij}=G2G_{ij}^{p}$, such that $Pr(G2G_{ij} \leq B_{ij})=p$ where p is a specified percentile
- If percentile used is in the 5th to 20th range, this measure could have desirable properties:
  - Realistic time since a significant percentage of flights were able to achieve that performance
  - Neither overly optimistic nor overly conservative
  - Would cover a broad range of periodic and meteorological conditions, and runway configurations

Choice of the baseline

- Use the fifteenth percentile of gate-to-gate time as a robust estimate of the baseline transit times
- Consistent with potential use for national policy purpose
- Sample data for 618 O-D pairs
  - January, April, July, October 1995
  - January, April, July, October 1997
  - January, April, July 2000
- Calculate fifteenth percentile of gate-to-gate time for each O-D pair in each month $P_{ij}(m,y)$
- Calculate the average of the percentiles ($AP_{ij}(y)$) in each year
- The baseline is taken to be the minimum of the averages of the fifteenth percentiles over the 1995-2000 period=> $B_{ij}=MIN(AP_{ij}(95), AP_{ij}(97), AP_{ij}(00))$

Baseline Flight Times (mins)

	ORIGIN AIRPORT																										
DESTINATION AIRPORT	ATL	BOS	BWI	CLE	CLT	CMH	CVG	DCA	DEN	DFW	DTW	EWR	FLL	IAD	IAH	LAX	LGA	MCO	MEM	MIA	MSP	ORD	PHL	PHX	PIT	SFO	TPA
ATL		148	98.4	92	56	80.1	72	97.4	153	109	103	126	97.4	93.3	103	229	129	76.7	63.5	101	135	99.3	111	191	90.3	253	77.8
BOS	134		70	91.9	112	97.5	111	74.6	209	198	99.8	58.2	164	75.8	205	303	49.8	154	154	179	148	120	60.4	273	83.3	312	160
BWI	92	74.8		60	68.5		73		179	157	79.4		137		161	271	50.5	116		140	129	94.5	36.8		52.5	282	121
CLE	89.4	105	61.5		78.8		51.3	66.2	154	141	39.8	82.8	154		145	249	83.2	131	94.5	157	94.1	61.3	71.5	212		250	133
CLT	51.3	121	69.5	75.1		63.5		65.6	167	132	84.3	94.4	105	63	125	249	98.3	86	77	110	129	93.2	82	217	72.9	266	85.8
CMH	77	114			66.5		37	64.5	148	133	45.3	90			135	234	91	122			93.8	59.5	73.9	198	40.1		121
CVG	71.8	125	83	49.8		37.3		80	136	118	56.1	102	139			225	109	119	70.4	143	91.5	58	92.3	187	57	238	117
DCA	88.7	85.3		61.3	65	57.5	69.5			152	75	56.7	132		158		54.5	113	107	136	124	90.8	42.5		50		119
DEN	176	252	210	177	203	166	160			108	168	233		204	129	122	235	210	136	239	108	136	222	93	188	131	206
DFW	123	229	183	157	155	146	130	181	100		156	207	169	176	56.3	166	211	155	79.5	174	136	129	195	124	165	187	145
DTW	100	117	83.2	42.5	91.3	50.3	59	85.3	150	142		98.5	167	79.7	146	241	99.8	147	98.8	169	88.3	60	91.9	209	52.5	249	147
EWR	117	67.8		76.8	92.2	83.8	95.5	55.9	196	185	85.3		154		184	290		138	140	161	140	107		256	67.3	299	143
FLL	95.9	177	140	156	103		131	138		146	160	157		141	130	275	160	46.3				160	147		146		
IAD	87.9	83.3			63.6				173	149	73.8		135		153	266	59.5	112		133	127	89.5	43.3	224	46.7	271	116
IAH	112	232	176	161	141	147		178	123	52.5	160	205	146	176		175	209	135		148	157	137	194	139	168	206	122
LAX	262	352	313	285	291	276	257		129	180	273	334	314	304	193			297	229	314	217	239	323	69.3	289	68.3	289
LGA	114	52	47	76.6	89.8	78.8	95.7	48.3	195	179	88.8		156	53.1	184			138	134	160	141	107	37.8		65.3		141
MCO	72.9	166	119	131	80.5	115	108	121	188	137	140	146	43.7	118	120	259	146		104	50.3	171	137	132	226	122	288	32.9
MEM	65.5	172		105	90.3		72.8	121	119	73.2	104	150				197	151	115		137	105	84.8	140	159		218	108
MIA	95.8	182	139	152	106		133	139	211	149	162	163		140	129	273	162	50.3	124		197	162	149	245	147	303	
MSP	142	172	143	107	152	106	101	145	100	126	98.5	160		144	146	192	160		111	212		70.8	154	167	120	194	187
ORD	104	142	110	69	105	63.7	60	106	123	118	59.5	126	171	102	132	218	127	151	88.8	175	64		117	180	79.5	222	147
PHL	105	69.8	37.3	67.3	78.4	68.3	83.3	46.3	189	168	80		144	48.2	174	277	41.8	129	124	149	133	102		250	55.3	292	133
PHX	223	319		246	254	230	216		97.5	136	234	302		268	150	64.3		259			180	200	290		252	101	
PIT	86.5	93.3	50.8		71.6	39.3	53.5	52.5	163	147	48.3	72	146	47.9	148	253	73	126		150	106		58	219		262	128
SFO	286	363	329	303	314		269		141	208	285	351		314	228	65.3		322	249	343	225	249	339	108	305		
TPA	74.3	179	128	139	85.3	119	113	127	185	130	143	155	46	121	110	258	160	32.9	98	46.5	172	138	141		129		

Application: Evolution of O-D delays from 1995 to 2000

- If actual gate-to-gate time exceeds the baseline => “true” delay
- The average true O-D delay in each year can be computed as the difference between the average gate-to-gate time that year and the baseline time (equivalent to taking the average of individual flight delays in year y on (i,j))
- $D_{ij}(y)=AG_{ij}(y)-B_{ij}$

Example: True O-D delays in 2000 (min/op)

DESTINATION AIRPORT	ORIGIN AIRPORT																										
	ATL	BOS	BWI	CLE	CLT	CMH	CVG	DCA	DEN	DFW	DTW	EWR	FLL	IAD	IAH	LAX	LGA	MCO	MEM	MIA	MSP	ORD	PHL	PHX	PIT	SFO	TPA
ATL		22.1	15.5	17.1	19.6	13.4	18.6	14.8	13.9	16.8	18.6	18.8	17.0	16.7	17.0	22.2	22.8	12.4	13.0	15.5	15.8	15.1	23.1	21.1	16.3	14.3	14.4
BOS	19.8		15.8	18.0	19.7	13.2	19.2	18.7	18.3	24.0	17.8	21.7	32.9	20.4	23.3	22.4	23.8	23.9	17.8	19.9	20.8	22.3	23.3	18.2	17.1	17.9	25.2
BWI	15.0	13.4		12.2	11.2		16.5		13.9	15.6	11.6		11.4		17.2	14.6	22.2	10.8		12.8	14.8	15.2	13.0		10.5	15.9	10.4
CLE	16.6	15.8	11.9		16.8		11.8	15.1	12.9	15.5	13.4	20.8	14.2		14.3	12.2	22.2	14.1	7.7	14.8	16.4	13.2	21.4	10.4		12.7	12.3
CLT	12.1	17.8	10.5	13.0		9.8		12.8	9.5	12.8	15.9	18.6	12.4	15.0	15.4	14.4	20.4	10.7	12.2	10.2	11.4	12.6	21.1	12.0	11.5	13.9	9.4
CMH	12.7	12.5			10.9		12.3	13.4	12.3	10.6	12.5	20.9			14.4	9.2	20.2	11.1			11.1	10.5	20.9	17.0	8.9		11.9
CVG	16.0	20.1	12.4	14.2		11.8		15.7	13.0	14.6	17.1	19.6	13.9			21.1	22.1	13.3	14.8	15.9	15.5	14.1	20.7	17.9	15.4	16.3	14.0
DCA	12.0	12.1		9.8	10.1	8.5	11.2			15.7	10.7	15.5	10.5		16.0		16.6	12.4	12.9	10.0	14.1	14.6	14.7		9.6		10.2
DEN	19.0	18.1	21.3	18.5	11.0	20.8	16.3			12.5	17.6	27.3		22.4	12.1	13.1	21.8	21.0	11.2	18.3	15.0	16.8	31.1	11.9	14.4	13.7	19.5
DFW	15.5	21.4	14.1	17.1	14.0	12.3	15.0	15.0	9.7		16.1	22.7	15.3	16.1	11.7	12.6	21.9	12.5	13.2	12.5	15.8	14.0	22.3	13.5	14.7	16.3	12.1
DTW	15.9	17.0	13.7	14.5	16.2	12.1	13.2	12.8	13.2	13.6		18.8	15.3	17.7	17.8	17.0	21.4	14.4	11.2	13.9	17.1	14.1	18.7	16.0	15.1	15.7	12.9
EWR	19.7	13.6		17.1	14.7	14.1	19.4	15.2	25.0	23.9	16.3		20.8		23.0	22.4		17.7	15.5	18.8	18.3	20.6		20.5	16.2	20.7	18.4
FLL	12.8	30.5	12.5	11.3	9.8		14.7	12.0		17.1	15.0	25.3		13.6	13.1	13.6	22.5	5.7				15.0	16.7		11.5		
IAD	17.9	18.1			13.5				16.6	22.2	17.8		16.7		24.6	18.1	21.7	16.3		17.6	13.7	18.6	20.1	22.6	15.0	23.7	15.3
IAH	14.8	19.5	28.4	14.7	18.0	11.9		12.1	12.4	11.9	17.1	20.6	11.5	15.2		19.0	22.7	8.9		10.3	14.5	15.4	24.5	14.2	15.7	14.0	10.3
LAX	20.9	20.0	19.8	13.3	16.2	15.9	24.6		13.4	11.6	22.3	31.4	13.3	22.2	16.4			16.4	12.2	18.2	20.3	19.1	27.6	11.6	21.0	15.0	15.5
LGA	19.6	19.2	18.6	14.9	16.4	13.9	19.4	16.0	16.7	23.4	14.5		20.4	18.9	19.4			17.4	17.6	22.1	17.1	18.6	13.9		16.0		18.1
MCO	12.6	23.4	12.3	11.0	10.4	9.9	15.4	14.4	12.4	13.2	16.4	20.4	7.9	13.3	13.4	20.6	19.5		9.4	11.6	15.6	14.6	16.8	11.4	11.3	11.8	7.1
MEM	11.2	17.3		10.7	10.4		12.1	13.2	10.7	13.1	14.8	15.4				17.1	16.7	8.6		10.6	12.0	12.2	17.3	17.3		11.3	8.1
MIA	14.4	18.7	16.0	17.1	10.2		12.6	13.3	13.0	14.7	16.0	20.5		17.3	12.7	20.3	22.3	9.6	9.7		13.3	14.9	17.8	13.1	10.1	15.0	
MSP	19.0	20.9	19.9	18.5	19.7	13.5	21.5	17.9	12.5	18.8	16.5	23.4		19.8	20.2	13.1	22.5		12.7	17.4		16.1	25.2	13.7	17.3	13.3	17.7
ORD	20.5	23.9	15.5	20.5	18.4	15.3	17.3	20.7	16.9	21.2	19.4	27.3	21.4	21.5	20.9	17.0	26.3	19.8	13.1	22.2	16.0		25.7	21.0	18.4	17.2	19.5
PHL	20.1	22.4	11.9	20.5	17.9	17.8	19.7	10.2	18.6	21.1	18.9		17.7	10.4	22.4	23.3	16.7	15.6	14.0	17.7	20.2	18.5		17.1	18.0	19.2	18.4
PHX	19.5	24.2		13.9	9.5	15.8	23.1		10.6	13.0	21.2	27.5		26.6	13.5	11.6		13.2			18.3	20.6	21.1		12.8	10.0	
PIT	15.1	15.4	9.9		11.3	9.9	17.1	8.9	9.9	14.7	12.9	18.2	12.9	18.3	16.2	11.0	21.7	11.7		14.2	10.9		18.2	12.7		12.8	12.7
SFO	24.7	27.2	24.8	17.3	18.2		28.2		17.5	21.4	27.1	31.1		33.9	19.9	13.3		19.0	17.9	20.4	24.4	25.4	32.7	12.8	22.5		
TPA	12.7	21.9	11.1	12.4	10.4	9.6	12.8	12.4	9.9	11.0	14.1	21.9	7.3	12.8	15.1	10.8	21.5	10.1	7.8	15.0	12.7	13.2	20.1		11.2		

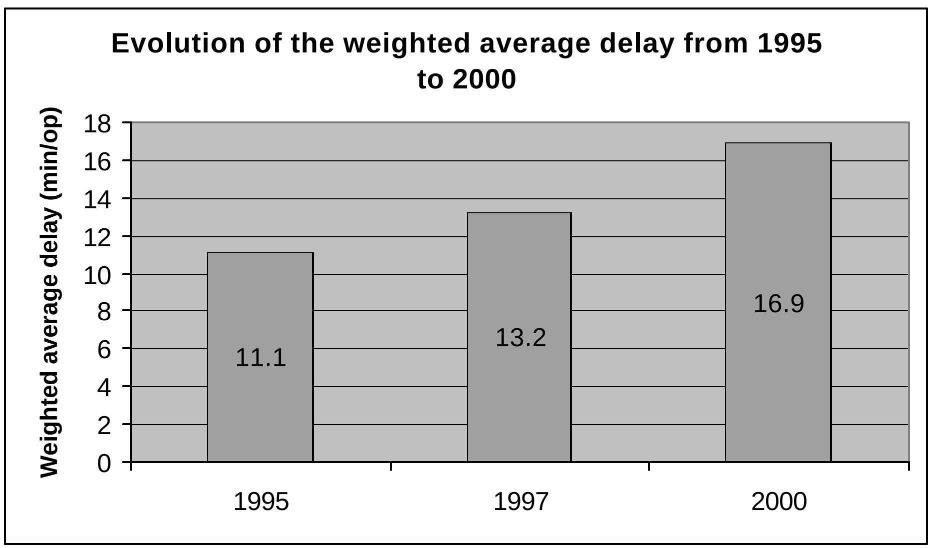
True Delays in 2000

- True delays in 2000 on the routes considered range from 5 min/op to 34 min/op
- 94% of the 618 routes considered experienced an average delay of at least 10 min/op; 56% experienced at least 15 min/op; 21% at least 20 min/op

Evolution of aggregate delay from 1995 to 2000

- Overall weighted delay in year y is the weighted average of average delays incurred on each of the 618 O-D pairs **

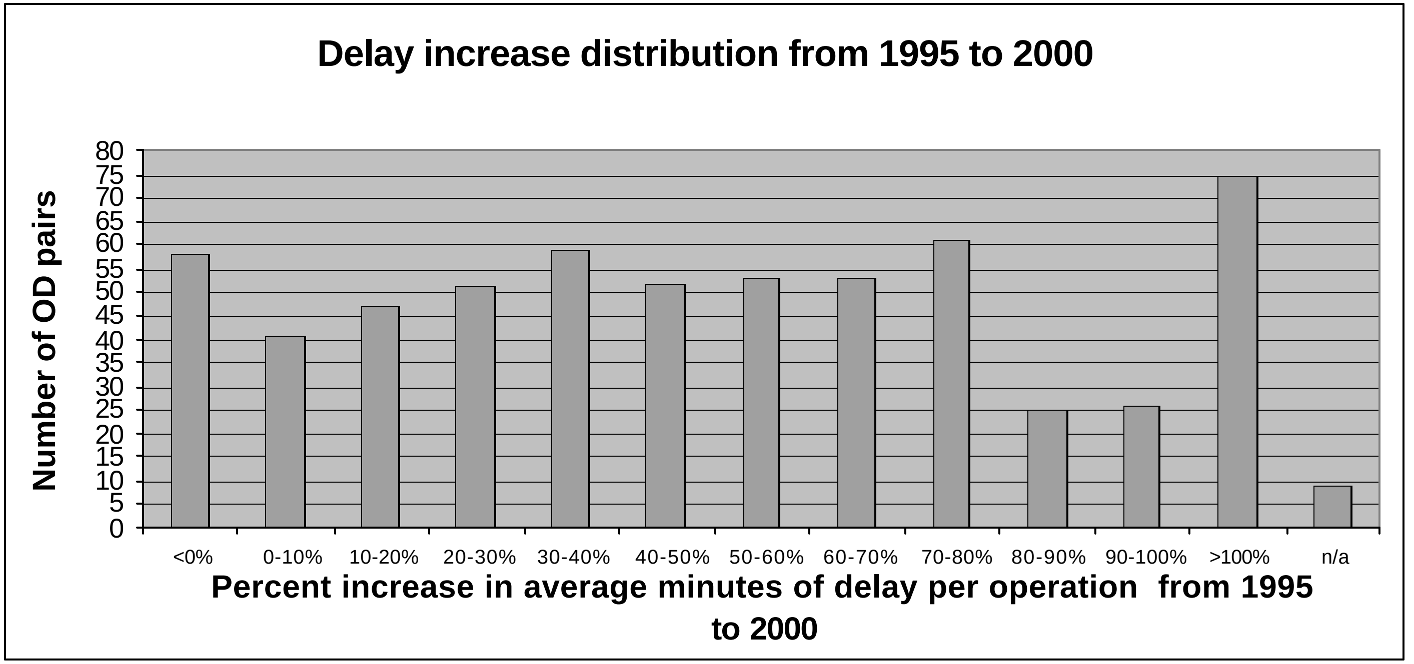
$$WD_{ALL}(y) = \sum_{i} \sum_{j \neq i} TF_{ij}(y) * D_{ij}(y) / (\sum_{i} \sum_{j \neq i} TF_{ij}(y))$$



Overall weighted delay has increased by 52% from 1995 to 2000

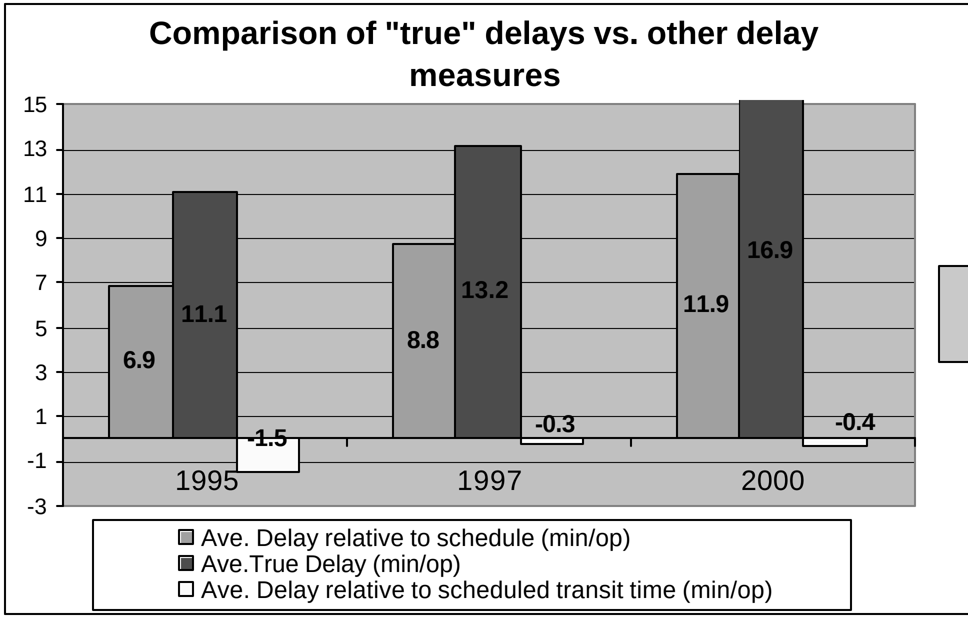
** weighted by total number of flights flown

Distribution of delay increase from 1995 to 2000



- 57 of the 618 O-D pairs experienced a drop in the average “true” delay per operation in the 1995 to 2000 period
- All other pairs experienced an increase
- Average “true” delay more than doubled on 75 of the 618 pairs

Comparison with DOT statistics and delay relative to scheduled G2G time

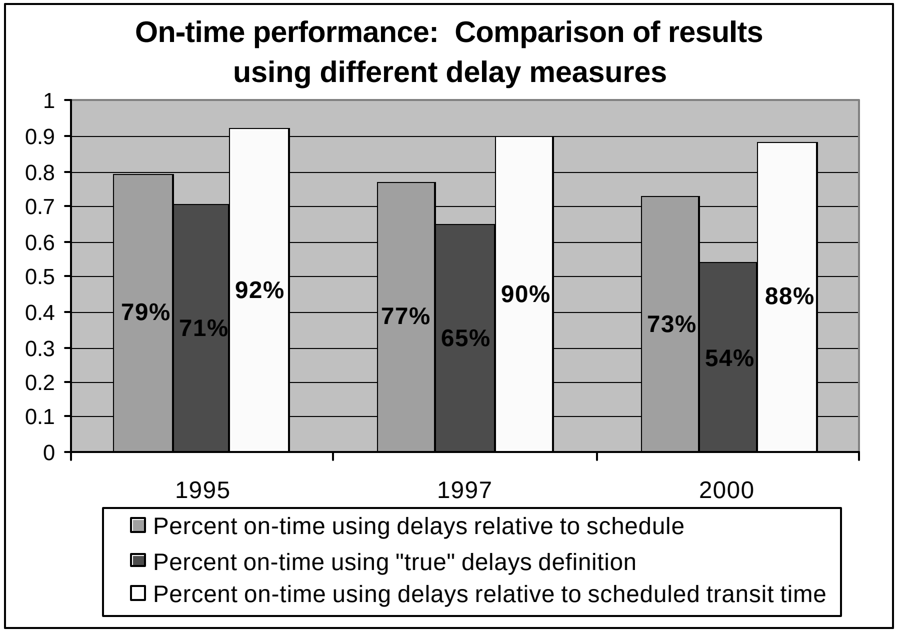


Average true delays about 40% to 60% larger than average delay relative to schedule

- Average scheduled transit time increased on average 10.5 min from 1995 to 2000 (based on analysis of 618 routes)
- Average delay relative to scheduled transit time slightly negative on average => actual gate-to-gate time on average shorter than scheduled gate-to-gate time

=> Suggests that airlines are good at predicting gate-to-gate times, but are susceptible to unpredictable departure times, which results in delay relative to schedule

Comparison with DOT stats and delay relative to scheduled G2G time (2)



- DOT definition of on-time performance: any flight arriving within 15 min of scheduled arrival time is considered on-time
- Used similar 15 min rule to calculate on-time performance using "true" delay definition and delay relative to scheduled transit time definition

- True on-time performance considerably lower than reported on-time performance
- Using "true delay" definition, only 54% of all flights operating on the 618 O-D pairs in 2000 would have been considered "on-time"

AIRPORT DELAY ATTRIBUTION AND SAMPLE APPLICATIONS

Role of airports in generating delays

- Used two different methodologies to attribute delays to the airports of origin and destination
- Method 1: iterative method based on the attribution of a variable portion of the overall O-D delay to the airports of origin and destination, depending on the relative congestion at those airports
- Method 2: method based on the decomposition of gate-to-gate time into its three components (taxi out, taxi in, airborne times), the calculation of individual component delays, and the attribution of component delays to the relevant airport or to the airspace
  - taxi out delay attributed to origin airport
  - taxi in delay attributed to destination airport
  - airborne delay allocated among the destination airport and the airspace

Results

- Results showed that:
  - The overall average increase in delays from 1995 to 2000 at the 27 airports considered was of the order of 2- 3 min/op for both methods, which represents an average increase in airport delay of 40% - 53% per airport depending on the method used
  - Further analysis on individual components of delays suggest that there is a strong correlation between taxi out delay and airport of origin, as well as between taxi in and destination airport
  - Second methodology suggests that about 60% of the airborne delay on any given O-D pair is attributable to airspace congestion whereas the remaining 40% is attributable to the destination airport

Application: Calculating Logan airport delays

- Calculation of Logan Airport (BOS) delays using average airport delay figures
- Best estimate showed that annual “true” delays at Logan doubled from 1995 to 2000: “true” delays were on the order of 80,000 to 105,000 hours for the year 2000, up from 40,000 - 45,000 hours for 1995
- Application can be extended easily to all 27 airports covered in this study

Application: Airport rankings

- Derived delay-rankings of airports based on the individual airport delays obtained previously
- Compared rankings with FAA and DOT’s airport rankings (such as OPSNET delays, ASPM delays) using the Spearman correlation test
- Results suggest that ASQP on-time statistics and average delay relative to schedule are poor indicators of the true extent of air traffic delays
- Although OPSNET statistics severely underestimate delays, they yield very similar rankings to those obtained using delay attribution methods => suggests that OPSNET statistics can be useful in determining the relative extent of congestion at different airports

Summary

- Simple and practical way of assessing evolution of congestion-related delays
- Constant benchmark allows for meaningful comparison over time
- Methodology can be extended to the US domestic network as a whole => (congestion-free) baselines for all domestic O-D pairs
- Delay attribution methodologies can help point to sources responsable for true delays

Backup

PRELIMINARY UPDATE

Extension of methodology to year 2002

Backup

	DELAY 2000_1	DELAY 2002_1,2,3
ATL	18.2	14.1
BOS	24.5	20.0
BWI	18.6	15.8
CLE	18.3	17.4
CLT	17.5	15.0
CMH	14.6	15.8
CVG	20.6	17.3
DCA	18.3	13.3
DEN	9.8	10.9
DFW	13.9	12.2
DTW	18.9	16.6
EWR	25.9	21.0
FLL	15.5	15.1
IAD	21.3	19.9
IAH	14.1	15.3
LAX	10.0	7.5
LGA	22.6	17.0
MCO	15.1	11.8
MEM	12.1	13.8
MIA	18.2	16.0
MSP	17.3	15.8
ORD	15.9	14.1
PHL	24.6	23.3
PHX	11.9	9.5
PIT	19.2	17.1
SFO	8.5	8.8
TPA	14.8	12.3
ALL	**17.0**	**14.9**

- Delays since 9/11 are said to have decreased considerably
- Could use year 2002 to update the congestion-free baseline times
- Year 2001 is an anomaly
- 2002 data available only for January, February and March.

- Delay measures were computed for the following period:
  - 2002: January, February, March
- Comparison of delay data in winter 2000 and winter 2002
- TRUE delays seem to have decreased by about 13% on average from 2000 to 2002

Baseline as a function of seasonality, time of day, day of week

Backup

- $B_{ij} = b_0 + b_1*f(time) + b_2*f(dow) + b_3*f(season)$
- Each flight would have its own baseline, adjusted for each given set of conditions.
- Only includes periodic factors, not stochastic factors
- Advantage: controlling for periodic factors that could result in potential discrepancies in gate-to-gate time
- Disadvantages:
  - not interested in day-to-day fluctuations and are only looking at long-term trends
  - Can view seasonality, time of the day and day of the week as periodic factors strongly associated with fluctuations in demand levels. However, baseline should be independent of demand levels because it is intended to be used to estimate inefficiencies in the system that are created by excessive demand and lack of proper infrastructure to accomodate it.

Backup

Estimating airport delays

- Need to attribute O-D delays to airports and airspace
- Most of delay on O-D pair occurs at origin or destination airport => airports typically constitute the bottlenecks in air transportation system
- Only concerned with allocating O-D delays to airports of origin and destination
- Examined 2 methods to do so

Method A

Backup

- Assume that O-D delays are exclusively due to airports of origin and destination and both contribute equally to the O-D delay (Step 1)

⇒ Half of the O-D delay is attributed to origin airport (departure delay), half to the destination airport (arrival delay)

- Accuracy of Method A improved by relaxing the simple approximation in Step 1. Origin and destination airports no longer assumed to contribute equally to the O-D delay, as some airports are more sensitive than others to increased traffic, bad weather, and congestion (Step 2)

=> Attribution of O-D delay depends on relative weights of airport of origin and destination

Iterative Procedure Method A

Backup

- Weights (CORGin(y), CDESij(y) initially taken to be a function of the origin delay and destination delay calculated in Step 1. In each succeding iteration, the relative weights will be a function of the origin delay and destination delay results obtained in the previous iteration
- Departure delay on an O-D pair is attributed to origin airport
- Arrival delay on an O-D pair attributed to destination airport
- Origin delay at airport obtained by averaging departure delays attributed to this airport
- Destination delay at airport obtained by averaging arrival delays attributable to that airport
- Procedure iterated until “convergence”

Iterative Procedure Method

Backup

Compute
$CORG_{ij,iter=0}(y)$
$CDES_{ij,iter=0}(y)$

Compute
$DepD_{ij,iter=k}(y)$
$ArrD_{ij,iter=k}(y)$

Compute
$OrgAD2_{a,iter=k}(y)$
$DestAD2_{a,iter=k}(y)$

CHECK IF

$|OrgAD2_{a,iter=k}(y) - OrgAD2_{a,iter=k-1}(y)| <= 0.001$

$|DestAD2_{a,iter=k}(y) - DestAD2_{a,iter=k-1}(y)| <= 0.001$

NO

Compute
$CORG_{ij,iter=k}(y)$
$CDES_{ij,iter=k}(y)$

YES

$OrgAD2_a(y) = OrgAD2_{a,iter=k}(y)$

$DestAD2_a(y) = DestAD2_{a,iter=k}(y)$

Compute $A_a 2(y)$

Method A: Results

Backup

	METHOD A (Step A2)								
	AIRPORT DELAYS 1995			AIRPORT DELAYS 1997			AIRPORT DELAYS 2000		
	ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
ATL	6.0	5.7	5.8	5.5	8.7	7.1	8.5	8.9	8.7
BOS	5.7	5.5	5.6	7.8	7.4	7.6	11.6	12.8	12.2
BWI	4.4	3.8	4.1	3.5	3.2	3.4	6.7	5.6	6.1
CLE	4.6	4.3	4.4	5.5	5.4	5.5	7.2	6.4	6.8
CLT	4.0	3.7	3.9	4.3	5.0	4.6	6.5	5.2	5.9
CMH	3.6	3.1	3.4	4.4	4.3	4.3	4.9	4.8	4.8
CVG	4.0	3.0	3.5	5.8	6.0	5.9	8.9	7.8	8.3
DCA	4.8	3.5	4.1	5.6	4.0	4.8	6.6	4.3	5.4
DEN	5.3	5.6	5.4	5.7	5.1	5.4	5.2	8.2	6.7
DFW	6.4	7.8	7.1	8.6	8.7	8.7	8.1	6.9	7.5
DTW	6.5	5.9	6.2	6.5	6.5	6.5	8.6	7.3	8.0
EWR	8.6	6.7	7.6	11.5	9.4	10.5	14.8	11.8	13.3
FLL	4.2	5.3	4.7	4.0	5.5	4.7	7.2	6.4	6.8
IAD	4.6	4.1	4.3	5.9	5.6	5.8	9.9	10.2	10.0
IAH	5.1	6.6	5.9	5.8	6.1	5.9	8.4	7.1	7.7
LAX	5.4	7.2	6.3	7.9	7.1	7.5	6.9	9.0	8.0
LGA	6.9	5.0	5.9	8.8	6.0	7.4	14.1	10.6	12.3
MCO	4.2	5.4	4.8	4.5	5.6	5.0	5.8	5.7	5.8
MEM	3.5	3.8	3.6	4.6	4.8	4.7	4.6	4.3	4.5
MIA	7.3	7.0	7.1	6.7	7.3	7.0	7.2	6.5	6.9
MSP	6.3	5.4	5.9	6.7	7.5	7.1	7.8	9.1	8.4
ORD	5.5	6.2	5.8	6.3	7.4	6.9	8.4	11.8	10.1
PHL	5.5	4.0	4.8	8.0	7.1	7.5	14.1	11.3	12.7
PHX	3.7	4.6	4.1	5.8	4.4	5.1	5.8	7.2	6.5
PIT	4.9	3.6	4.3	4.3	4.0	4.1	6.5	5.2	5.9
SFO	5.9	8.7	7.3	8.0	7.2	7.6	6.7	12.6	9.6
TPA	4.1	4.8	4.5	4.9	5.1	5.0	6.1	4.5	5.3
	5.5	5.6	5.5	5.5	7.7	6.6	8.4	8.4	8.4

Method B

Backup

- Method B is based on the decomposition of gate-to-gate time into three components: taxi out, airborne, and taxi in times
  - Gate-to-gate time decomposed into three segments
  - Baseline for each segment calculated using fifteenth percentile method
  - Taxi out, taxi in, airborne delays calculated for each O-D pair
- Initial assumption: taxi out delay, taxi in delay, airborne delay can be computed independantly and are completely uncorrelated
- Step 1:
  - taxi out delay attributable to origin airport
  - Taxi in delay attributable to destination airport
  - Airborne delay attributable to destination airport

Step B2: Correcting for potential correlation

Backup

- Delay results obtained with Step B1 were significantly higher than those obtained with Method A
- This suggested potential correlation between taxi out, taxi in, and airborne times => need to adjust results to take into account correlation
- Taxi out, taxi in, and airborne delays obtained from Step B1 are multiplied by a correction factor CORRij (0<CORRij<=1), specific to each O-D pair. Correction factor taken to be equal to the ratio of the sum of taxi out, taxi in, and airborne baselines divided by the gate-to-gate baseline time

$$CORR_{ij}(y) = (BTO_{ij}^{15} + BTI_{ij}^{15} + BAIR_{ij}^{15}) / B_{ij}^{15}$$

- Even after adjustment for potential correlation, delays obtained in Step B2 are significantly higher than those in Step A2 => systematic overestimation of destination delays, which suggests that assumption that airborne delays are fully attributable to the destination airport may be invalid.

Step B3: Revisiting the airborne delay attribution assumption

Backup

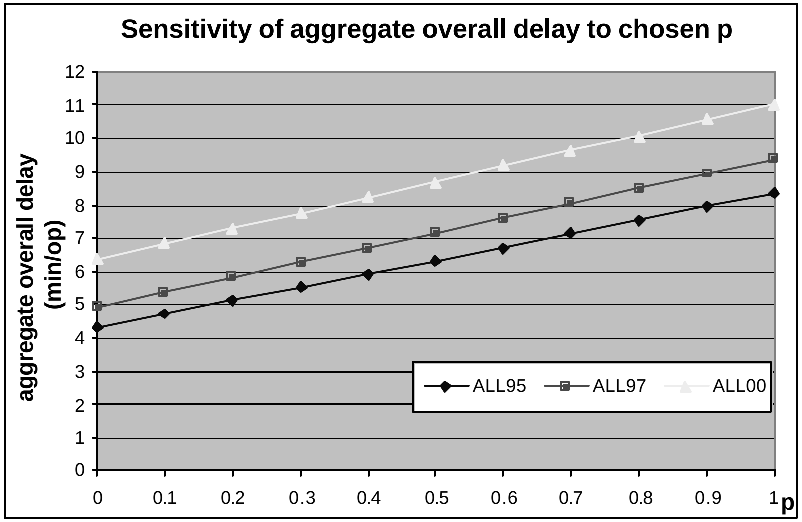
- Step B3: assume that airborne delay is due exclusively to airspace congestion unrelated to any specific O-D pair => in this respect, it should not be attributed to any airport
- Taxi out and taxi in delays are calculated as in Step B1.
- Average origin delay at airport calculated by taking the average of all taxi out delays attributable to that airport
- Average destination delay at airport calculated by taking the average of all taxi in delays attributable to that airport
- Results yield extremely small destination delay results (on the order of half the destination delay results obtained with Method A) => suggests that assumption that airborne delay is exclusively caused by to airspace congestion is not valid either

=> Some portion of the airborne delay should indeed by attributed to the destination airport

Step B4: Revisiting the airborne delay attribution assumption

Backup

- Neither of the hypotheses used in Step B1, B2 and B3 regarding the allocation of airborne delays is well-founded
- Step B4: Assume that a fraction p of the airborne delay is due to the destination airport and the remaining portion is due to airspace congestion
- Choose *p* such that the differences between average overall delay results obtained using Step A2 and Step B4 are minimized



⇒Differences are minimized for p=0.4

⇒Makes sense intuitively

Method B: Results

Backup

	METHODB (Step B4)								
	AIRPORT DELAYS 1995			AIRPORT DELAYS 1997			AIRPORT DELAYS 2000		
	ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
ATL	7.9	5.9	6.9	7.4	7.2	7.3	10.4	7.6	9.0
BOS	5.2	5.4	5.3	6.3	6.4	6.3	10.4	8.8	9.6
BWI	4.1	4.2	4.2	3.6	4.2	3.9	6.3	5.2	5.7
CLE	4.7	4.4	4.6	6.5	4.8	5.7	9.4	5.0	7.2
CLT	5.1	4.8	4.9	5.3	5.4	5.4	8.1	5.4	6.7
CMH	3.4	3.5	3.4	4.2	4.2	4.2	5.4	4.2	4.8
CVG	5.3	3.8	4.6	6.6	5.1	5.8	9.5	5.6	7.5
DCA	5.1	4.6	4.8	5.8	5.0	5.4	8.1	4.7	6.3
DEN	5.4	6.4	5.9	5.9	6.3	6.1	6.5	7.8	7.1
DFW	8.0	8.7	8.4	8.8	9.6	9.2	8.6	8.3	8.4
DTW	7.5	7.1	7.3	8.3	7.6	7.9	10.9	8.1	9.5
EWR	9.2	5.8	7.5	12.8	7.3	10.1	15.5	8.3	11.9
FLL	3.8	4.7	4.3	3.7	5.1	4.3	6.8	5.8	6.4
IAD	4.3	4.1	4.2	5.0	5.2	5.1	9.7	7.1	8.4
IAH	5.5	6.4	6.0	6.6	6.5	6.5	8.8	6.7	7.8
LAX	5.8	7.6	6.7	6.2	7.9	7.0	7.4	8.7	8.1
LGA	7.7	5.0	6.3	9.9	6.0	7.9	15.5	7.4	11.4
MCO	4.0	5.3	4.7	3.7	5.3	4.5	5.5	5.2	5.4
MEM	4.3	4.3	4.3	6.0	5.2	5.6	5.8	4.9	5.4
MIA	8.1	7.1	7.6	7.5	7.4	7.5	8.1	7.0	7.6
MSP	6.5	5.6	6.1	7.8	6.9	7.4	9.9	7.7	8.8
ORD	6.0	6.2	6.1	6.8	7.0	6.9	9.6	8.9	9.3
PHL	4.9	4.5	4.7	7.5	6.3	6.9	14.0	8.1	11.1
PHX	4.0	4.7	4.3	5.1	5.3	5.2	6.7	6.9	6.8
PIT	4.8	4.4	4.6	4.5	4.6	4.5	7.3	5.1	6.3
SFO	6.3	6.6	6.4	7.3	6.4	6.8	7.9	8.2	8.1
TPA	3.4	4.5	4.0	4.3	5.0	4.7	5.2	4.8	5.0
	6.0	**5.8**	**5.9**	**6.9**	**6.5**	**6.7**	**9.2**	**7.2**	**8.2**

Comparative Analysis

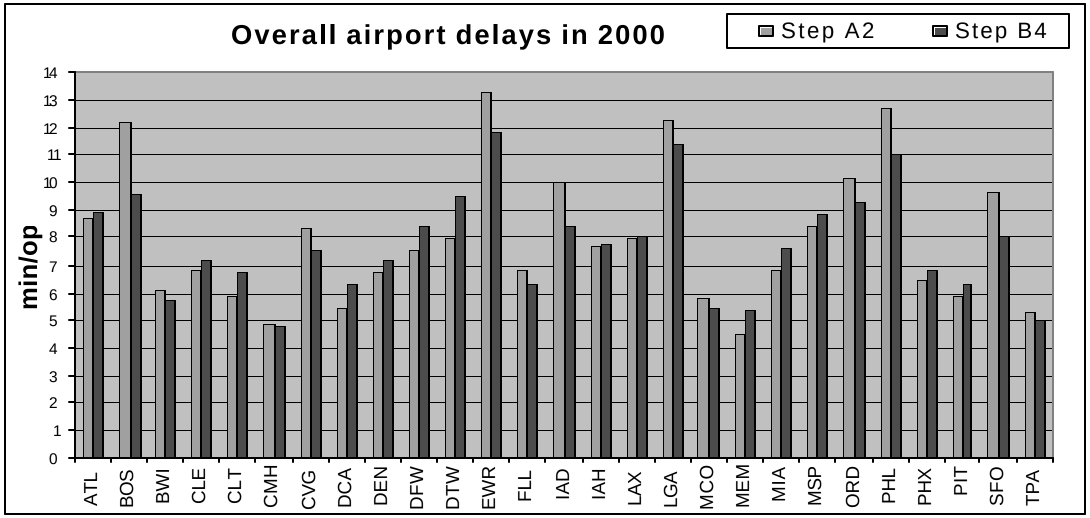
Backup

		AIRPORT DELAYS 1995			AIRPORT DELAYS 1997			AIRPORT DELAYS 2000		
		ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
Weighted Average	Step A2	5.5	5.6	5.5	5.5	7.7	6.6	8.4	8.4	8.4
	Step B4	6.0	5.8	5.9	6.9	6.5	6.7	9.2	7.2	8.2

- At the aggregate level:
  - Both methods show an increase in the aggregate overall delay per airport from 1995 to 2000. Increase of about 53% (Method A) and 39% (Method B)
  - Aggregate average destination delay is greater than or equal to origin delay for Step A2 whereas aggregate average destination delay is smaller than average origin delay for Step B4

Comparative Analysis ([illegible])

Backup



- At the individual airport level, some of the observations made at the aggregate level no longer hold. Specifically:
  - Both methods show increases in the average overall delay from 1995 to 2000, at the individual airports (except MIA)
  - There does not seem to be any trend concerning a systematically higher origin or destination delay for either method.
  - Airport delays in 2000 range from 4.5 min/op to 13.3 min/op depending on airport under consideration and mthod used to estimate the delay

Comparative Analysis (3

Backup

		Spread (min/op)								
		ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
Weighted Average	Step A2	5.2	5.7	4.3	8.0	6.2	7.1	10.2	8.5	8.8
	Step B4	5.8	5.2	4.9	9.2	5.4	6.2	10.3	4.7	7.1

- The gap between average delay incurred by the airport with the most and least delay has increased over the 1995-2000 period
- For Step A2, the gap has increased from 4.3 to 8.8 min/op, which represents a 105% increase; for step B4, the gap has increased from 4.9 to 7.1 min/op (45% increase)
- Shows that over the years, delays have increased significantly more at certain airports than at others => due to the fact that delays increase non-linearly when airports operate near their capacity => airports operating near capacity in 1995 saw their delays increasing at faster rate than airports that were not operating near capacity.
- Greatest increase in spread occurred for the origin delay, for both methods

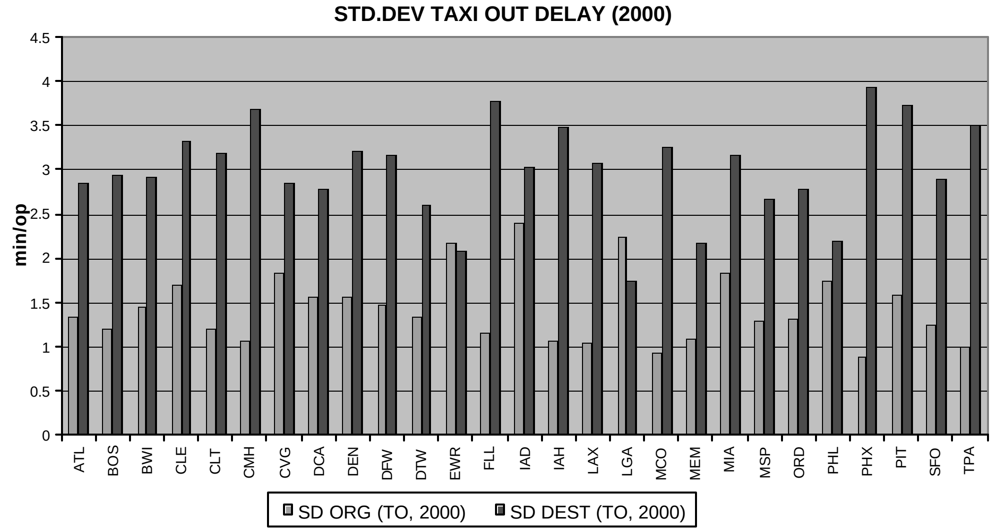
Backup

Additional Insights

- Method B results yields additional insights
- Standard deviations of taxi out delays were computed for the airport of origin and destination for the years 1995,1997,2000
- Results show that taxi out delays at a specific origin airport tend to be similar on average, regardless of their destination (this is indicated by the small std. Dev.

Standard Deviations of Taxi Out Delay

Backup

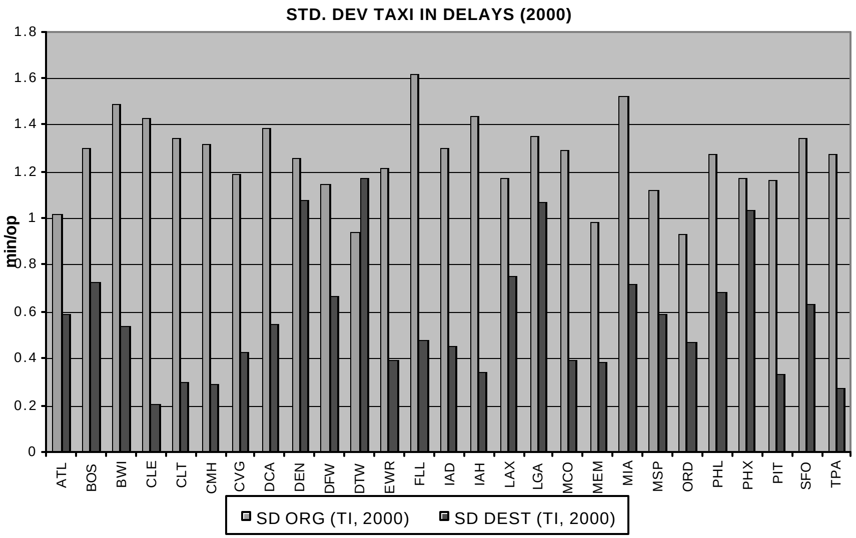


- Std. Dev for taxi out delay for all O-D pairs originating at a given airport are much smaller than the std. Dev of taxi out delays for all O-D pairs arriving at that airport
- Std. Dev grouped by origin airport mostly in the 0.7-1.5 min range. Coeff of variation range from 0.12 to 0.25, indicating a tight distribution of taxi out delays at each origin airport

=> Indicates strong correlation between taxi out delay and airport of origin and justifies decision to attribute taxi out delay to origin airport

Standard Deviations of Taxi in Delay

Backup

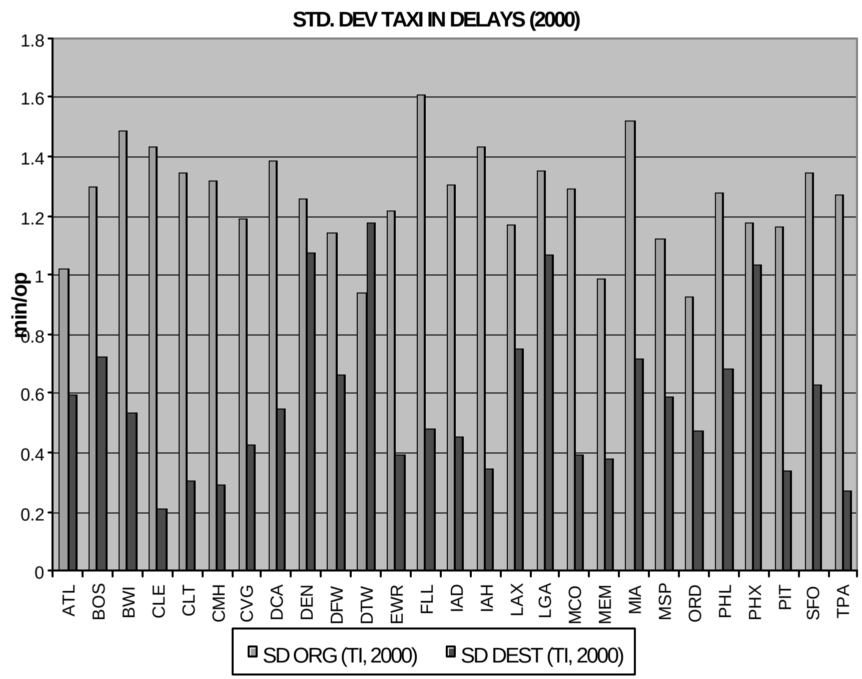


- Std. Dev for taxi in delays occurring on O-D terminating at given airport are much smaller on average than the std. Dev of taxi in delays for all O-D pairs originating at that airport
- Std. Dev grouped by origin airport mostly in the 0.2-0.7 min range. Coeff of variation range from 0.1 to 0.3, indicating a tight distribution of taxi out delays at each origin airport

=> Indicates strong correlation between taxi in delay and destination airport and justifies decision to attribute taxi in delay to destination airport

Standard Deviations of Airborne

Backup



- Std. Dev for airborne delays occurring on O-D with the same destination airport are slighlty smaller, but comparable in magnitude to the std. Dev of airborne delays occurring on all O-D pairs originating at that airport
- Coeff of variation range from 0.19 to 0.43, suggesting that airport delays are not that strongly correlated with the destination airport

⇒ Confirms previous hypothesis that airspace congestion , which cannot be attributed to any specific airport, might be at least partly responsible for airborne delays.

⇒ Explains why destination results in Step B1 and B2 were so high, and suggests that Step B4 is the most appropriate approach to estimate airport delays.

Backup

APPLICATIONS

Logan Airport Annual Delays

Backup

- Logan International Airport (BOS)
  - 32nd busiest airport in the world in terms of pax volume
  - Serviced by over 55 scheduled airlines (of which 8 are major domestic carriers, 16 are non-US flag carriers, 13 are regional and commuter airlines)
  - Operations include general aviation flights

	AIRPORT BOS								
	ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
FLIGHTS (SAMPLE)	25,882	25,933	51,815	28,004	28,105	56,109	22,112	22,107	44,219
AVERAGE DELAY USING STEP A2 (min/op)	5.7	5.5	5.6	7.8	7.4	7.6	11.6	12.8	12.2
AVERAGE DELAY USING STEP B4 (min/op)	5.2	5.4	5.3	6.3	6.4	6.3	10.4	8.8	9.6

	Airport BOS		
	1995	**1997**	**2000**
Annual Operations	476,846	502,187	508,283

Logan Airport Annual Delays (2)

Backup

	AIRPORT BOS								
	ORG DELAY 95	**DEST DELAY 95**	**TOTAL DELAY 95**	**ORG DELAY 97**	**DEST DELAY 97**	**TOTAL DELAY 97**	**ORG DELAY 2000**	**DEST DELAY 2000**	**TOTAL DELAY 2000**
TOTAL ANNUAL DELAYS BOS USING STEP A2 (hrs/year)	22,750	21,952	44,702	32,788	30,803	63,590	49,017	54,191	103,208
TOTAL ANNUAL DELAYS BOS USING STEP B4 (hrs/year)	20,768	21,433	42,201	26,205	26,928	53,133	44,230	37,196	81,426

- Best estimate of annual aircraft delay hours incurred at BOS in 2000 is in the range of 80,000-105,000.
- Annual delays at Logan have almost doubled from 1995 to 2000
- Assumptions:
  - Delay figure obtained based on ASQP database, which only reports info for the 10 major US airlines, and only contains data for scheduled jet operations. However, ASQP carriers' scheduled jet operations only represent a fraction of total annual operations at BOS.
  - Implicitly assumed that all flights, whether GA or commercial flights, experience delays similar to those of jets flown by major carriers => approximation => future direction of research could be to compute separately delays for regional carriers and GA operations

Airport Rankings

Backup

- Compared airport rankings derived from 2000 delay results to airport rankings obtained based on OPSNET proportion of delayed flights (based on 2001 benchmark report) to rank
- Only considered airports that were common to both data set

Airport Rankings (2)

Backup

	Airport rankings in 2000		
	Method A (Step A2)	Method B (Step B4)	OPSNET proportion of delayed flights (based on 2001 benchmark report)
ATL	8	7	7
BOS	4	4	5
BWI	18	23	18
CLT	20	19	20
CVG	10	15	14
DCA	22	21	17
DEN	16	17	22
DFW	14	9	9
DTW	11	5	13
EWR	1	1	2
IAD	6	10	12
IAH	13	13	8
LAX	12	11	11
LGA	3	2	1
MCO	21	24	19
MEM	24	25	24
MIA	15	14	16
MSP	9	8	15
ORD	5	6	3
PHL	2	3	6
PHX	17	18	10
PIT	19	22	21
SFO	7	12	4
TPA	23	26	23

Spearman Correlation Coefficient		
Step A2 & B4	Step A2 & FAA ranking	Step B2 & FAA ranking
0.92	0.87	0.83

- Airport were ranked in decreasing order of delay
- Spearman Rank Correlation test to compare the rankings and test whether they were comparable
- Coefficients obtained are close to 1, indicating a high correlation between the different rankings
- Despite severe underestimation of total delays by OPSNET, airport rankings derived from OPSNET and those using Step A2 and B4 are very consistent

Airport Rankings (3)

Backup

Airport	RANKINGS OBTAINED USING…									
	Method A (Step B2)	Method B (Step B4)	OPSNET proportion of delayed flights	OPSNET Number of Delays	ASPM Average Arrival Delay	ASQP on-time arrivals	Enplaned Pax.	OPSNET Total Ops.	Optimum Cap./Total Ops.	Reduc[illegible] Cap./Total Ops
ATL	8	7	7	4	9	7	1	1	4	8
BOS	4	4	5	6	3	8	14	10	11	6
BWI	18	23	18	20	14	20	19	23	20	15
CLT	20	19	20	17	24	24	17	15	17	18
CVG	10	15	14	14	15	23	20	14	15	19
DCA	22	21	17	18	18	16	23	22	9	9
DEN	16	17	22	22	7	5	6	7	23	24
DFW	14	9	9	8	17	6	3	3	18	12
DTW	11	5	13	12	20	19	7	6	16	17
EWR	1	1	2	3	5	11	10	16	10	5
IAD	6	10	12	13	11	18	22	13	13	16
IAH	13	13	8	11	19	21	11	11	12	14
LAX	12	11	11	9	8	1	4	4	2	3
LGA	3	2	1	1	1	9	15	19	3	2
MCO	21	24	19	19	13	14	13	21	22	21
MEM	24	25	24	24	22	17	24	20	21	22
MIA	15	14	16	16	10	15	12	9	14	11
MSP	9	8	15	15	23	12	5	8	7	13
ORD	5	6	3	2	4	4	2	2	5	7
PHL	2	3	6	7	6	10	16	12	6	10
PHX	17	18	10	10	12	3	9	5	1	1
PIT	19	22	21	21	21	22	18	17	19	20
SFO	7	12	4	5	2	2	8	18	8	4
TPA	23	26	23	23	16	13	21	24	24	23

Airport Rankings (4)

Backup

Spearman's Rank		RANKS OBTAINED USING…									
		1	2	3	4	5	6	7	8	9	10
RANKS OBTAINED USING	1		0.92	0.87	0.85	0.67	0.37	0.39	0.39	0.62	0.59
	2			0.83	0.84	0.48	0.31	0.46	0.48	0.58	0.56
	3				0.98	0.69	0.50	0.47	0.38	0.75	0.82
	4					0.67	0.54	0.54	0.47	0.77	0.82
	5						0.68	0.30	0.16	0.47	0.61
	6							0.65	0.47	0.52	0.61
	7								0.81	0.41	0.41
	8									0.45	0.33
	9										0.89
	10										

1	Method A ([illegible])
2	Method B (Step B4)
3	OPSNET proportion of delayed flights
4	OPSNET Number of Delays
5	ASPM Average Arrival Delay
6	ASQP on-time arrivals
7	Enplaned Pax.
8	OPSNET Total Ops.
9	Optimum Cap./Total Ops.
10	Reduced Cap./Total Ops

- Airport Rankings obtained using Step A2, Step B4, OPSNET proportion of delayed flights, and OPSNET total number of delayed flights are all strongly correlated
- Very weak relationship between ASQP on-time rank and Steps A2 and B4 ranks Weak relationship between ASPM average arrival delay and Steps A2 and B4
- Good correlation between OPSNET total number of delayed flights ranking and ratio of reduced capacity over total operations ranking => shows relationship between number of flights delayed and the reduction in capacity due to poor weather at an airport.

=> suggests that on-time statistics are a poor indicator of the true severity of delays at different airports