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Wake Vortex Advisory System (WakeVAS) Evaluation of Impacts on the National Airspace System

Jeremy C. Smith and Samuel M. Dollyhigh
Swales Aerospace, Hampton, Virginia

January 2005

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Executive Summary

This report is one of a series which describes an ongoing effort in high-fidelity modeling/simulation, evaluation and analysis of the benefits and performance metrics of the Wake Vortex Advisory System (WakeVAS) Concept of Operations being developed as part of the Virtual Airspace Modeling and Simulation (VAMS) project. The initial WakeVAS concept was delivered to NASA Ames Research Center in mid-January 2003. The current deliverable for VAMS is a self-evaluation of the concept, the goal of which is a quantification of the concept's expected benefits and effects upon the National Airspace System (NAS). To perform a detailed analysis of the key benefit mechanisms required a multi-pronged effort involving the LaRC Airborne Systems Competency as concept developers and the LaRC Systems Analysis Branch, responsible for the self-evaluation analysis.

A previous study, determined the overall increases in runway arrival rates that could be achieved at 12 selected airports[1] due to WakeVAS reduced aircraft spacing under Instrument Meteorological Conditions.

This study builds on the previous work to evaluate the NAS wide impacts of equipping various numbers of airports with WakeVAS.

A queuing network model of the National Airspace System, built by the Logistics Management Institute, Mclean VA, for NASA (LMINET) was used to estimate the reduction in delay that could be achieved by using WakeVAS for the projected air traffic demand in 2010. The results from LMINET were used to estimate the total annual delay reduction that could be achieved using WakeVAS under non-visual meteorological conditions and from this, an estimate of the air carrier variable operating cost saving was made.

The results of this current study indicate that the estimated 2010 annual reduction in NAS wide total delay is between 46563 hours or 2.7% for WakeVAS deployment at 12 airports for arrivals only and 108481 hours or 6.3% for all of the 64 airports modeled in LMINET using WakeVAS for arrivals and departures.

The corresponding saving in air carrier variable operating costs would be between $75 million and $165 million in 2004 $ based on the latest FAA cost data.

In the next phase of this work, the VAMS ACES simulation of the National Airspace System will be used to model the effects of WakeVAS at a higher level of fidelity and the results compared to those currently obtained.

1. ATL, BOS, CLT, DFW, EWR, JFK, LAX, LGA, MIA, ORD, SFO, STL

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Abstract

This report is one of a series that describes an ongoing effort in high-fidelity modeling/simulation, evaluation and analysis of the benefits and performance metrics of the Wake Vortex Advisory System (WakeVAS) Concept of Operations being developed as part of the Virtual Airspace Modeling and Simulation (VAMS) project.

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1. ATL, BOS, CLT, DFW, EWR, JFK, LAX, LGA, MIA, ORD, SFO, STL

Introduction

NASA Langley Research Center (LaRC) is currently supporting the Virtual Airspace Modeling and Simulation (VAMS) project at Ames Research Center by acting as a concept developer for future wake vortex hazard/impact mitigation in the National Airspace System (NAS).

Current safe wake vortex separations are achieved with a set of rules for air traffic control and procedures for pilots. The pilot procedures apply any time aircraft are operated under Visual Flight Rules (VFR) and summarize safe operational practices based on a general understanding of wake behaviour. The important point is that the responsibility for wake avoidance lies with the pilot under VFR. The exception to this is departures at a towered airport behind a B757 or heavy aircraft.

In Instrument Meteorological Conditions (IMC), pilots cannot necessarily see other aircraft so the controller has the responsibility to provide separation to aircraft for wake avoidance.

The rules for wake avoidance were determined empirically with experiments such as tower flybys with wingtip smoke generators, and represent the worst-case estimation of wake behaviour, as is necessary for any static criteria when safety is a parameter. Over the 30+ years of wake vortex research it has become known that wake behaviour after generation is influenced heavily by atmospheric factors such as winds and turbulence.

Wake vortex avoidance rules that are sensitive to the dynamic influences on wake behaviour could provide much more optimum spacing criteria than the worst-case criteria currently used.

The Wake Vortex Advisory System (WakeVAS) predicts wake behaviour based on an assessment of the local meteorological conditions and provides dynamic separation criteria for each aircraft generator/ follower category (Heavy, B757, Large, and Small).

A previous report, reference 1, describes the WakeVAS concept in detail and contains an analysis of the performance of WakeVAS at 12 selected U.S. airports; see Table 1 for airports list.

The previous analysis determined that under IMC conditions, WakeVAS could provide an improvement in runway arrival rates of between 4.5% and 19% for each airport with an overall improvement under IMC of 10% averaged over the 12 airports. WakeVAS also has the potential to improve departure rates, but initial analysis of departure rate improvement showed a large variation in performance and further work is needed to verify the results.

This report extends the previous analysis at individual airports to consider the overall impacts of WakeVAS on the NAS.

Analysis Methods and Data

Previous analysis, reference 1, determined the expected improvement in runway arrival rates under IMC at the 12 WakeVAS study airports. This data can be used as input to a NAS wide simulation to enable the overall system wide benefits, in terms of increased capacity and reduced delay, to be assessed.

Initial results for NAS wide delay reduction, presented here, were obtained using the LMINET 64 airport queuing model of the NAS. The intention is to verify and extend the initial results using the ACES Build 3 software when available. Build 3 contains enhancements necessary for a WakeVAS study, specifically:

- Individual Runway Identification and Aircraft Spacing Matrices
- Site-specific VFR and IFR configuration models for each airport based on current airport designs
- Representative Set of Terminal Areas (currently only ORD, EWR)
- International Flights
- Tail number connectivity feature (keeps track of individual aircraft within ACES)

The LMINET 64 airport model was developed for NASA, reference 2. The LMINET is a calibrated model which accurately represents the capacity of the 64 included airports at the runway level under 5 categories of meteorological conditions: VMC, MVMC, and 3 categories of IMC, corresponding to ILS CAT1, CATII, and CATIII. The 64 airports modelled account for over 80% of air carrier operations in the NAS. The remaining traffic is included as arrivals from/ departures to the LMINET airports from out of network airports, so contributes to the demand at the LMINET airports.

The LMINET model was used to analyze NAS wide delays, with and without WakeVAS, for 3 representative weather days. The benefit of using WakeVAS at the 12 study airports only, at 30 of the FAA benchmark airports (excluding Honolulu) from reference 3, and at all 64 LMINET airports was examined; see Table 1 for list of airports. In addition, the additional delay reduction that could be obtained by using WakeVAS for departures as well as arrivals was investigated.

Two input schedule data sets were used representing demand in 2002 and 2010. For the 2010 analysis, the airport capacities were increased by the FAA Operational Evolution Plan (OEP) improvement values from reference 3. The intention is to use the ACES data sets with Build 3 of ACES when available to compare with and extend the results obtained using LMINET.

Id	Airport	WakeVAS Study Airport	FAA Benchmark Airport
ABQ	Albuquerque International Sunport Airport, New Mexico, USA		
ATL	The William B. Hartsfield Atlanta International Airport, Atlanta, Georgia	1	1
AUS	Austin-Bergstrom International Airport, Austin, Texas		
BDL	Bradley International Airport, Windsor Locks, Connecticut		
BNA	Nashville, Tennessee Airport	2	2
BOS	General Edward Lawrence Logan International Airport, Boston, Massachusetts		
BUR	Burbank, California Airport		
BWI	Baltimore-Washington International Airport		3
CLE	Hopkins International Airport, Cleveland, Ohio		
CLT	Douglas Airport, Charlotte, North Carolina	3	4
CMH	Columbus International Airport, Columbus, Ohio		5
CVG	Cincinnati-Northern Kentucky Airport, Cincinnati, Ohio		
DAL	Love Field, Dallas/Fort Worth, Texas		
DAY	Dayton International Airport, Dayton, Ohio		
DCA	Washington National Airport, Washington, D. C.		6
DEN	Denver International Airport, Denver, Colorado		7
DFW	Dallas-Fort Worth International Airport, Dallas/Fort Worth, Texas	4	8
DTW	Detroit Metropolitan Wayne County Airport, Detroit, Michigan		9
ELP	El Paso International Airport, El Paso, Texas		
EWR	Newark International Airport, Newark, Ohio	5	10
FLL	Fort Lauderdale/Hollywood International Airport, Florida		
GSO	Piedmont Triad International Airport, Greensboro, North Carolina		
HOU	William P. Hobby Airport, Houston, Texas		
HPN	Westchester County Airport, Westchester County, NY		
IAD	Dulles International Airport, Washington, D. C.		
IAH	Houston Intercontinental Airport, Houston, Texas		11
IND	Indianapolis International Airport, Indianapolis, Indiana		12
ISP	MacArthur Field, Long Island, New York		
JFK	John F. Kennedy International Airport	6	13
LAS	McCarran International Airport, Las Vegas, Nevada		14
LAX	Los Angeles International Airport, Los Angeles, California	7	15
LGA	La Guardia Airport, New York, New York	8	16

LGB	Daugherty Field, Long Beach, California		
MCI	Kansas City International Airport, Kansas City, Missouri		
MCO	Orlando International Airport, Orlando, Florida		17
MDW	Midway Airport, Chicago, Illinois		
MEM	Memphis International Airport, Memphis, Tennessee		18
MIA	Miami International Airport, Miami, Florida	9	19
MKE	General Mitchell Field, Milwaukee, Wisconsin		
MSP	Minneapolis-Saint Paul International Airport, Minneapolis-Saint Paul, Minnesota		20
MSY	New Orleans International Airport, New Orleans, Louisiana		
OAK	Oakland International Airport, Oakland, California		
ONT	Ontario International Airport, Ontario, California		
ORD	Chicago O'Hare International Airport	10	21
PBI	Palm Beach International Airport, Palm Beach, Florida		
PDX	Portland International Airport, Portland, Oregon		
PHL	Philadelphia International Airport, Philadelphia, Pennsylvania		22
PHX	Phoenix Sky Harbor International Airport, Phoenix, Arizona		23
PIT	Pittsburgh International Airport, Pittsburgh, Pennsylvania		24
RDU	Raleigh-Durham International Airport, North Carolina		
RNO	Reno/Tahoe International Airport, Nevada		
SAN	Lindbergh Field, San Diego, California		25
SAT	San Antonio International Airport, Texas		
SDF	Louisville International Airport-Standiford Field, Kentucky		
SEA	Seattle-Tacoma International Airport, Seattle, Washington		26
SFO	San Francisco International Airport, San Francisco, California	11	27
SJC	Norman Y. Mineta San Jose International Airport, California		
SLC	Salt Lake City International Airport, Utah		28
SMF	Sacramento International Airport, California		
SNA	John Wayne-Orange County Airport, Santa Ana, California		29
STL	Lambert Field, Saint Louis, Missouri	12	
SYR	Hancock Field, Syracuse, New York		
TEB	Teterboro Airport, New Jersey		
TPA	Tampa International Airport, Florida		30

Table 1: List of Airports

WakeVAS Runway Arrival Rate Improvements

The table below summarizes the mean improvement in runway arrival rates determined from the previous analysis, reference 1. The percentage improvement factor shown was used to adjust the runway Pareto frontiers for non-VMC conditions for the corresponding airport in the LMINET model. The mean improvement averaged over all runways for the 12 airports was 10%. This factor was used to scale the non-VMC runway Pareto frontiers for airports outside the WakeVAS study set to allow investigation of the use of WakeVAS at a larger airport set for some model runs. In addition for comparison purposes, an estimate of 5% improvement for runway departure rates was used for some model runs, this being a conservative estimate of the potential improvement, because reliable data for departure rate improvements is not currently available.

Airport	**Runways**	**WakeVAS IMC RAR Improvement %**
ATL	8L, 9R	8.3
BOS	27	10.0
BOS	33L	11.8
CLT	36L, 36R	4.5
DFW	17C, 17L, 18R	7.7
EWR	4R	7.8
JFK	22L	16.9
JFK	31L, 31R	18.9
LAX	25L, 24R	10.5
LGA	13	8.2
LGA	22	5.3
MIA	9L, 9R	15.4
ORD	27L, 27R	7.5
SFO	28L/28R	14.6
STL	30R	5.0

Table 2: Increase in Runway Arrival Rate under IMC due to WakeVAS for the 12 Study Airports

OEP Airport Capacity Improvements

The table below summarizes the airport capacity improvement factors from the FAA Operational Evolution Plan (OEP), described in reference 3. The values shown were used to increase the capacity of the corresponding airport model in the LMINET for analysis of delays due to 2010 demand.

Airport	**Optimum Conditions % Improvement**	**Reduced Conditions % Improvement**
LGA	10	3
EWR	10	7
ORD	6	12
SFO	0	3
BOS	4	4
PHL	17	11
JFK	2	3
ATL	37	34
IAH	42	41
DFW	4	21
PHX	40	60
LAX	11	4
IAD	49	60
STL	27	89
DTW	31	24
CVG	28	27
MSP	34	31
MIA	24	27
SEA	57	51
LAS	0	12
DCA	4	8
BWI	0	0
MCO	28	38
CLT	30	24
PIT	3	1
SAN	2	3
DEN	25	17
SLC	5	4
TPA	0	19
MEM	3	4
HNL	2	7

Table 3: OEP Airport Capacity Improvements

Demand Data Sets

LMINET requires a schedule of departures and arrivals for each of the 64 airports within the network at a resolution of 1 hour intervals. Flights from airports outside of the LMINET, including international flights, add to the demand at the 64 airports modeled in detail. Since flights between the 64 LMINET airports account for over 80% of air carrier operations in the NAS and flights external to the LMINET that depart or arrive at an LMINET airport are included, the majority of daily operations within the NAS are accounted for.

The 2002 demand dated was obtained from the Official Airlines Guide (OAG) for 17 May 2002, this being the VAMS Project mandated data set. The OAG does not include GA operations, so information about GA operations was obtained from FAA reported data, references 4 and 5.

The future 2010 demand schedule was generated from the baseline 2002 data set using models, references 6 and 7, and growth projections from the FAA Terminal Area Forecast, reference 8. Table 4 summarizes the number of flights and overall growth factors.

Traffic Type	**17 May 2002 Total Daily Flights**	**2010 Total Daily Flights**	**Growth**
Commercial + Cargo from OAG	30853	37163	20%
GA from FAA reported data	21294	27533	29%
Total	52147	64696	24%

Table 4: Demand Data Sets

Meteorological Conditions

WakeVAS was assumed to provide a reduction in aircraft spacing only during non-visual meteorological conditions for this analysis. Figure 1 shows the typical annual percentage time in IFR conditions for the FAA Benchmark Airports, from reference 9. Data from Figure 1 is used later to estimate the potential annual air carrier costs savings at specific airports with WakeVAS deployed.

LMINET requires weather input data which specifies wind speed and direction, ceiling, visibility, and temperature at 1 hour intervals for regions covering each of the 64 LMINET airports.

Included with LMINET are weather input files for 3 weather days, representing poor, moderate, and fair conditions. This data was for 8 April, 12 June, and 29 November 1996. Since these weather days were chosen by LMI to be a representative sample of different meteorological conditions, it was decided to use this data for the current study. In addition, to obtain a measure of the minimum delay under perfect weather conditions, a weather data set with VMC over all of the U.S. was created. Table 5 shows overall percentage of the different weather conditions for each of the data sets. Figures 2, 3, and 4 show weather conditions at each of the 64 LMINET airports and Tables 6, 7, and 8 show conditions at each of the 12 WakeVAS study airports.

The intention is to use ACES weather data sets to perform further analysis using ACES Build 3 when available.

Weather Set	**%VMC**	**%Marginal VMC**	**%IMC**
April	77.0	16.9	6.1
June	67.1	26.8	6.1
November	72.0	14.4	13.6
All VMC	100.0	0.0	0.0

Table 5: Weather Data Sets

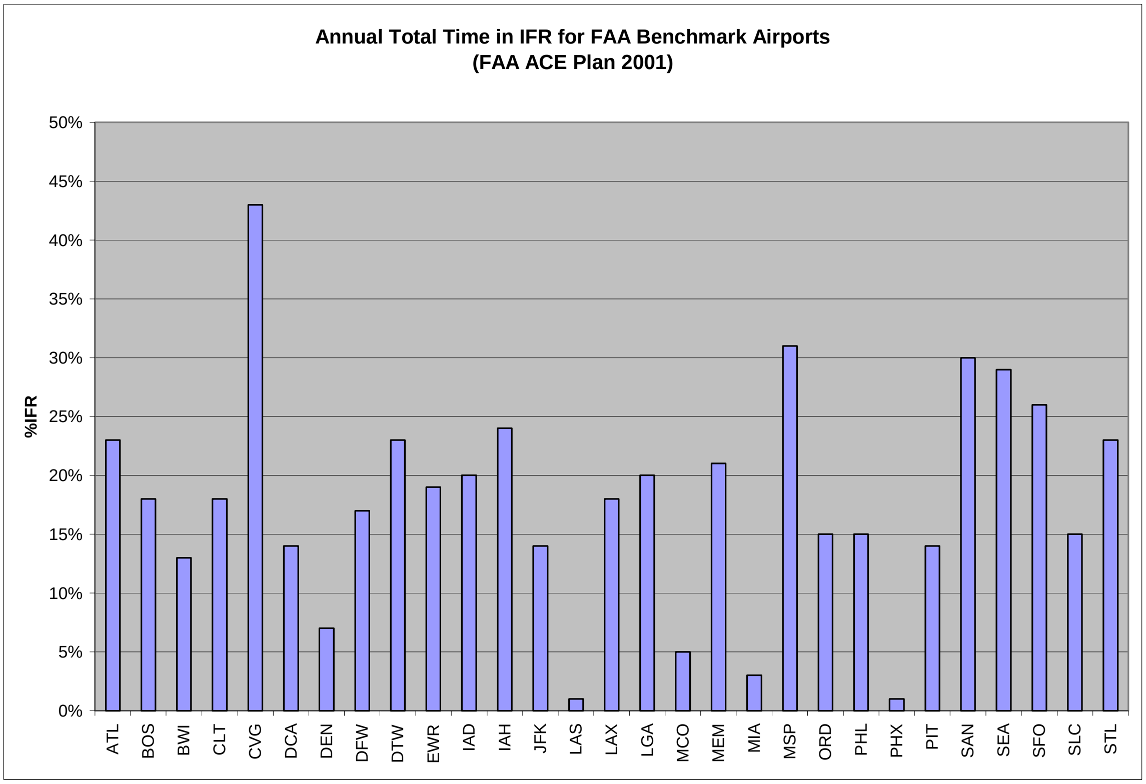

Figure 1: Annual Total Percentage Time in IFR for FAA Benchmark Airports

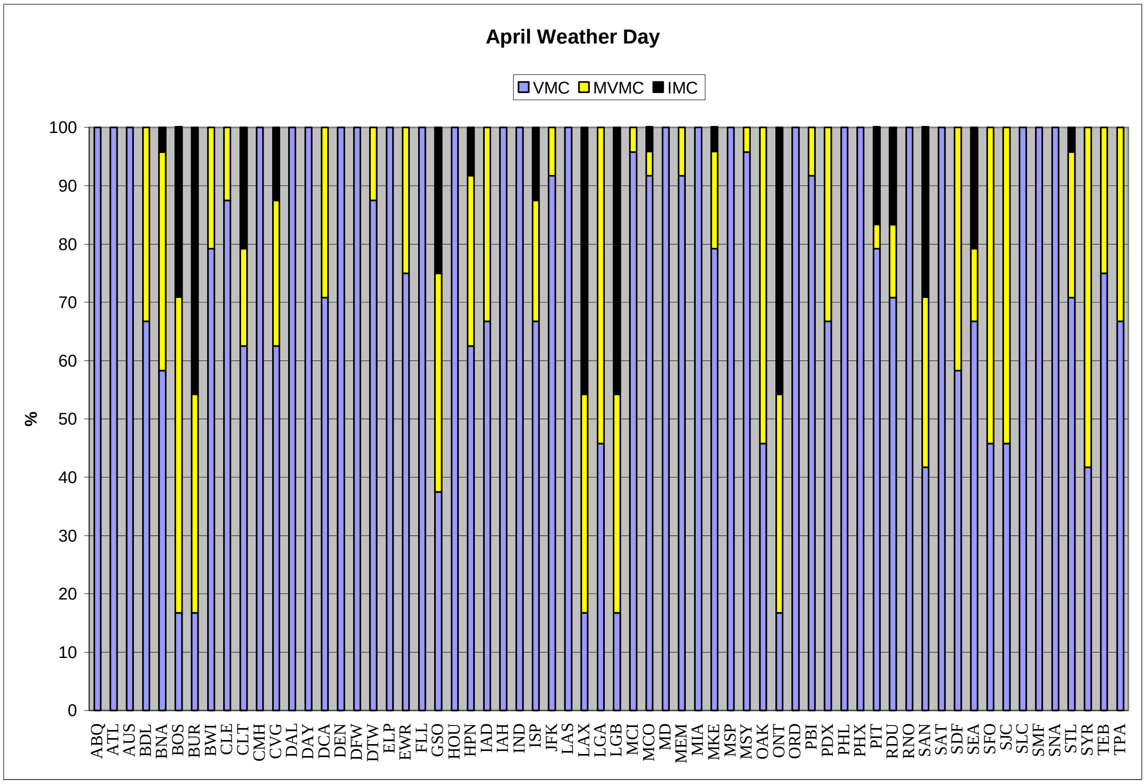

Figure 2: Meteorological Conditions for the 64 LMINET Airports for the April Weather Day

Airport	%VMC	%Marginal VMC	%IMC
ATL	100.0	0.0	0.0
BOS	16.7	54.2	29.1
CLT	62.5	16.7	20.8
DFW	100	0	0.0
EWR	75.0	25.0	0.0
JFK	91.7	8.3	0.0
LAX	16.7	37.5	45.8
LGA	45.8	54.2	0.0
MIA	100.0	0.0	0.0
ORD	100.0	0.0	0.0
SFO	45.8	54.2	0.0
STL	70.8	25.0	4.2

Table 6: Meteorological Conditions for the 12 WakeVAS Airports for the April Weather Data Set

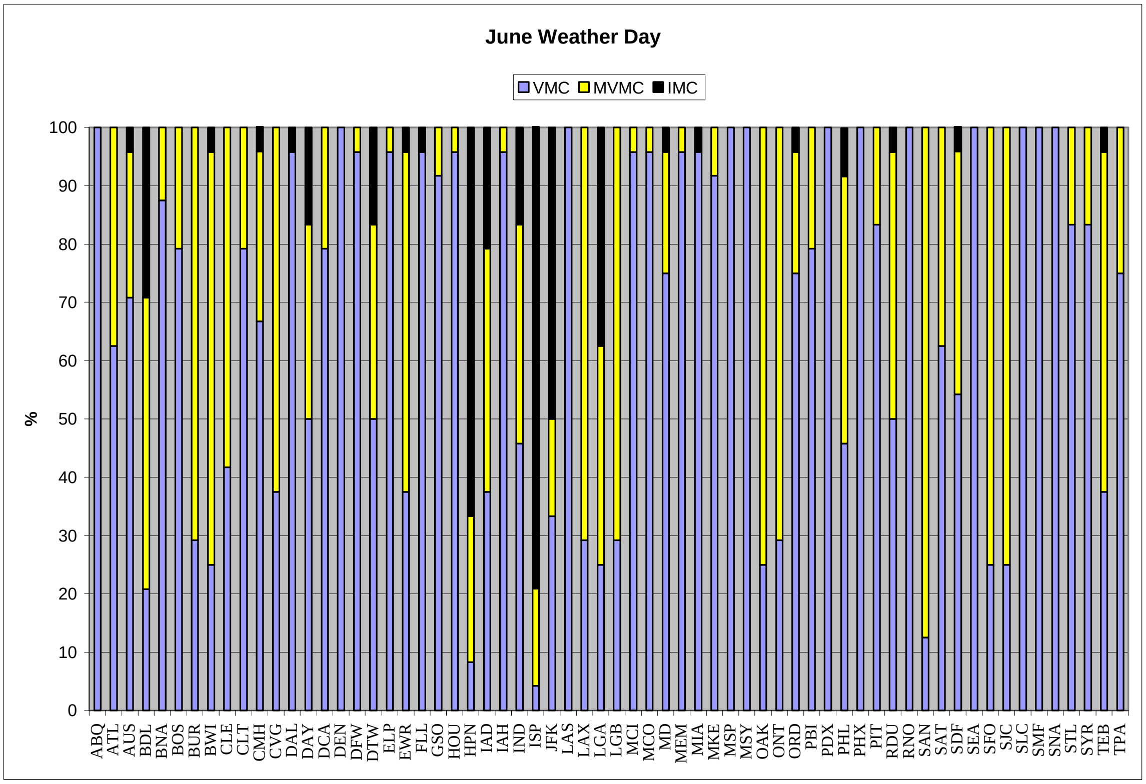

Figure 3: Meteorological Conditions for the 64 LMINET Airports for the June Weather Data Set

Airport	%VMC	%Marginal VMC	%IMC
ATL	62.5	37.5	0.0
BOS	79.2	20.8	0.0
CLT	79.2	20.8	0.0
DFW	95.8	4.2	0.0
EWR	37.5	58.3	4.2
JFK	33.3	16.7	50.0
LAX	29.2	70.8	0.0
LGA	25.0	37.5	37.5
MIA	95.8	0.0	4.2
ORD	75.0	20.8	4.2
SFO	25.0	75.0	0.0
STL	83.3	16.7	0.0

Table 7: Meteorological Conditions for the 12 WakeVAS Airports for the June Weather Data Set

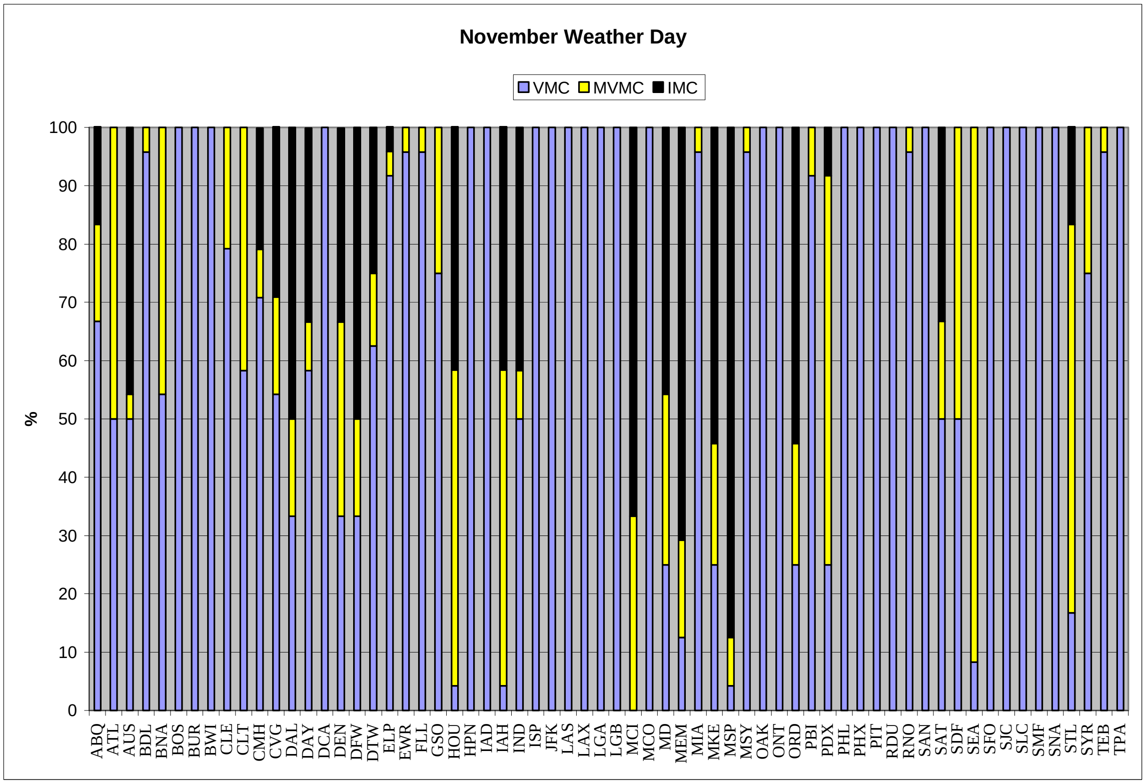

Figure 4: Meteorological Conditions for the 64 LMINET Airports for the November Weather Data Set

Airport	%VMC	%Marginal VMC	%IMC
ATL	50.0	50.0	0.0
BOS	100.0	0.0	0.0
CLT	58.3	41.7	0.0
DFW	33.3	16.7	50.0
EWR	95.8	4.2	0.0
JFK	100.0	0.0	0.0
LAX	100.0	0.0	0.0
LGA	100.0	0.0	0.0
MIA	95.8	4.2	0.0
ORD	25.0	20.8	54.2
SFO	100.0	0.0	0.0
STL	16.7	66.6	16.7

Table 8: Meteorological Conditions for the 12 WakeVAS Airports for the November Weather Data Set

NAS Delay Analysis

The LMINET model was used to analyze NAS wide delay due to terminal area constraints. Enroute delay due to sector capacity constraints was not assessed for this study, since the LMINET 64 airport model does not model actual NAS sectors.

LMINET outputs the following measures of delay:

- Departure Queue
- Arrival Queue
- Departure Taxi Queue
- Arrival Taxi Queue
- Ground Hold
- Wait for Aircraft (aircraft not available for departure)
- Total Delay (sum of the above)

Output is available as an aggregate value for each airport over the 24 hours of scheduled demand and at 1 hour epoch intervals.

A detailed description of the measures of delay is contained in reference 2.

LMINET was used to run test cases using 2002 and 2010 demand data for each of the 3 weather days for the following WakeVAS configurations:

1) WakeVAS @ 12 Airports for Arrivals Only
2) WakeVAS @ 12 Airports for Arrivals and Departures

3) WakeVAS @ 30 Airports for Arrivals Only
4) WakeVAS @ 30 Airports for Arrivals and Departures

5) WakeVAS @ 64 Airports for Arrivals Only
6) WakeVAS @ 64 Airports for Arrivals and Departures

This gave a total of 36 test runs for LMINET.

The airports included in each test set are listed in Table 1.

2002 Demand Set Results

This section presents selected results using the 2002 demand data set. Although the results were obtained using historic data and hence have no direct applicability to a future WakeVAS, they are useful for comparison with the 2010 data. For this reason, only summary results are presented for the 2002 data and a full analysis of WakeVAS performance is presented in the 2010 Demand Set Results section.

All VMC Minimum Delays

Figure 5 shows 2002 total delay over 24 hours of operations for each LMINET airport for the all VMC weather day. It is evident that there is some delay, around 3.1 minutes per flight on average, even with perfect weather conditions using the artificially created weather set with VMC over all of the U.S. The largest total delays occurred at ORD, ATL, DFW, and LGA which are listed as being within the top 10 airports with most delay in the FAA 2001 ACE Plan, reference 9.

Summary of WakeVAS Delay Reduction

Tables 8 and 9 summarize the NAS total delay reduction due to WakeVAS. Results are presented for the 3 weather days, using WakeVAS for the 12 study airports, 30 FAA benchmark airports, and 64 LMINET airports for arrivals only and then for arrivals and departures. The reduction in total delay varied between 1.1% for the November weather day using WakeVAS for arrivals only at the 12 study airports and 8.6% using WakeVAS for all 64 LMINET airports for arrivals and departures.

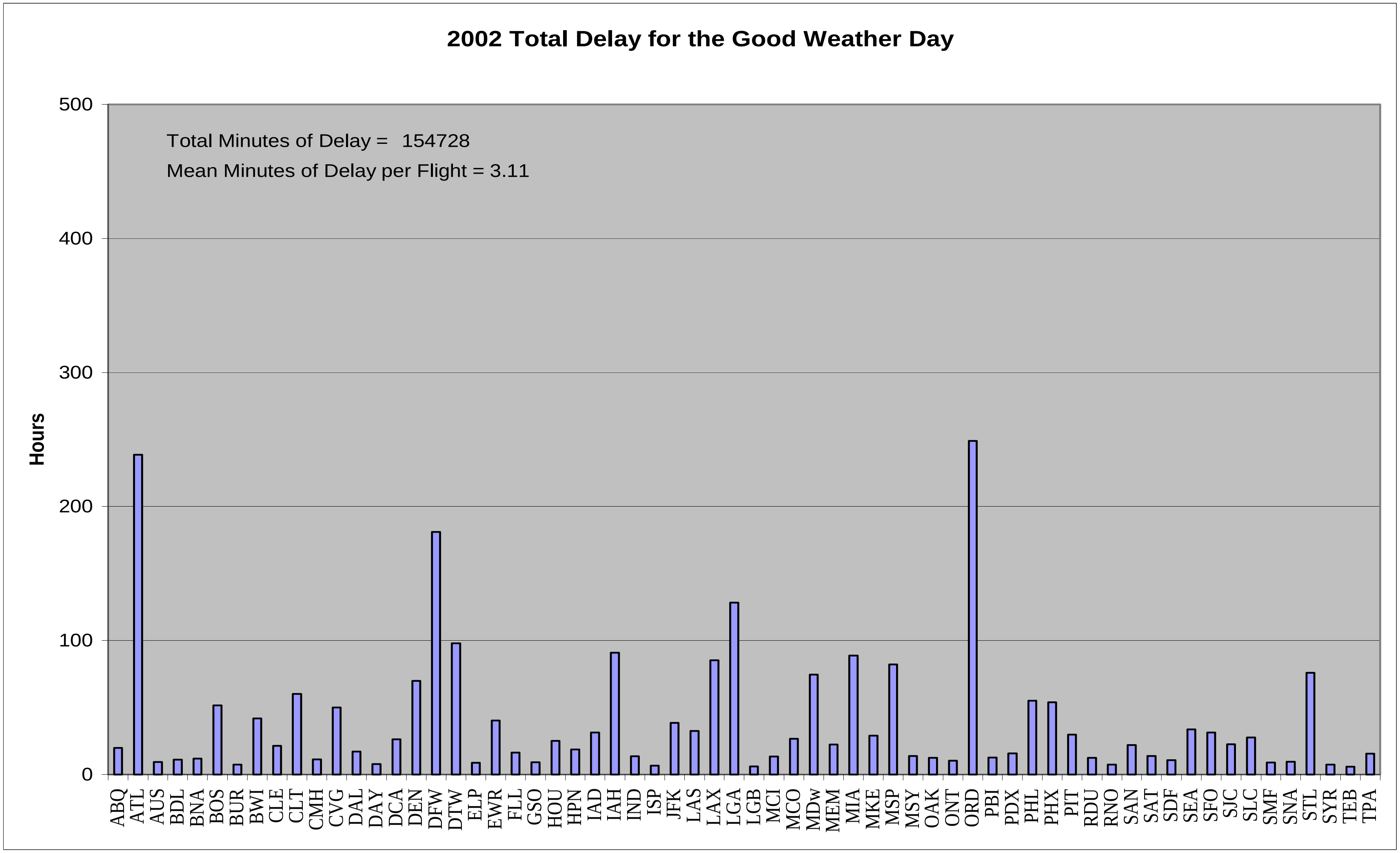

Figure 5: Delay for the all VMC Weather Day with 2002 Demand

Total Hours of Delay for 24 hours of Operations with 2002 Demand

	Default	WakeVAS for Arrivals Only at 12 Airports		WakeVAS for Arrivals Only at 30 FAA Benchmark Airports		WakeVAS for Arrivals Only at 64 LMINET Airports	
	Delay (hrs)	**Delay (hrs)**	**%Reduction**	**Delay (hrs)**	**%Reduction**	**Delay (hrs)**	**%Reduction**
April	3561	3387	4.89	3354	5.81	3350	5.93
June	3217	3154	1.96	3128	2.77	3115	3.17
November	11199	11075	1.11	10753	3.98	10711	4.36
All VMC	2579	N/A	N/A	N/A	N/A	N/A	N/A

Table 9: Reduction in Delay for 2002 Demand using WakeVAS for Arrivals Only

	Default	WakeVAS for Arrivals and Departures at 12 Airports		WakeVAS for Arrivals and Departures at 30 FAA Benchmark Airports		WakeVAS for Arrivals and Departures at 64 LMINET Airports	
	Delay (hrs)	**Delay (hrs)**	**%Reduction**	**Delay (hrs)**	**%Reduction**	**Delay (hrs)**	**%Reduction**
April	3561	3317	6.85	3259	8.48	3256	8.57
June	3217	3127	2.80	3096	3.76	3076	4.38
November	11199	10891	2.75	10359	7.50	10309	7.95
All VMC	2579	N/A	N/A	N/A	N/A	N/A	N/A

Table 10: Reduction in Delay for 2002 Demand using WakeVAS for Arrivals and Departures

Note 1: Assumed 10% arrivals capacity improvement during non-VMC conditions for airports other than the 12 study airports.

Note 2: Assumed 5% departures capacity improvement during non-VMC conditions.

Note 3: Total Delay includes Departure Queue + Arrival Queue + Departure Taxi Queue + Arrival Taxi Queue + Ground Hold + Wait for Aircraft as defined by the LMINET model.

2010 Demand Set Results

All VMC Minimum Delays

Figure 6 shows 2010 total delay over 24 hours of operations for each LMINET airport for the all VMC weather day. The mean delay per flight is just over 3 minutes or about the same as 2002, although the total hours of NAS delay are larger since there are 24% more flights. The mean delay per flight has not increased because the airport capacities for the 2010 demand analysis were increased by the FAA Operational Evolution Plan (OEP) improvement values from reference 3, as documented in Table 2 of this report.

Summary of WakeVAS Delay Reduction

Tables 11 and 12 summarize the NAS total delay reduction due to WakeVAS. Results are presented for the 3 weather days, using WakeVAS for the 12 study airports, 30 FAA benchmark airports (excluding HNL), and 64 LMINET airports for arrivals only and then for arrivals and departures. The reduction in total delay varied between 1.1% for the November weather day using WakeVAS for arrivals only at the 12 study airports and 8.8% using WakeVAS for all 64 LMINET airports for arrivals and departures. The smaller percentage improvement for the November weather day using only 12 airports was due to only 5 of the 12 airports experiencing significant hours of IMC or MVMC and due to the largest delay being at airport MSP which was not using WakeVAS for this specific test run.

Weighted Annual Delay Reduction Estimate

The results for each weather day must be weighted according to their probability of occurrence to obtain an unbiased estimate of annual delay reduction, since poor weather days occur far less frequently than fair weather days over all of the U.S. The weights used were: APR (0.13), JUN (0.8), NOV (0.07); as calculated by LMI, reference 10.

Figure 7 shows the weighted results, an estimated annual total delay reduction of between 46563 hours or 2.7% for WakeVAS deployment at 12 airports for arrivals only and 108481 hours or 6.3% for 64 airports using WakeVAS for arrivals and departures. This indicates that equipping only the 12 study airports does not sufficiently capture the potential improvement available from WakeVAS. The chart shows an almost linear relationship between delay reduction and number of airports with WakeVAS deployment, but these results are preliminary. For the nonstudy airports where exact data was not available, a flat 10% improvement in runway arrival rate was assumed, this being the mean improvement achieved at the 12 airports studied in detail.

The departure rate improvement factor has not been determined with any certainty. An estimate of 5% was assumed, because initial analysis of results from the Parametric Wake Vortex Model described in reference 1 yielded widely varying values. It is clear that the assumed 5% increase in departure rates is having a significant effect, reducing annual total delay by an additional 1% to 2%. This is despite the reduction in airport departure capacity being typically less severe than the reduction in arrivals capacity under IMC and runway departure rates being greater than arrival rates under equal conditions. To allow direct comparison between results obtained using WakeVAS for arrivals only, the departure rate improvement was only applied during non-VMC conditions, whereas current rules for departure spacing behind Heavy or B757 apply in all weather conditions. The assessment of the effect of WakeVAS on runway departure rates and the consequent delay reduction requires further analysis.

Results for Each Weather Day

Charts are presented for the minimal case with WakeVAS at the 12 study airports for arrivals only and for the best case studied with all 64 LMINET airports equipped with WakeVAS, used for arrivals and departures. Results for all test cases, including intermediate cases not discussed in this section, are summarized in Tables 11 and 12.

Figures 8, 9, and 10 show results using WakeVAS at the 12 study airports for arrivals only. The April weather day showed significant delay reductions at BOS and LGA, because the weather at these airports was poor with IMC/MVMC for a majority of the day, see Table 5. ATL, DFW, and ORD had significant delays, but WakeVAS gave no improvement since these airports were under VMC all day. The June weather day showed a useful reduction in delay at JFK, LGA, and ORD, correlating with poor weather at these airports, see Table 6. The November weather day showed less percentage reduction in delay than April and June. This is because the largest delays occurred at MSP which was under IMC virtually all day, see Figure 4, and for this test case MSP was not equipped with WakeVAS. Only 5 of the 12 WakeVAS equipped airports were under non-VMC for a significant part of the day, see Table 7. Of these 5, ATL and ORD showed a useful reduction in delay due to WakeVAS. Even though the overall percentage reduction in delay was smaller than for the April and June weather days, the actual number of hours of delay saved was similar since the delays were larger.

Figures 11, 12, and 13 show results for WakeVAS at all 64 LMINET airports used for arrivals and departures. The average percentage delay reduction over all 3 weather days was more than twice that obtained with 12 airports equipped with WakeVAS for arrivals only. The November weather day in particular showed a much greater reduction in delay compared to using WakeVAS at 12 airports for arrivals only. This is mainly due to the significant reduction in delay at MSP and improvement in delay reduction at ORD compared to the 12 airports case which did not include MSP in the set of WakeVAS equipped airports.

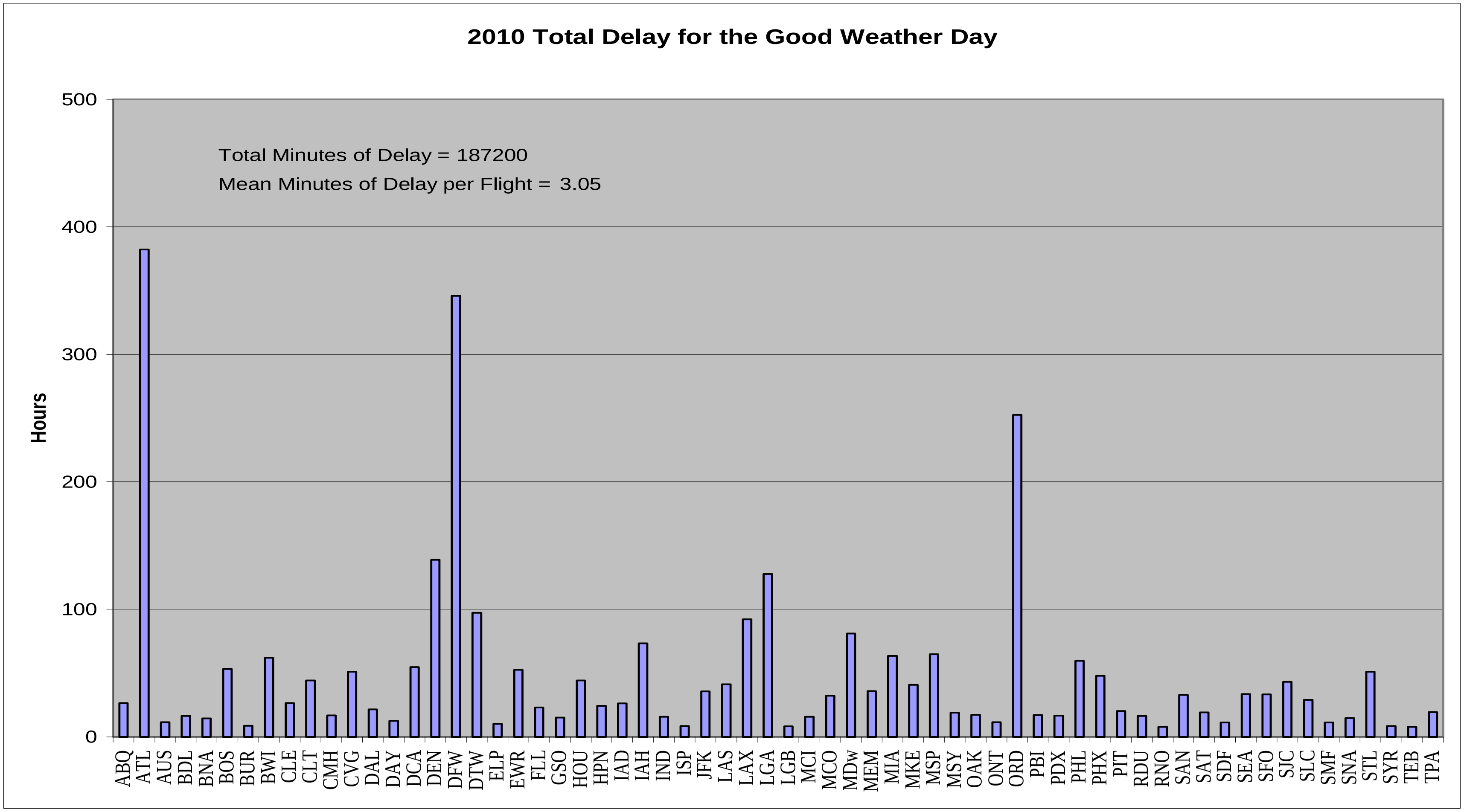

Figure 6: Delay for the all VMC Weather Day with 2010 Demand

Total Hours of Delay for 24 hours of Operations with 2010 Demand

	Default	WakeVAS for Arrivals Only at 12 Airports		WakeVAS for Arrivals Only at 30 FAA Benchmark Airports		WakeVAS for Arrivals Only at 64 LMINET Airports	
	Delay (hrs)	**Delay (hrs)**	**%Reduction**	**Delay (hrs)**	**%Reduction**	**Delay (hrs)**	**%Reduction**
April	3780	3634	3.86	3631	3.94	3621	4.21
June	4035	3913	3.02	3878	3.89	3851	4.56
November	14120	13963	1.11	13631	3.46	13579	3.83
All VMC	3119	N/A	N/A	N/A	N/A	N/A	N/A

Table 11: Reduction in Delay for 2010 Demand using WakeVAS for Arrivals Only

	Default	WakeVAS for Arrivals and Departures at 12 Airports		WakeVAS for Arrivals and Departures at 30 FAA Benchmark Airports		WakeVAS for Arrivals and Departures at 64 LMINET Airports	
	Delay (hrs)	**Delay (hrs)**	**%Reduction**	**Delay (hrs)**	**%Reduction**	**Delay (hrs)**	**%Reduction**
April	3780	3591	5.00	3574	5.45	3564	5.71
June	4035	3877	3.92	3841	4.81	3807	5.65
November	14120	13641	3.39	12950	8.29	12881	8.77
All VMC	3119	N/A	N/A	N/A	N/A	N/A	N/A

Table 12: Reduction in Delay for 2010 Demand using WakeVAS for Arrivals and Departures

Note 1: Assumed 10% arrivals capacity improvement during non-VMC conditions for airports other than the 12 study airports.

Note 2: Assumed 5% departures capacity improvement during non-VMC conditions.

Note 3: Total Delay includes Departure Queue + Arrival Queue + Departure Taxi Queue + Arrival Taxi Queue + Ground Hold + Wait for Aircraft as defined by the LMINET model.

Note 4: Baseline airport capacity was increased by OEP values documented in FAA 2001 Airport Capacity Benchmarks report.

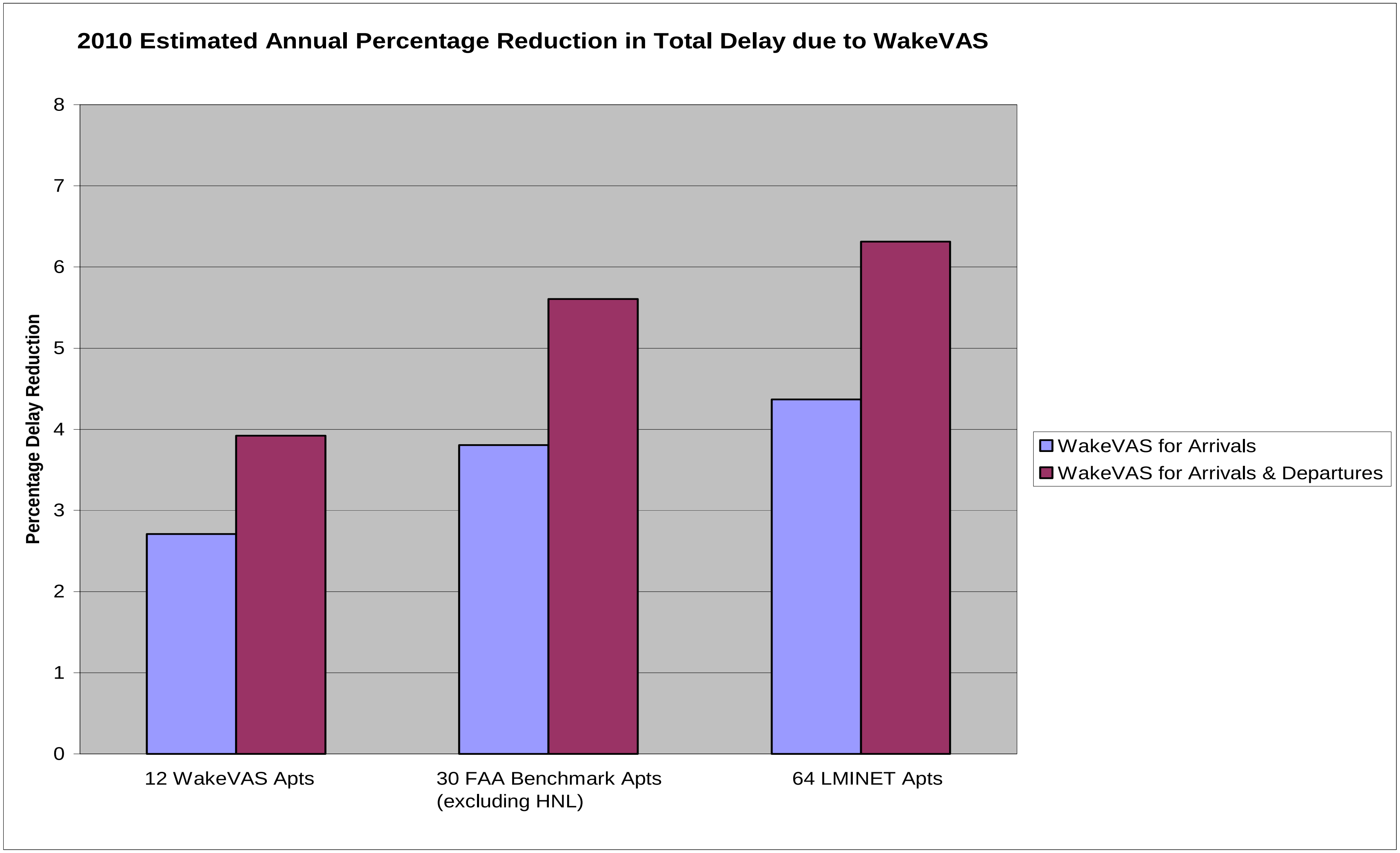

Figure 7: Reduction in Annual Total Delay for 2010 Demand

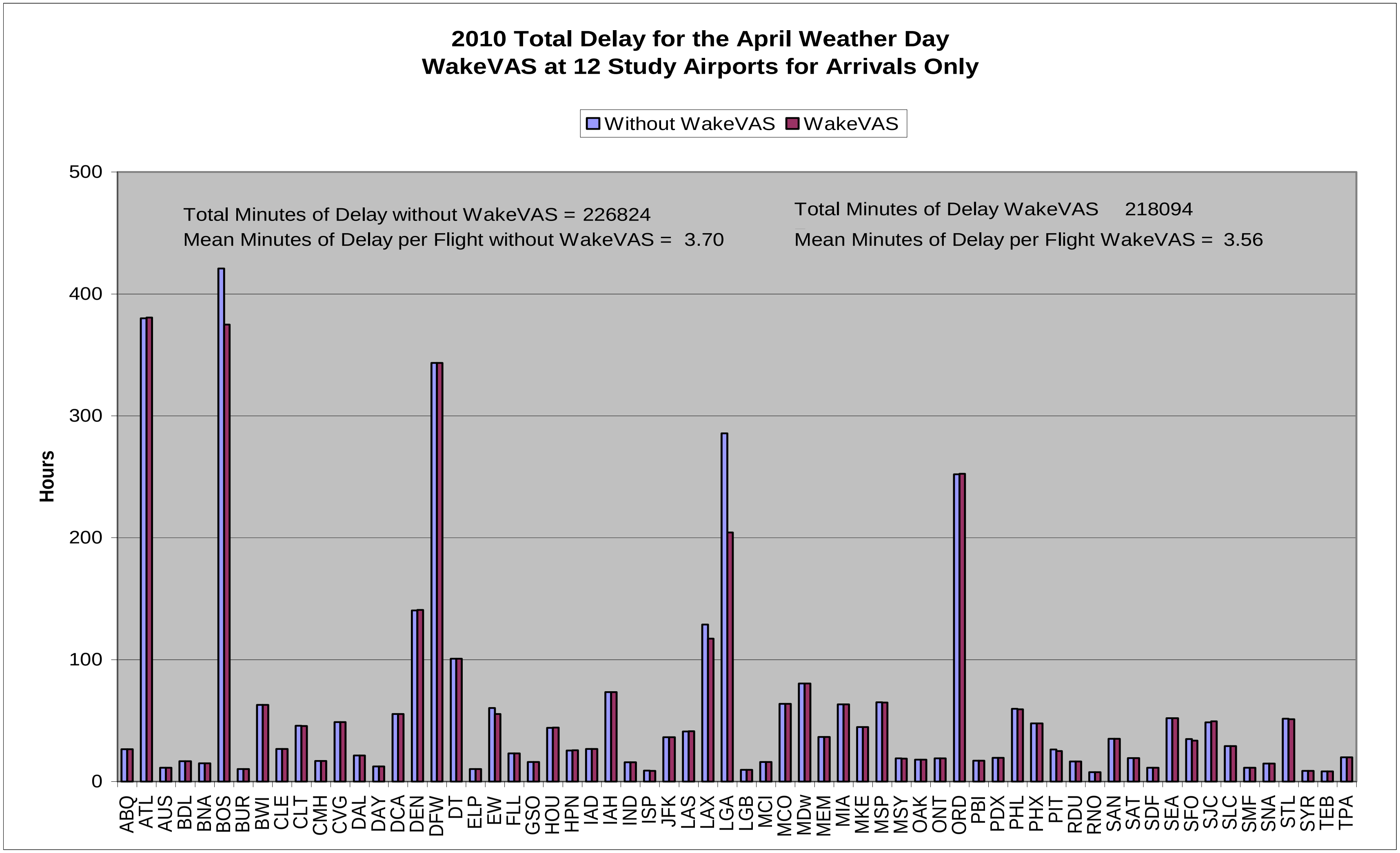

Figure 8: Delay for the April Weather Day with 2010 Demand using WakeVAS at 12 Airports for Arrivals Only

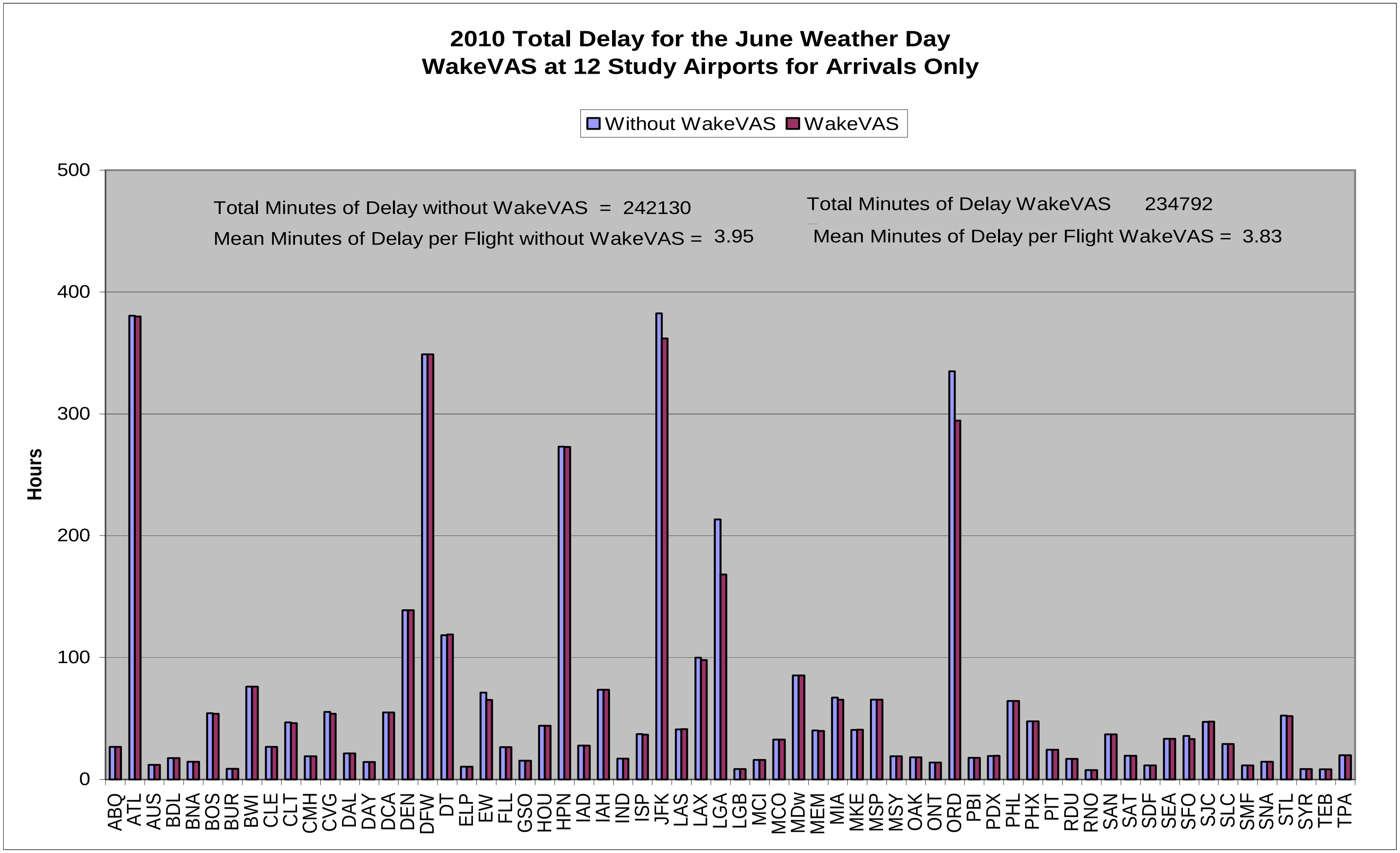

Figure 9: Delay for the June Weather Day with 2010 Demand using WakeVAS at 12 Airports for Arrivals Only

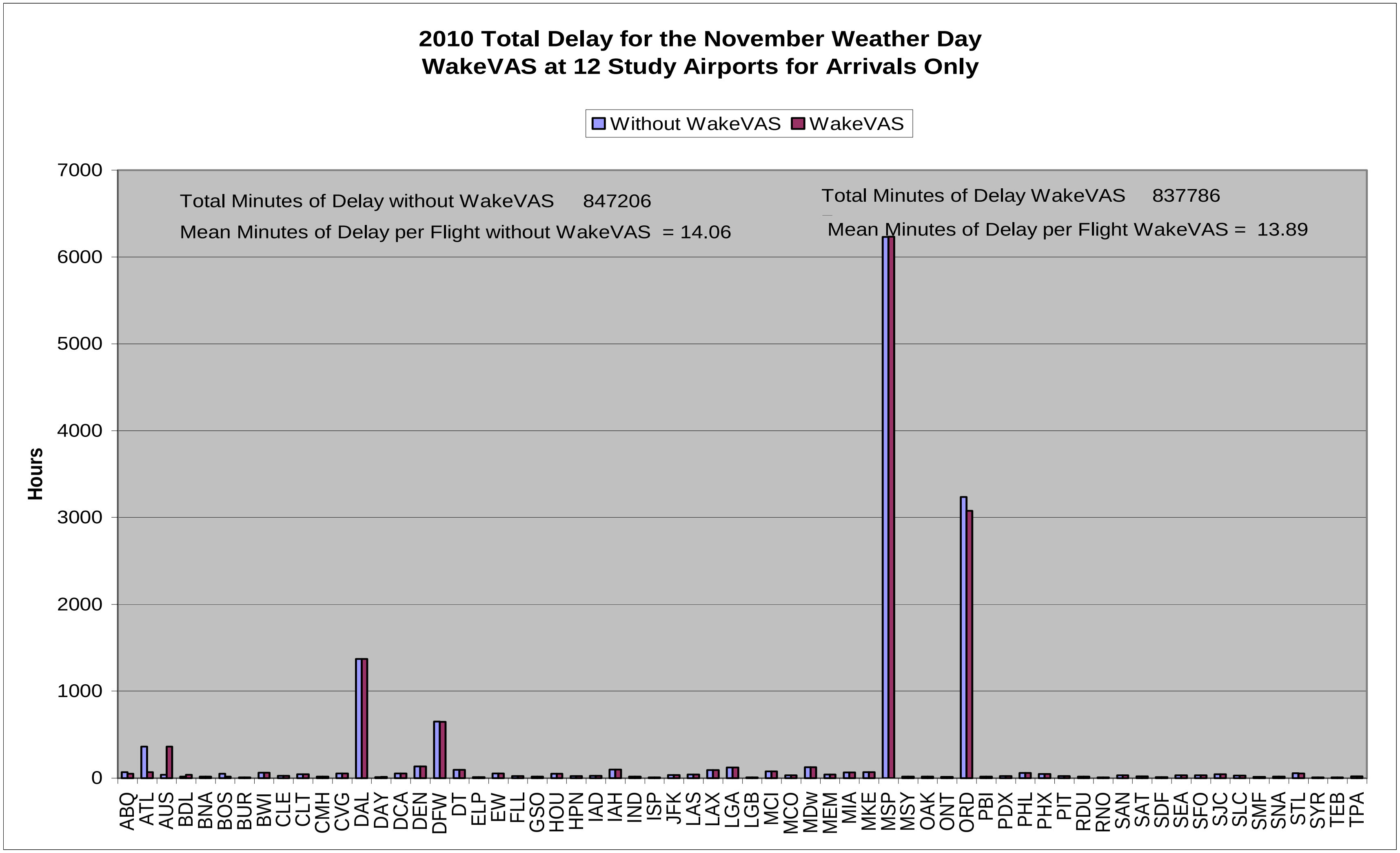

Figure 10: Delay for the November Weather Day with 2010 Demand using WakeVAS at 12 Airports for Arrivals Only

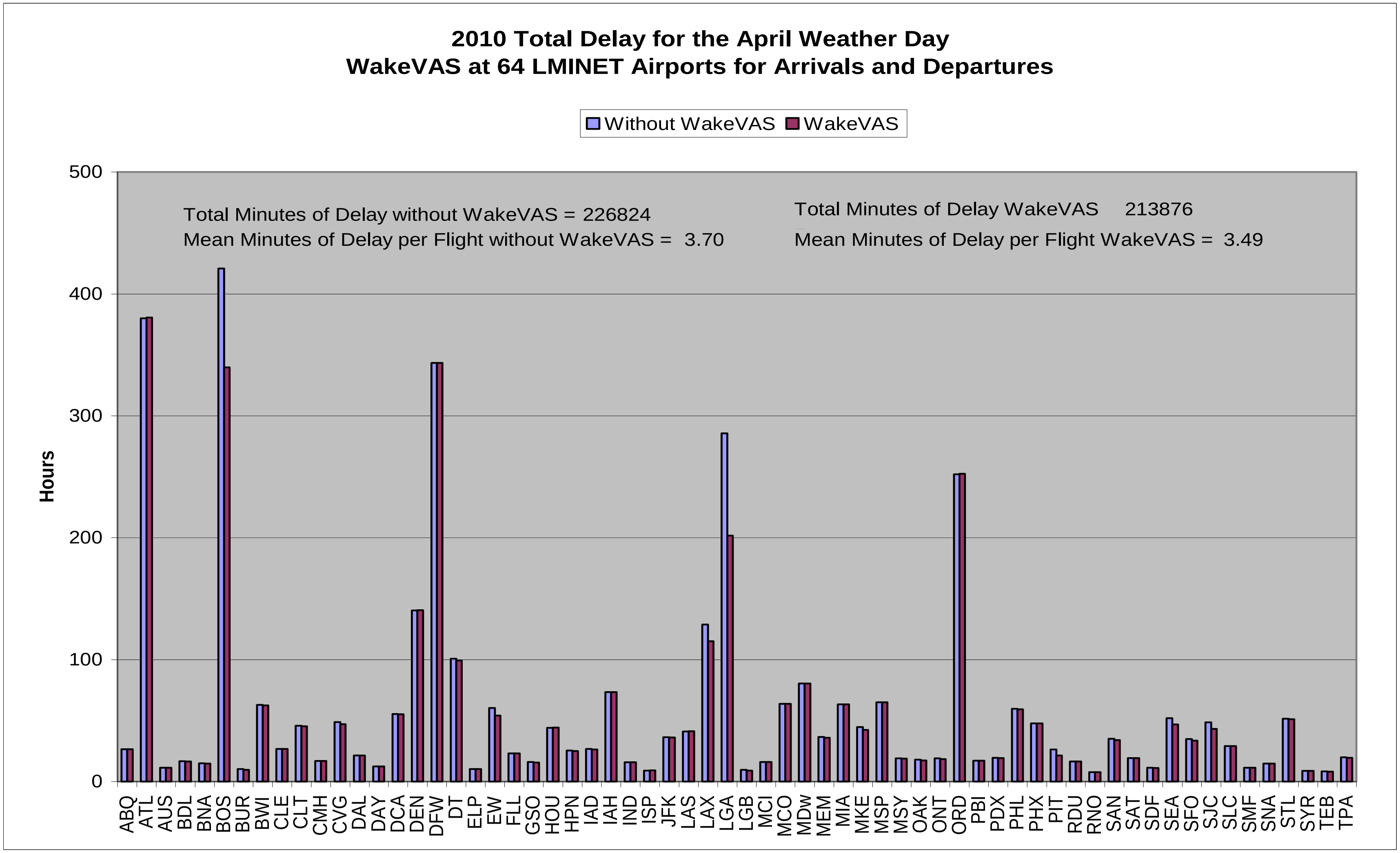

Figure 11: Delay for the April Weather Day with 2010 Demand using WakeVAS at 64 Airports for Arrivals and Departures

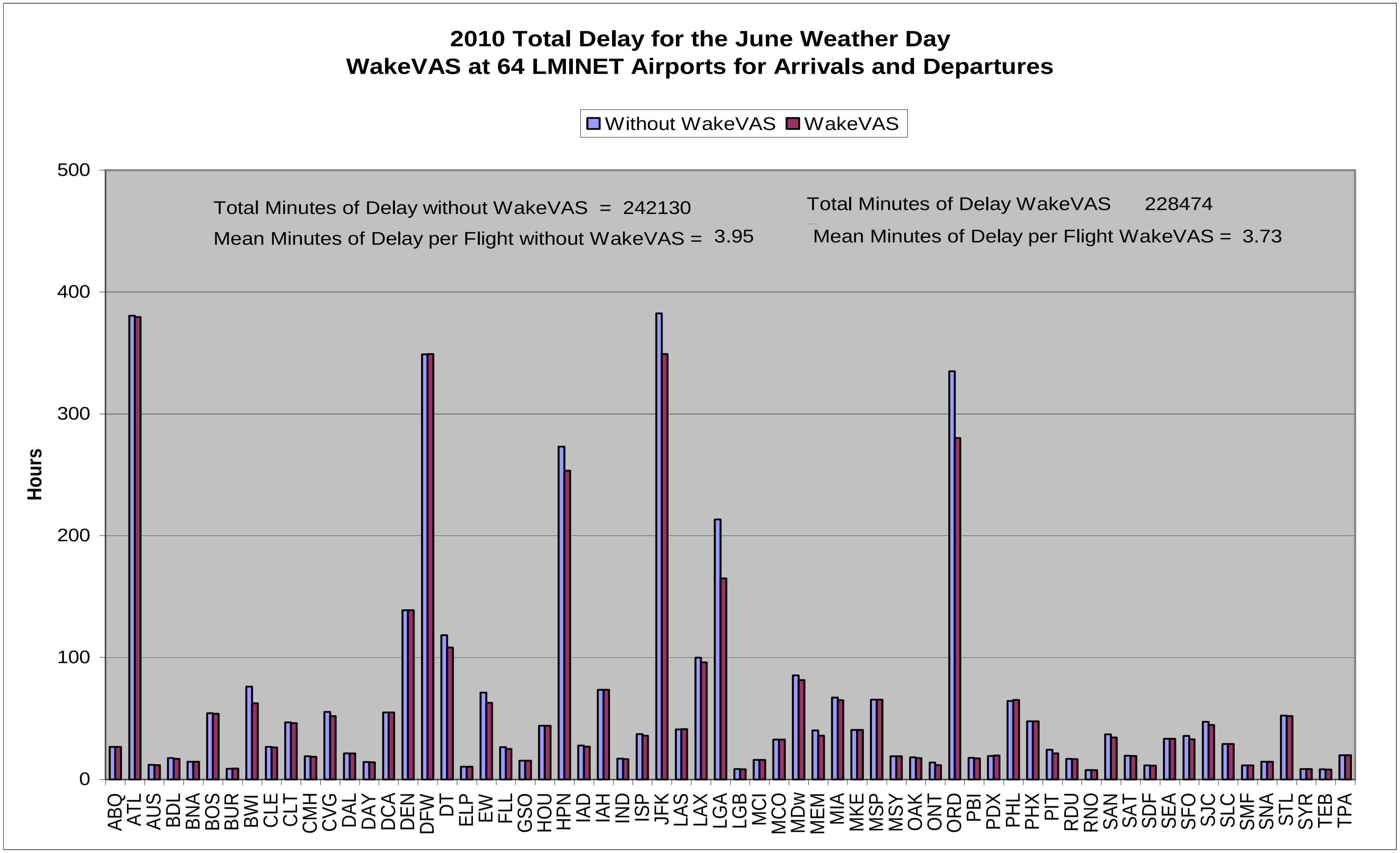

Figure 12: Delay for the June Weather Day with 2010 Demand using WakeVAS at 64 Airports for Arrivals and Departures

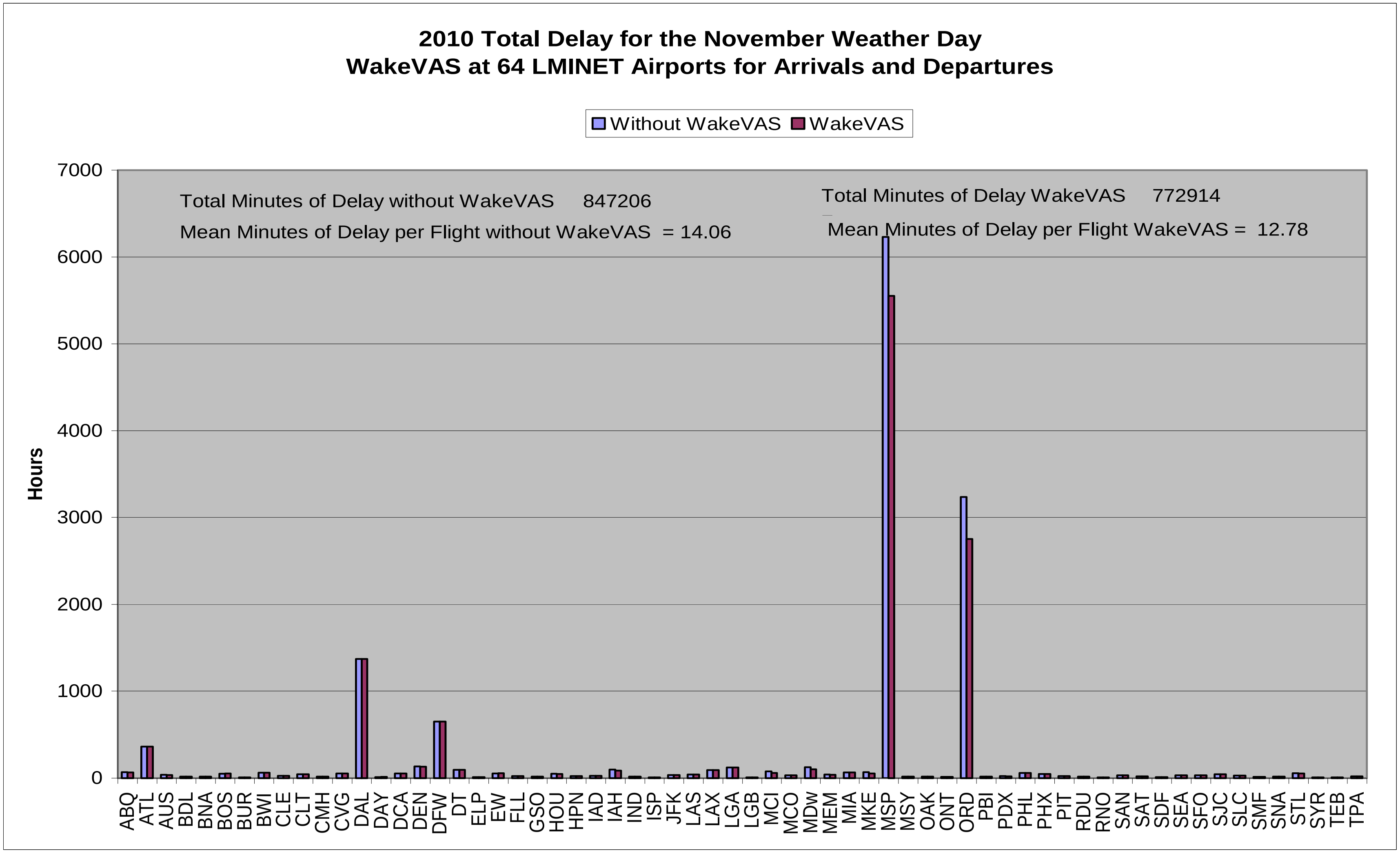

Figure 13: Delay for the November Weather Day with 2010 Demand using WakeVAS at 64 Airports for Arrivals and Departures

Detailed Results for Selected Airports

Several airports were selected for further analysis, based either on an interesting result or particularly good reduction in delay from WakeVAS. All delay reduction values are from the results obtained using WakeVAS at the 46 LMINET airports for arrivals and departures, Figures 11, 12, and 13. The selections are summarized in Table 13.

ATL for the June weather day showed very little delay reduction, despite having non-VMC for 37% of the day. The main cause of the delay in this case was due to taxi delay which totalled 336 hours for arrivals plus departures out of 380 hours total delay. WakeVAS has no direct effect on taxi delay so it is not surprising that the overall delay reduction was very small. The excessive taxi delay indicates that the ATL airport model is not truly representative of the ATL configuration for 2010; the overall capacity was increased by the OEP values but the taxi-capacities were not specifically increased over the 2001 values.

BOS for the April weather day showed a 19% reduction in total delay. The weather for BOS was non-IMC for 83% of the time, providing a good opportunity for WakeVAS to improve throughput. Figure 14 shows the reduction in delay by category for 24 hours of operations. WakeVAS at BOS reduced departure and arrival queue delay by a significant amount, but it is also clear that delay due to aircraft being held on the ground at airports with departures for BOS was a very significant factor. This ground hold delay reduction, due to increased throughput, illustrates the network wide effects of WakeVAS. The wait for aircraft was also reduced substantially, due to more aircraft arriving nearer to the scheduled time. Figure 15 shows the increased capacity that resulted from WakeVAS use and the subsequent reduction in delay. Demand exceeded capacity during the early part of the day due to IMC, leading to a buildup of delays. The weather started to improve to MVMC near the peak of the demand curve and over the next 4 hours the delay reduced to minimal levels. Of interest is the significant reduction in delay due to WakeVAS; despite a modest increase in capacity and the faster recovery, delays returned to minimal levels about 1 hour sooner using WakeVAS. This is in part due to the network wide effects of using WakeVAS at airports with departures for BOS, increasing the throughput of the whole NAS.

LGA for the April weather day showed a 29% reduction in total delay. This large reduction was due mainly to the decrease in arrival queue times and ground holds at airports with aircraft departing for LGA. Figure 16 shows that arrival queue delay is the most significant cause of delay and as a consequence of the backing up of arrivals, feeder airports are holding aircraft on the ground. Figure 17 shows that without WakeVAS, arrival demand first exceeds capacity at epoch 4 and continues to show peaks exceeding demand for most of the busiest part of the day, when LGA is under MVMC. Total delay without WakeVAS builds up and peaks at epoch 13 before improved weather conditions and reduced demand leads to minimal delays from epoch 17 on. WakeVAS increases arrival capacity to just meet or exceed the demand during the early part of the day, leading to a slower buildup and lower peak delay, with subsequent faster recover to minimal delay levels about 1 to 1.5 hrs sooner than without WakeVAS.

ORD for the June weather day showed a 16% reduction in total delays. Figure 18 shows that delays were evenly distributed between arrivals and departures with some aircraft being held on the ground due to arrivals stacking up. Figure 19 shows that although IMC in the early part of the day reduced capacity substantially, there was little delay since demand was also low. Later, at epoch 4 on, MVMC reduced capacity somewhat, and demand exceeded capacity. Delays started to build since for 8 hours during the busiest part of the day, demand peaks were close to or exceeded the airport capacity. The increased capacity due to WakeVAS during the periods of MVMC was sufficient to ensure that demand did not quite exceed capacity. This gave somewhat lower arrival and departure delays, and the increase in arrival rate allowed a reduction in ground holds.

MSP for the November weather day showed an 11% reduction in total delays. Figure 20 showed that MSP had severe delay problems due to exceptionally poor weather with IMC for 87% of the 24 hours of operations. The poor conditions led to long periods of ground holds at airports with scheduled departures arriving at MSP and these nonarrivals led to a long wait for aircraft available to depart. The scheduled number of operations per hour during the busiest part of the day peaks at about 110 to 120 at MSP. Figure 21 shows that the ground holds had the effect of reducing demand to around 70 to 80 operations per hour, but this still exceeded the reduced capacity of the airport. WakeVAS gave a small increase in capacity, which provided the useful delay reduction shown, but total delay was still large.

Airport	**Weather Day**	**%VMC/ %MVMC/ %IMC**	**Delay without WakeVAS (hrs)**	**Delay with WakeVAS @ 64 Airports for Arrivals and Departures (hrs)**	**Reduction (hrs / %)**
ATL	JUN	62.5/37.5/0.0	380.6	379.5	1.1 (0.3%)
BOS	APR	16.7/54.1/29.2	420.8	340	80.8 (19.2%)
LGA	APR	45.8/54.2/0.0	285.7	201.9	83.8 (29.3%)
ORD	JUN	75.0/20.8/4.2	334.9	280.1	54.8 (16.4%)
MSP	NOV	4.2/8.3/87.5	6230.3	5551.4	678.9 (10.9%)

Table 13: Reduction in Delay for 2010 Demand using WakeVAS at Selected Airports

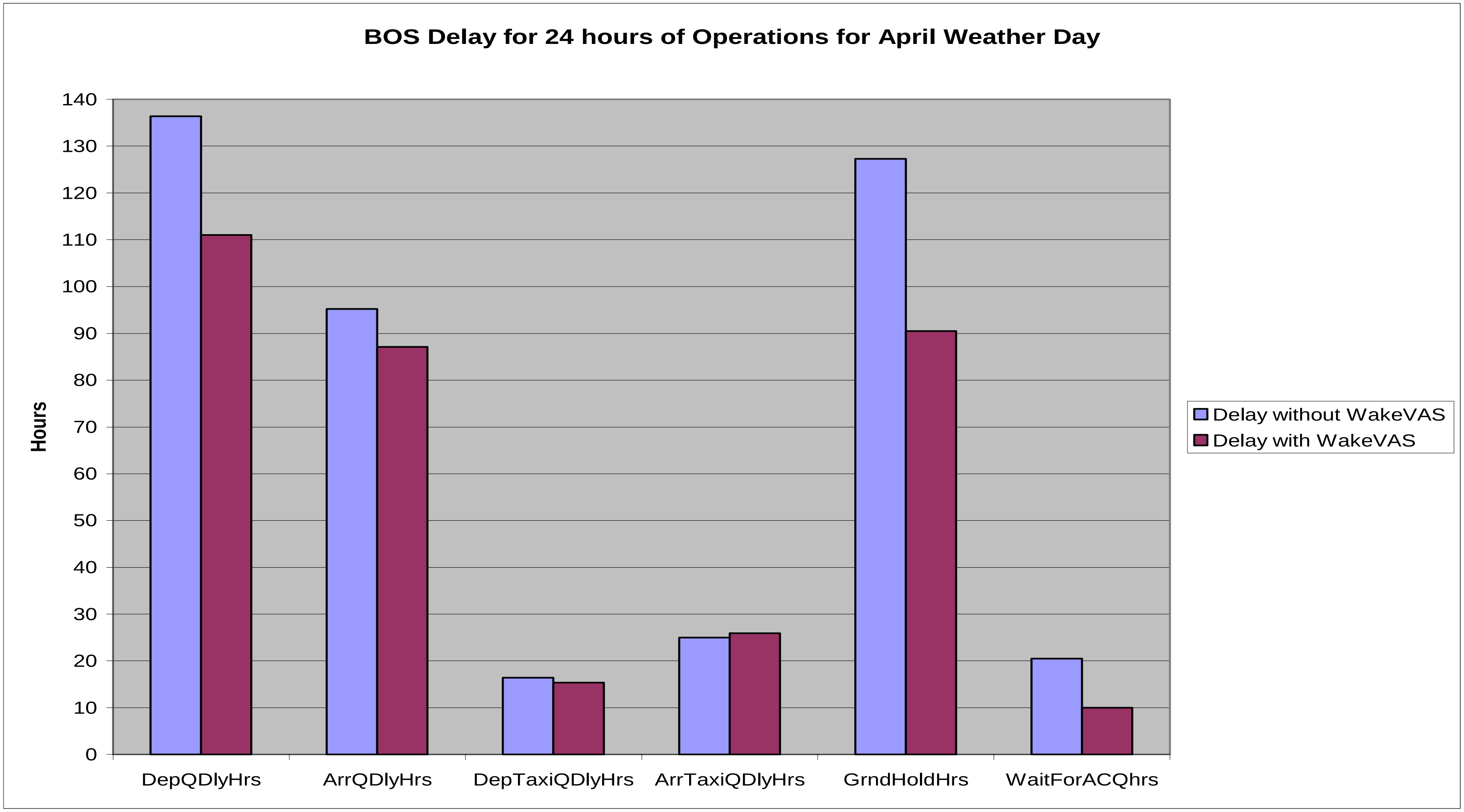

Figure 14: BOS 2010 Delay for April Weather Day

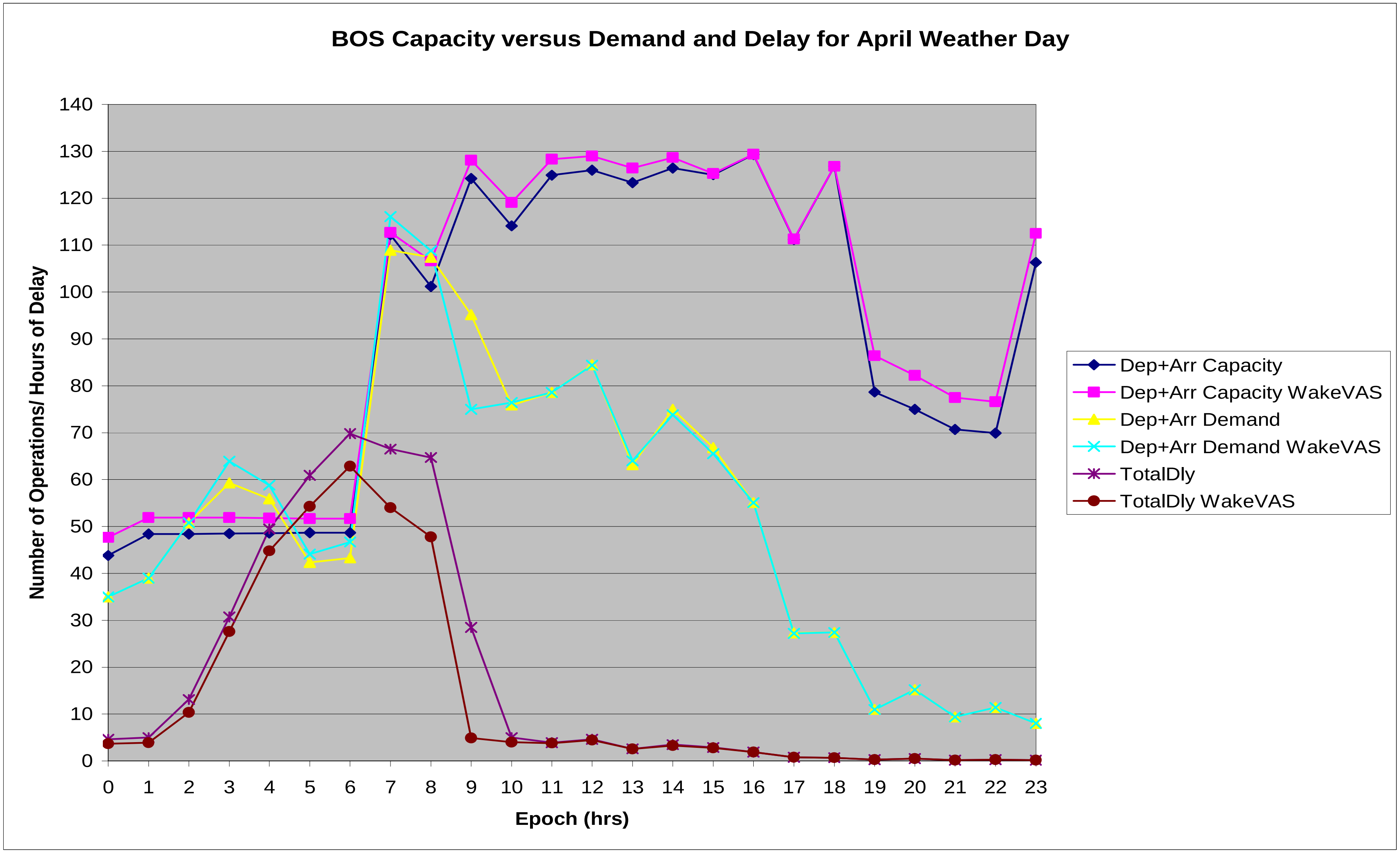

Figure 15: BOS 2010 Capacity versus Demand and Delay for April Weather Day

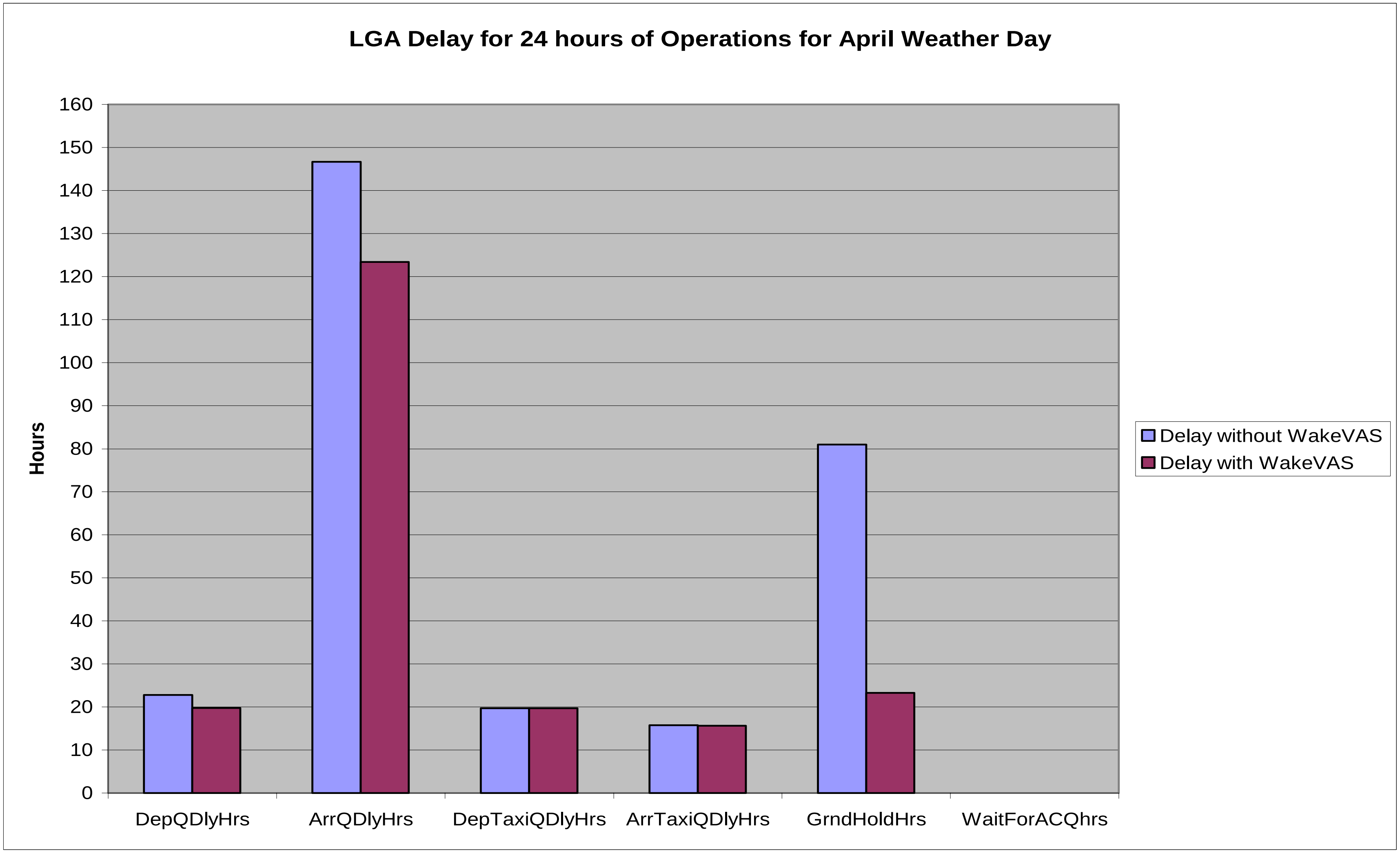

Figure 16: LGA 2010 Delay for April Weather Day

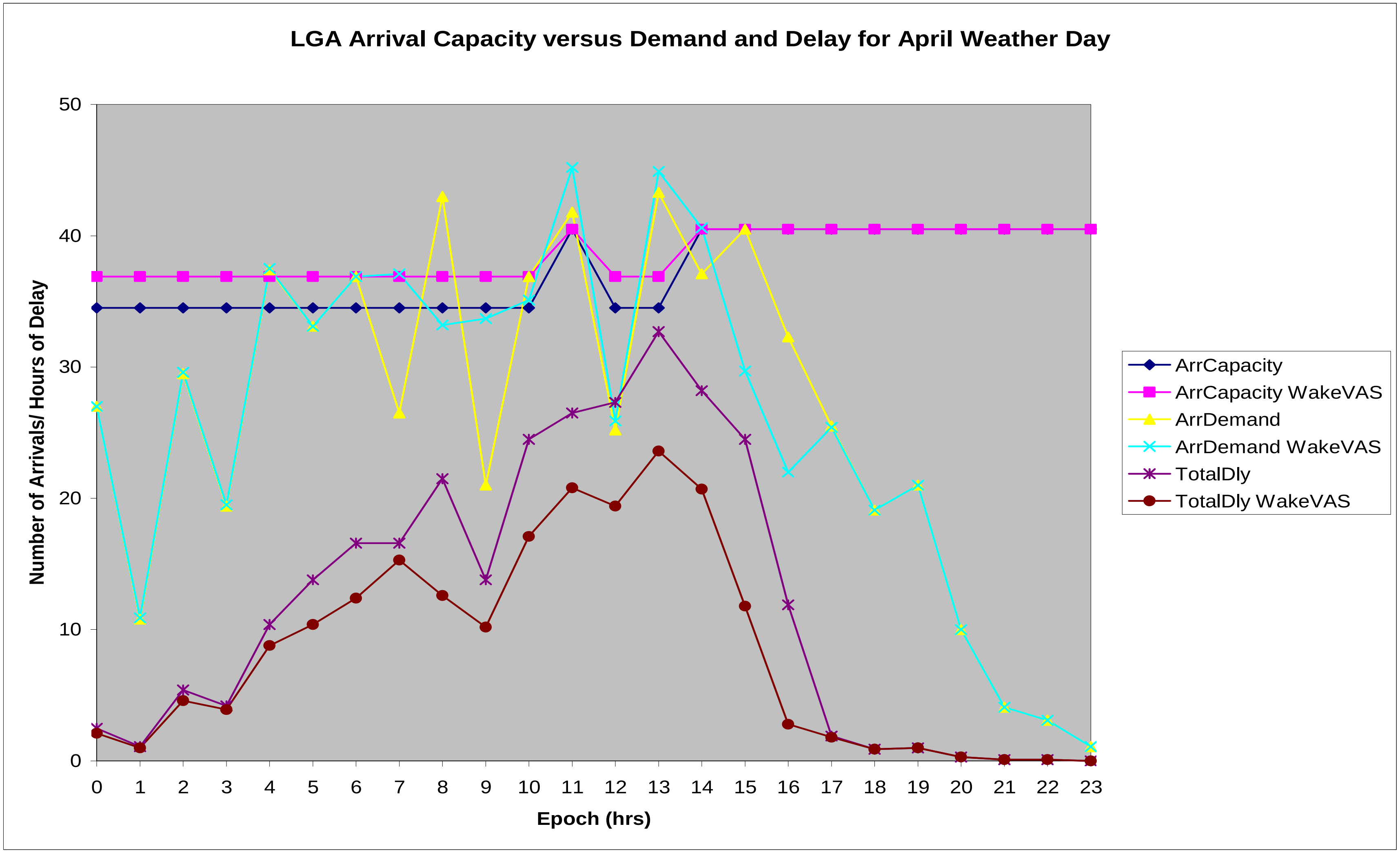

Figure 17: LGA 2010 Arrival Capacity versus Demand and Delay for April Weather Day

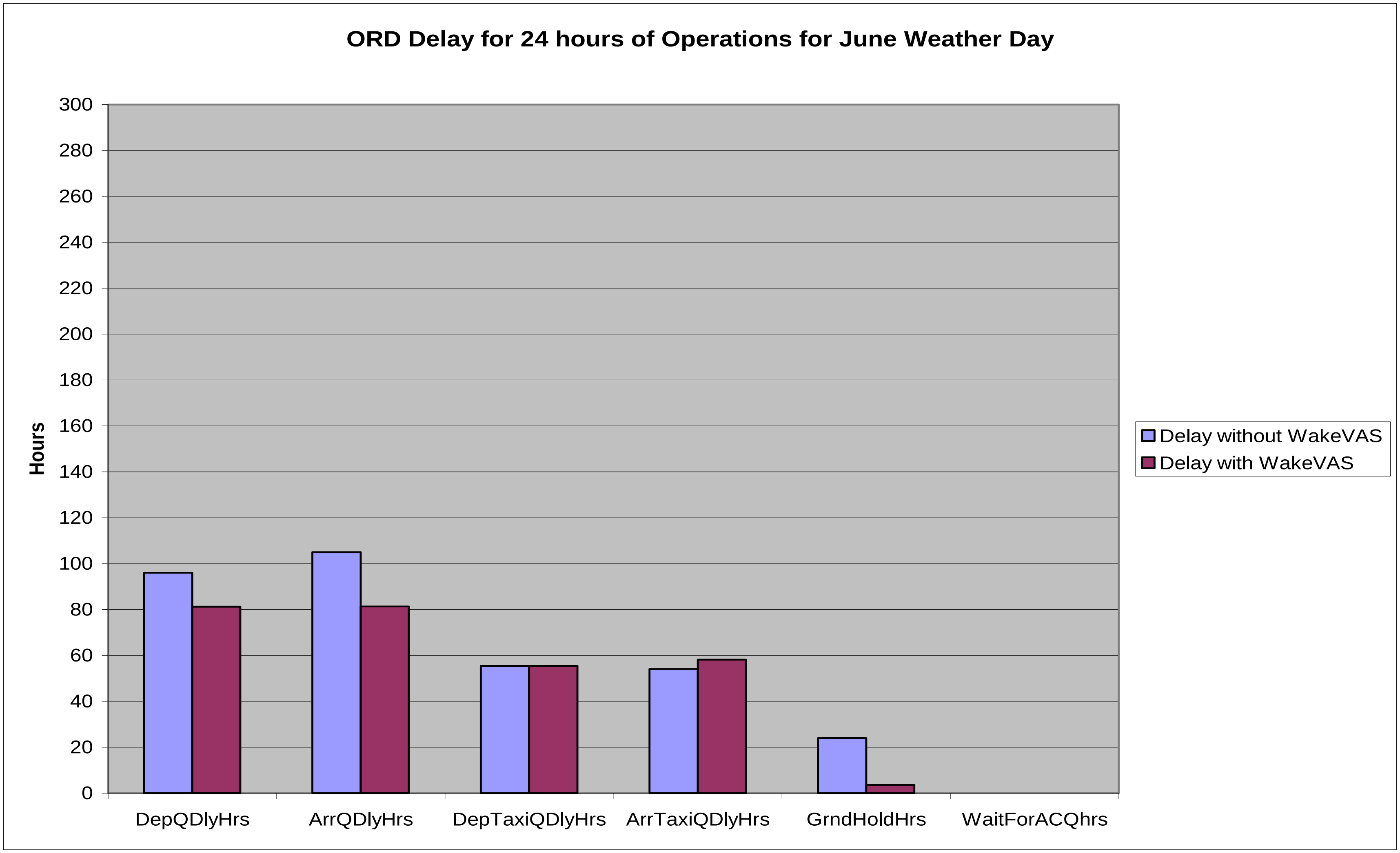

Figure 18: ORD 2010 Delay for June Weather Day

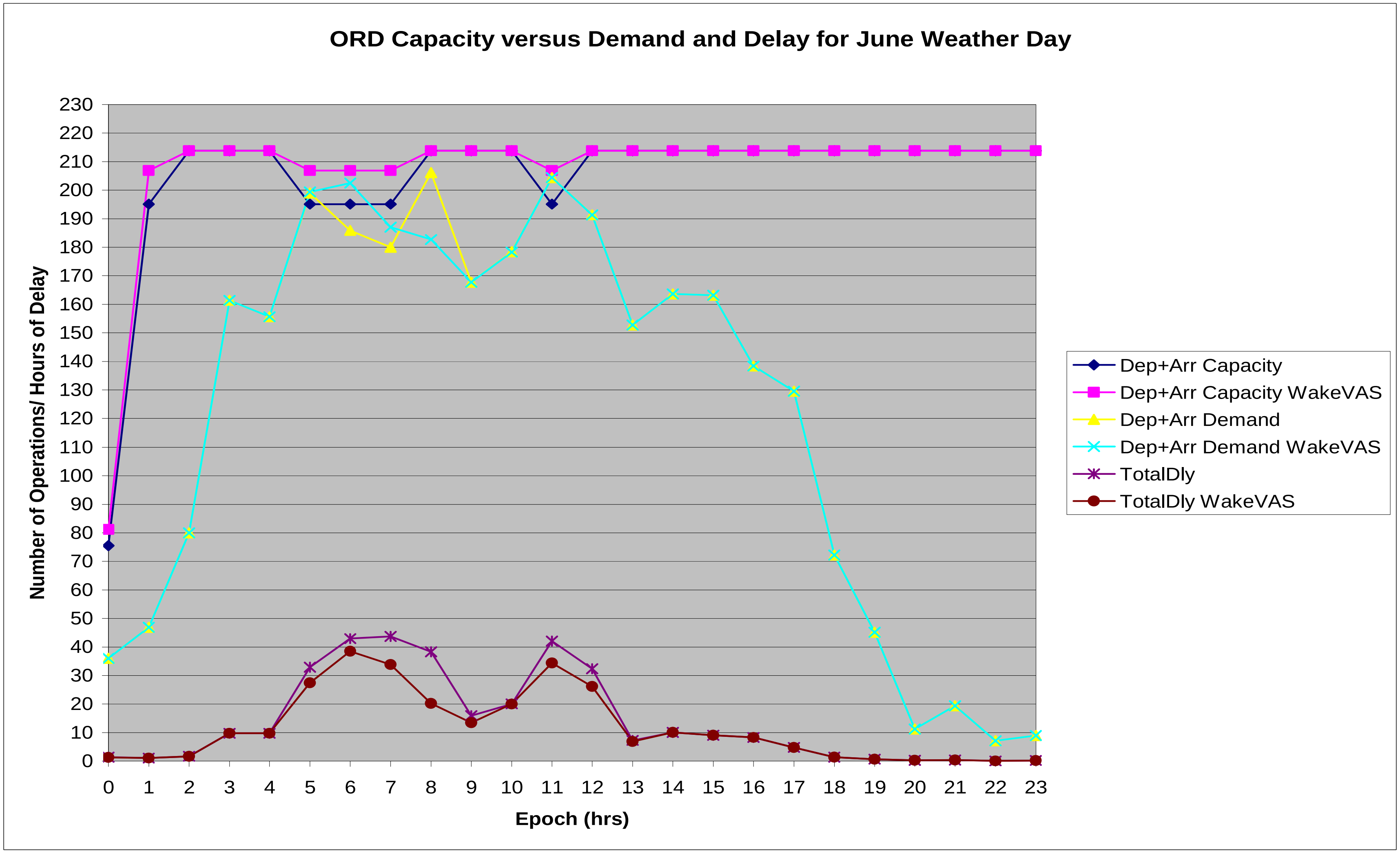

Figure 19: ORD 2010 Capacity versus Demand and Delay for June Weather Day

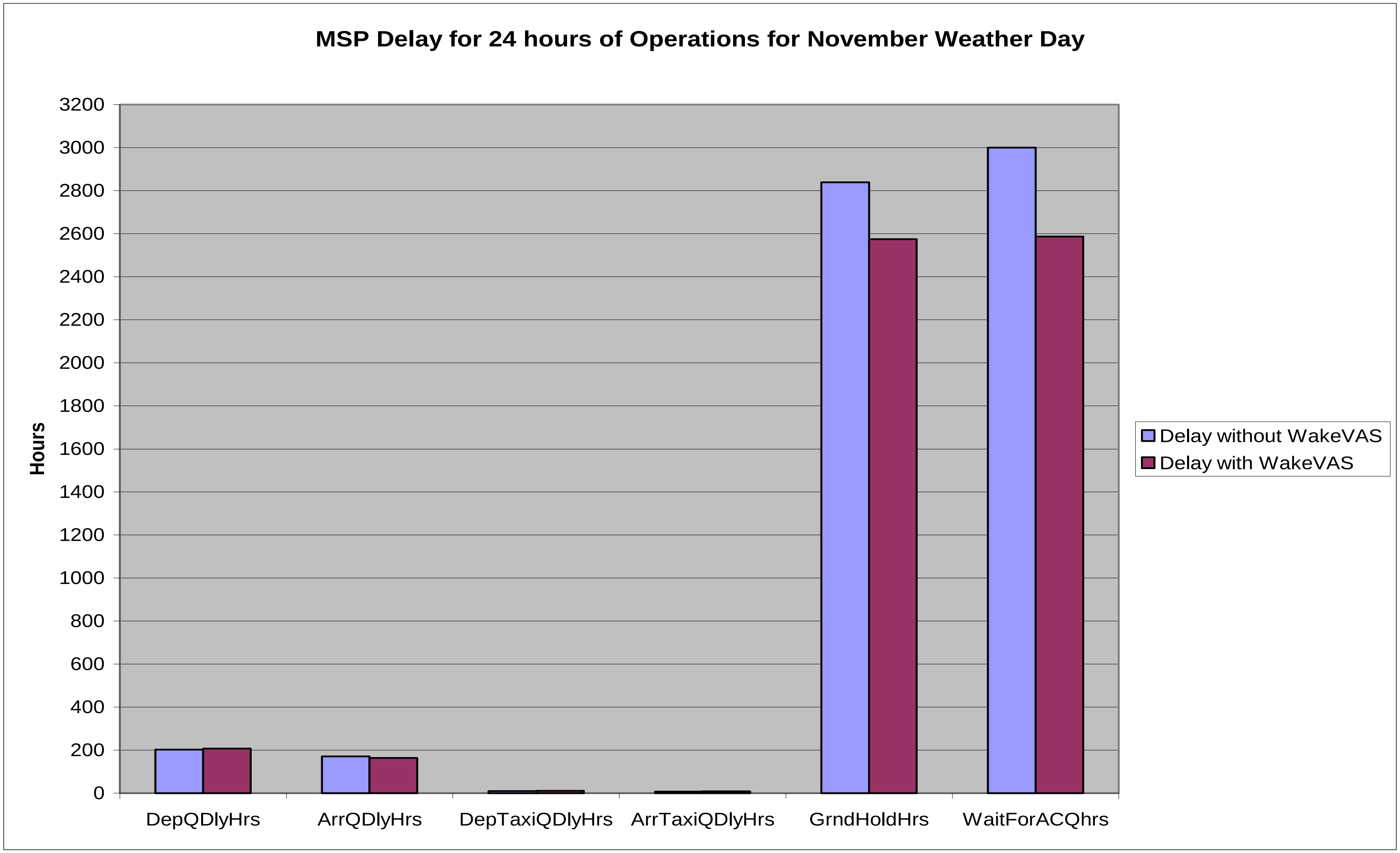

Figure 20: MSP 2010 Delay for November Weather Day

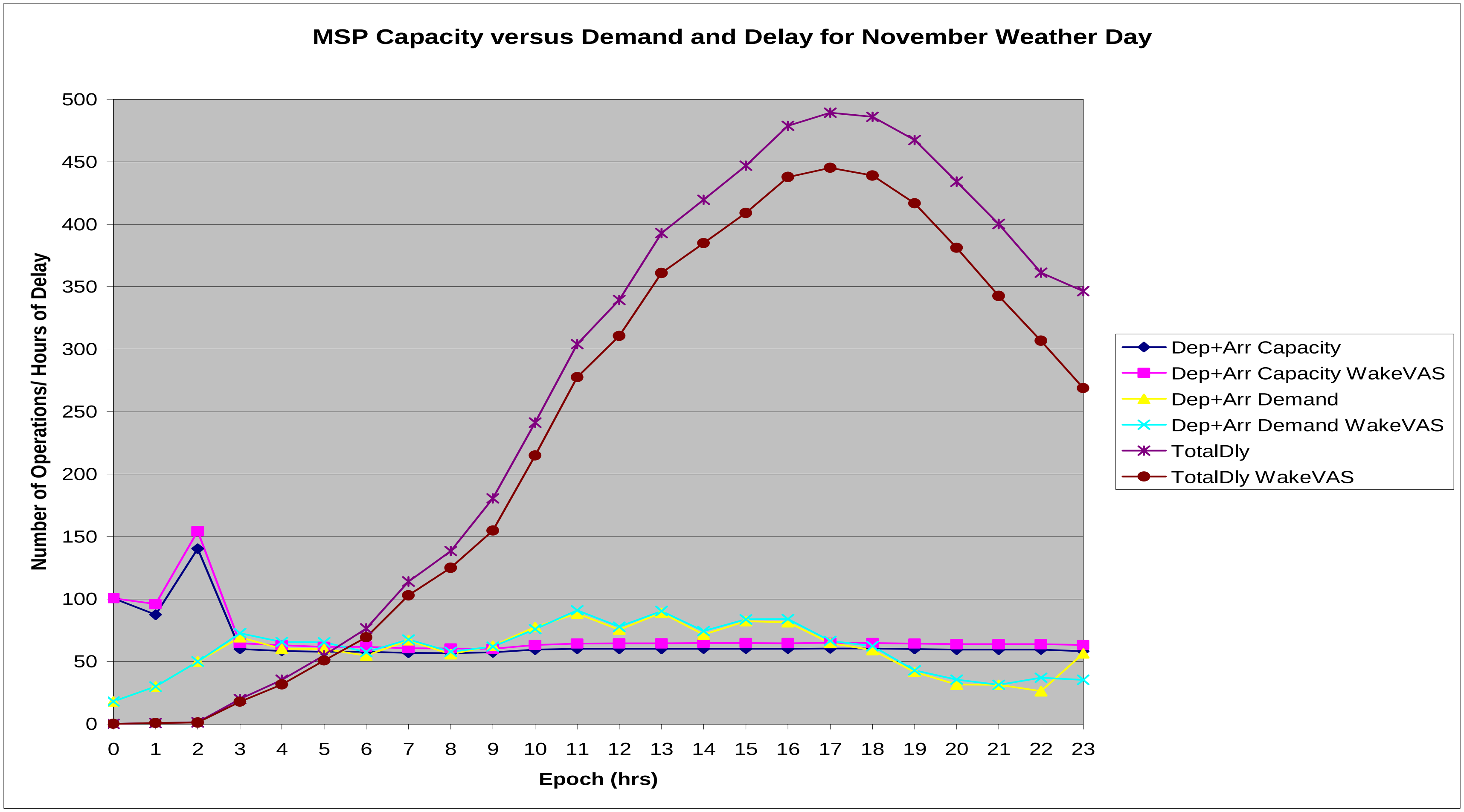

Figure 21: MSP 2010 Capacity versus Demand and Delay for November Weather Day

Estimated Air Carrier Cost Savings for 2010 Demand

The latest available data on air carrier costs are contained in reference 11. From this FAA sponsored source, the average air carrier variable operating cost for aircraft adjusted to 2004 $ is $2209 per hour in the air, $1702 on the ground with engines operating while taxiing or waiting for takeoff, and $852 while waiting in ground hold with engines off and only auxiliary power units operating. The reduced costs on the ground reflect 66% and 95% reduction in fuel/oil costs, respectively, compared to in the air consumption. The cost data used in this analysis are summarized in Table 22.

These values are used to calculate the estimated cost savings due to WakeVAS delay reduction, according to the flight segment where the delay occurred.

Weighted Annual NAS Wide Cost Savings Estimate

The results for each weather day must be weighted according to their probability of occurrence to obtain an unbiased estimate of annual delay reduction, because poor weather days occur far less frequently than fair weather days over all of the U.S. The weights used were: APR (0.13), JUN (0.8), NOV (0.07); as calculated by LMI, reference 10.

Figure 22 shows the weighted annual cost savings calculated using the weighted annual delay reduction values from Figure 7 and using the cost values calculated from reference 9. The cost savings range from $75 million if WakeVAS is used at the 12 study airports for arrivals only to as much as $165 million if WakeVAS is used at all of the 64 LMINET airports for arrivals and departures.

Estimated Annual Cost Savings at Selected Airports

The estimate of annual air carrier cost savings at individual airports is complicated by the network interactions and ripple effect of delays at airports other than the selected airport. In addition with the limited number of weather data sets used in this study it was not possible to select days with significant IMC for all of the 12 WakeVAS study airports. For this reason cost savings at only 3 of the airports were analyzed in detail.

An estimate of the annual air carrier cost savings at individual airports can be made by calculating the savings per non-VMC hour for a typical poor weather day and multiplying this value by the average number of IFR hours at the specific airport shown in Figure 1, obtained from reference 9.

The average airline operating cost per hour from reference 9 was further refined to estimate the cost per aircraft category as shown in Table 14. The traffic mix at the 3 airports selected for analysis is shown in Table 15.

For BOS for the April weather day, the cost saving is calculated to total $3220 per hour of non-VMC on this day which yields an estimated annual cost saving of $5.1 million if BOS is equipped with WakeVAS.

For LGA for the April weather day, the cost saving is calculated to be $4760 per hour of non-VMC on this day which yields an estimated annual cost saving of $8.3 million if LGA is equipped with WakeVAS.

For ORD for the June weather day, the cost saving is calculated to be $10236 per hour of non-VMC on this day which yields an estimated annual cost saving of $13.5 million if ORD is equipped with WakeVAS.

Aircraft Category	Airborne	Ground	Ground Hold
Small	$644	$532	$247
Large	$1,380	$1,057	$519
757	$1,980	$1,547	$780
Heavy	$3,977	$2,964	$1,468
All Aircraft	$2,209	$1,702	$852

Table 14: Air Carrier Variable Operating Costs in 2004$

Aircraft Category	BOS	LGA	ORD
Small	21.4%	19.4%	5.0%
Large	64.3%	72.4%	80.0%
757	9.2%	7.1%	9.0%
Heavy	5.1%	1.1%	6.0%

Table 15: Traffic Mix at Selected Airports

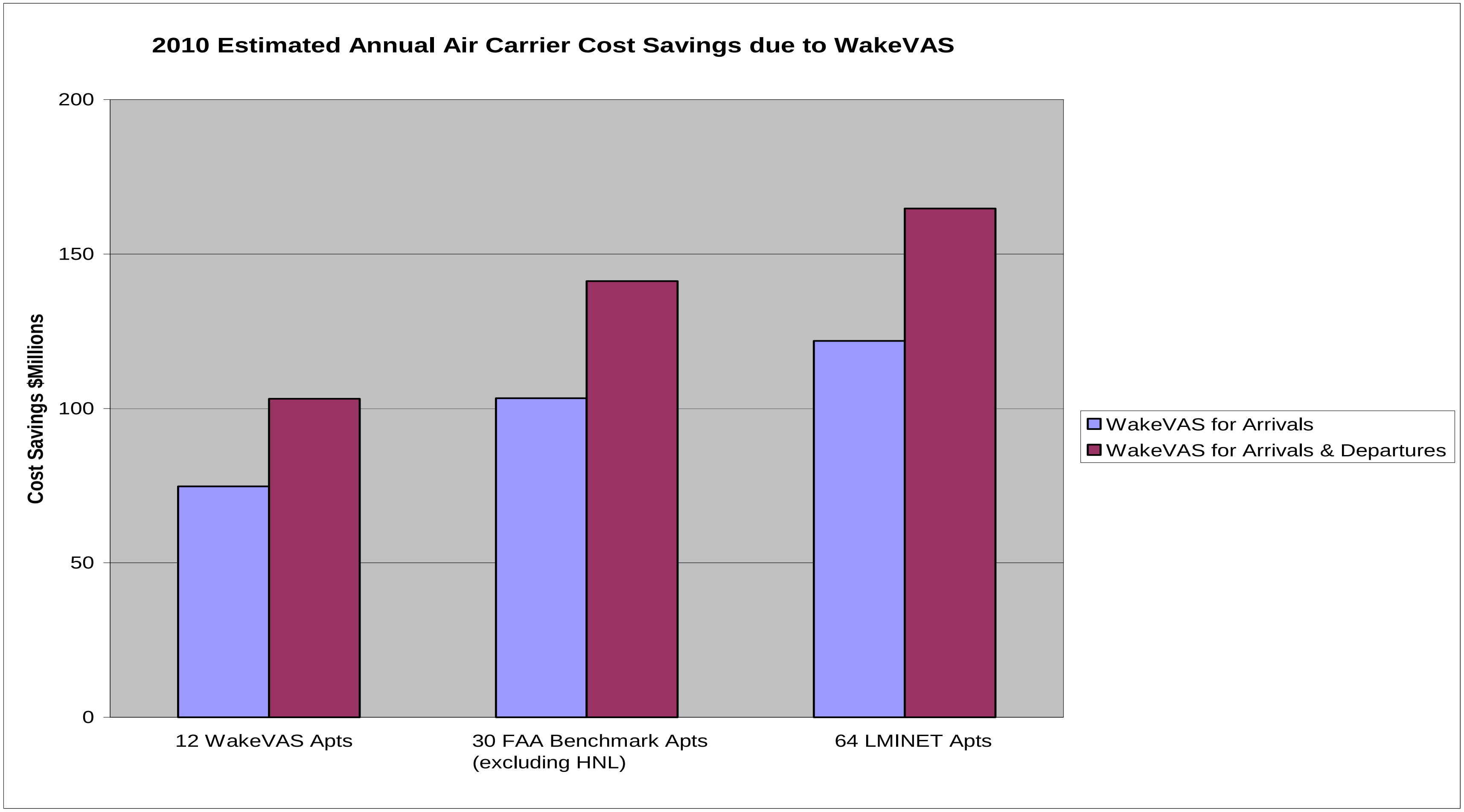

Figure 22: Estimated Annual Air Carrier Cost Savings for 2010 Demand

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14. ABSTRACT
This report is one of a series that describes an ongoing effort in high-fidelity modeling/simulation, evaluation and analysis of the benefits and performance metrics of the Wake Vortex Advisory System (WakeVAS) Concept of Operations being developed as part of the Virtual Airspace Modeling and Simulation (VAMS) project. A previous study, determined the overall increases in runway arrival rates that could be achieved at 12 selected airports due to WakeVAS reduced aircraft spacing under Instrument Meteorological Conditions. This study builds on the previous work to evaluate the NAS wide impacts of equipping various numbers of airports with WakeVAS. A queuing network model of the National Airspace System, built by the Logistics Management Institute, Mclean, VA, for NASA (LMINET) was used to estimate the reduction in delay that could be achieved by using WakeVAS under non-visual meteorological conditions for the projected air traffic demand in 2010. The results from LMINET were used to estimate the total annual delay reduction that could be achieved and from this, an estimate of the air carrier variable operating cost saving was made.

15. SUBJECT TERMS
Wake Vortex Advisory System; WakeVAS; Delay Reduction; National Airspace System; Virtual Airspace Modeling and Simulation Project; LMINET

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