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# Analysis of WakeVAS Benefits Using ACES Build 3.2.1

*Jeremy C. Smith*
*Swales Aerospace, Hampton, Virginia*

December 2005

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# Analysis of WakeVAS Benefits Using ACES Build 3.2.1

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# Summary

The FAA and NASA are currently engaged in a Wake Turbulence Research Program to revise wake turbulence separation standards, procedures, and criteria to increase airport capacity while maintaining or increasing safety. The research program is divided into three phases: Phase I – near term procedural enhancements; Phase II – wind dependant Wake Vortex Advisory System (WakeVAS) Concepts of Operations (ConOps); and Phase III – farther term ConOps based on wake prediction and sensing.

This report contains an analysis that evaluates the benefits of a closely spaced parallel runway (CSPR) Phase I ConOps, a single runway and CSPR Phase II ConOps and a single runway Phase III ConOps

Data from previous studies by NASA Langley (Phase III ConOps) and MITRE-CAASD (Phase II Conops) are the basis for the airport capacity increases due to WakeVAS used in this analysis. For the Phase I ConOps, an estimate was made of the arrivals rate increase that could be obtained by relaxation of the FAA rule that CSPRs with spacing between runways of less than 2500 ft must be treated as a single runway under Instrument Flight Rules conditions for separation purposes. The rule change would allow 1.5 nm diagonal spacing between aircraft on adjacent runways down to 1000 ft separation as currently used for runways spaced between 2500 ft – 4300 ft laterally. First, any category of aircraft was allowed to use 1.5nm diagonal spacing if following a large or small category aircraft. Secondly, restrictions were added to allow small and large aircraft to only follow small when using the rule change. For the purposes of this report the first version is termed the unrestricted rule change and the second the restricted rule change.

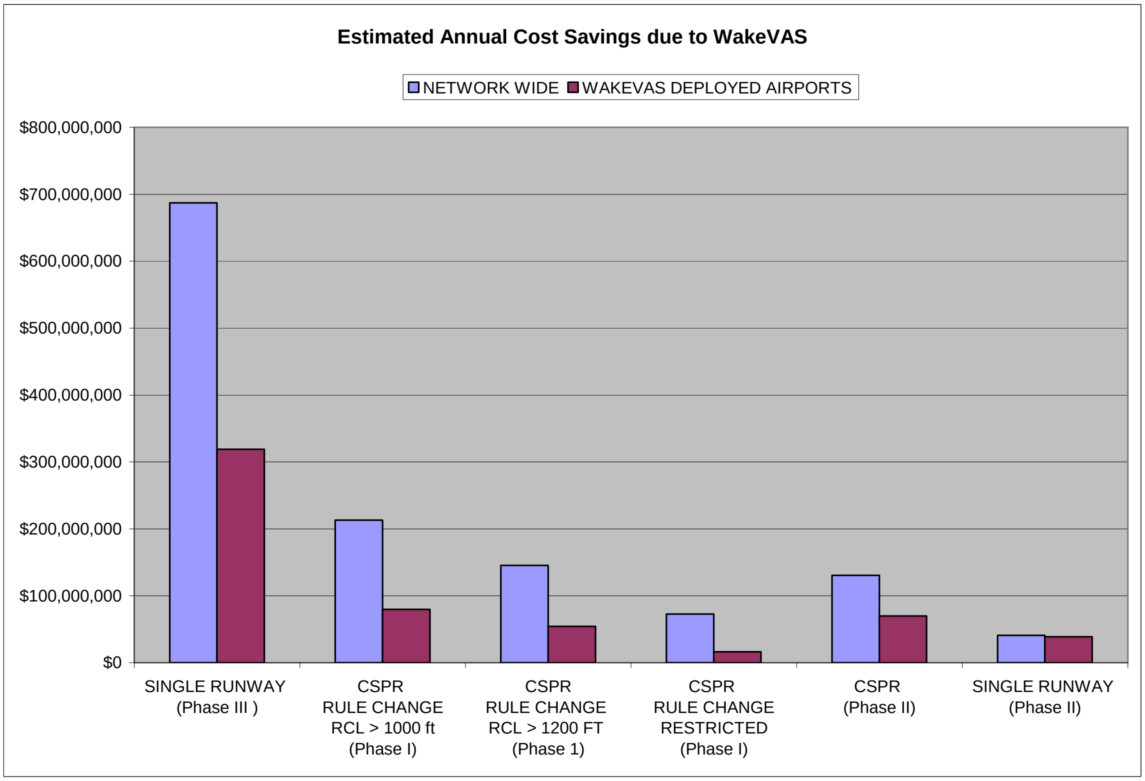
A series of simulation runs were performed using the Airspace Concepts Evaluation System (ACES) Build 3.21 air traffic simulator to provide an initial assessment of the reduction in delay and cost savings obtained by the use of a WakeVAS at selected U.S. airports. The ACES simulator is being developed by NASA Ames Research Center as part of the Virtual Airspace Modelling and Simulation (VAMS) program.

The annual airline cost savings from delay reductions due to the use of the WakeVAS ConOps at each of the selected airports were estimated from ACES simulation results. All simulation runs used a demand set containing approximately 1.4 times the current passenger enplanements. This represents the likely traffic load in the 2012 time frame.

The annual saving at an airport is the product of the saving obtained when WakeVAS is in use and the percentage of time that the ConOps would be available at that airport. The availability differs for each of the ConOps and depends on runway configuration, the proportion of visual to non-visual conditions, wind direction and strength and for the Phase III ConOps, other meteorological factors.

The figure below shows the estimated total annual airline cost savings due to the WakeVAS ConOps at 19 of the selected airports and the total network wide savings

which additionally includes airports having flights departing to, or arriving from any of the 19 airports.



The network wide total airline cost savings represent the total benefit to the airlines from WakeVAS deployment.

The largest annual network wide saving of **$687 million** occurs with use of the Phase III single runway ConOps, due to applicability to all of the airports studied and high availability obtained from the use of wake behaviour prediction using multiple meteorological factors, not just wind dependence.

The CSPR Phase I rule change ConOps is applicable to 9 of the 19 airports and saves an estimated **$213 million** for the unrestricted case as defined previously and **$72 million** for the more restricted rule change.

It is important to note that it has still to be verified from on-going research that using a rule change alone, without any wind dependence would allow the rule change to be fully applied down to 1000 ft lateral runway separation as assumed here. Increasing the runway lateral Runway Center Line (RCL) spacing requirement from 1000 ft to 1200 ft for the unrestricted case and allowing the use of the restricted rule down to 1000 ft gives a saving of **$145 million**. Further increasing the runway lateral spacing requirement to 1500 ft essentially reduces the benefit to that of the restricted case.

The savings for the restricted case are much reduced. This is almost entirely due to not allowing the rule change to apply to large following large aircraft. Aircraft in the large wake category make up the majority of flights (70% - 90%) at the busiest airports (except for JFK). Allowing small aircraft to use the 1.5nm diagonal spacing only when following another small category aircraft makes little difference, since the proportion of small category aircraft at the busiest airports is low (10% or less).

The CSPR Phase II wind dependant ConOps is applicable to 13 of the 19 airports and saves an estimated **$130 million.**

The single runway Phase II wind dependant ConOps is applicable to all airports studied, but saves a lesser amount of **$41 million** due to low availability caused by stringent requirements on wind conditions.

Included in the single runway ConOps savings are the savings due to substantial delay reductions at Chicago O'Hare (ORD). For the Phase III ConOps the ORD cost savings amounts to **$129 million** of the total savings. The Phase III ConOps result for ORD should be interpreted with caution, since the savings result from an excessive flight demand at ORD that imposes a mean delay of 81 minutes per flight operation under non-visual conditions. This excessive delay would not be tolerable in practice and measures would be taken to constrain the demand, so the benefits obtained from WakeVAS would likely be less at ORD than simulation suggests, since the baseline delay without WakeVAS would be less. However, the total network wide savings would still be substantial, even with a lower figure for the cost savings at ORD.

The Logistics Management Institute (LMI) published a business case analysis that contains an estimate of the costs for a Phase III WakeVAS including the wake vortex hardware and software and operating and support costs. The LMI report contains detailed cost estimates for SFO, DFW and STL only.

The cost to equip SFO or DFW is estimated to be $1.6 million for hardware and software and $280,000 per year for operation and support. For STL the costs estimates are $3.1 million for hardware and software and $690,000 per year for operation and support. The costs for implementing a wind dependant ConOps are not addressed by LMI but would be less than that for a Phase III system, since a wake sensing system is not needed.

Using these cost values, the savings that could be obtained by deployment of the WakeVAS Phase III single runway ConOps would yield a substantial overall benefit within the first year of operation at 16 of the 19 study airports. Assuming the cost of a Phase II wind dependent system is the same or less than for the Phase III system the CSPR ConOps would also yield a positive cost saving within the first year of operation at 11 of the 13 applicable airports.

The 19 airports analysed in this study were identified as having most potential for WakeVAS deployment from previous studies. WakeVAS single runway ConOps could be deployed at all of the 35 FAA benchmark airports. WakeVAS CSPR ConOps could be deployed at an additional 4 or 5 benchmark airports ((LAS, MCO, MDW, PIT) and possibly ATL. In addition there are airports not in the benchmark list which could have sufficient demand in the future to warrant deployment of WakeVAS.

An additional set of test cases analysed the benefits of using the Phase I ConOps rule change at the additional benchmark airports (LAS, MCO, MDW, PIT) and airports within the next 32 busiest category (OAK, OMA, SAT, SJC) with existing runways spaced between 1000 ft – 2500 ft. For the benchmark airports, the additional network wide cost saving was **$54 million** for the unrestricted case and **$21 million** for the restricted case. The additional saving for the next busiest non-benchmark airports was negligible, since the airports analysed are not capacity constrained at the future 1.4X demand level used for this study. However, if a higher demand level, for example 2X current operations, is reached in the farther term then the busiest of the non-benchmark airports could benefit from WakeVAS deployment.

# Acknowledgments

The author would like to acknowledge the work of the MITRE-CAASD team: Clark Lunsford, Laurence Audenaerd, Jillian Cheng, Chris Devlin, Amy Gross, Ralf Mayer, Anand Mundra, and Joe Sherry, which provides the basis for the wind-dependant Phase II ConOps airport capacity improvement factors and ConOps availability factors used in this current analysis.

The costs estimates of a Wake Vortex Advisory System are from a business case analysis by the Logistics Management Institute, Robert V. Hemm, Jeremy M. Eckhause, Virginia Stouffer, Dou Long and Jing Hees.

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# 1. Introduction

The FAA and NASA are currently engaged in a Wake Turbulence Research Program to revise wake turbulence separation standards, procedures, and criteria to increase airport capacity while maintaining or increasing safety.

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) Concepts of Operations (ConOps).

A series of simulation runs were performed using the Airspace Concepts Evaluation System (ACES) Build 3.21 air traffic simulator to provide an initial assessment of the reduction in delay and cost savings obtained by the use of a Wake Vortex Advisory System (Wake VAS) at U.S. airports.

The ACES simulator is being developed by NASA Ames Research Center as part of the Virtual Airspace Modelling and Simulation (VAMS) program. Reference 1 provides an overview of ACES.

The WakeVAS Concepts of Operations are described in a series of reports produced by a ConOps Evaluation Team, reference 2. The WakeVAS program is divided into three phases: Phase I – near term procedural enhancements; Phase II – wind dependant ConOps; and Phase III – farther term ConOps based on wake prediction and sensing.

This analysis evaluates the benefits of a single runway Phase III ConOps using data from a previous NASA Langley study, reference 3, a single runway and CSPR Phase II ConOps using data from a MITRE-CAASD study, reference 4 and a closely spaced parallel runway (CSPR) Phase I ConOps.

## 2. Airports for Analysis

The 19 Airports as used for the MITRE-CAASD study are included in this current analysis; all except for SDF are included in the FAA's benchmark list of the top 35 busiest airports in the U.S.

In addition to the 19 airport set, the benchmark airports (LAS, MCO, MDW, PIT) and the airports within the next 32 busiest category (OAK, OMA, SAT, SJC) with existing runways spaced between 1000 ft – 2500 ft were evaluated for benefits of the Phase I CSPR arrivals rule change ConOps.

Tables 1 and 2 show the selected airports and characterises the main runways at each airport.

The current day airport capacities used in the ACES simulator are shown in Table 3 for the 19 airports set. The capacity expected by 2010 including the FAA Operational Evolution Plan improvements documented in reference 5 are used as the basis for the WakeVAS evaluation in this analysis, as listed in Table 4 for the 19 airport set.

| **Airport** | **Code** | **Runways (Number, Type)** | **CSPR Spacing (ft)** |
|---|---|---|---|
| **19 Airport Set** | | | |
| Atlanta Hartsfield International | ATL | 5=2PR+NEWSGL | Not operated as CSPR pair |
| Boston Logan International | BOS | 4=CSPR+2INT+NEWSGL | 1500 |
| Cleveland Hopkins | CLE | 5=CSPR+INT+SGL+NEWSGL | 1240 |
| Charlotte/Douglas International | CLT | 3=PR+SGL | |
| Dallas-Fort Worth International | DFW | 6=2CSPR+2SGL | 1200 |
| Detroit Metro Wayne County | DTW | 5=CSPR+2INT+SGL | 2000 |
| Newark International | EWR | 3=CSPR+INT | 900 |
| George Bush Intercontinental | IAH | 4=CSPR+SGL+NEWSGL | 1000 |
| New York John F. Kennedy International | JFK | 4=PR+2SGL | |
| Los Angeles International | LAX | 4=2CSPR | 700 |
| New York LaGuardia | LGA | 2=2INT | |
| Memphis International | MEM | 4=CSPR+2SGL | 930 |
| Miami International | MIA | 3=CSPR+SGL | 800 |
| Chicago O’Hare International | ORD | 5=PR+3INT | |
| Philadelphia International | PHL | 4=CSPR+INT_SGL | 1400 |
| Louisville | SDF | 3=INT+2SGL | |
| Seattle-Tacoma International | SEA | 2=CSPR+NEWSGL | |
| San Francisco International | SFO | 4=2CSPR | 750 |
| Lambert St. Louis International | STL | 3=CSPR+INT+NEWSGL | 1300 |
| **Additional Benchmark** | | | |
| Cincinnati-Northern Kentucky Airport, Cincinnati, Ohio | CVG | 4=PR+INT+SGL+NEWSGL | |
| Washington National Airport, Washington, D. C. | DCA | 3=3INT | |
| Denver International Airport, Denver, Colorado | DEN | 5=PR+3SGL | |
| Fort Lauderdale/Hollywood International Airport, Florida | FLL | 3=INT+2GL | |
| Dulles International Airport, Washington, D. C. | IAD | 4=3SGL+NEWSGL | |
| McCarran International Airport, Las Vegas, Nevada | LAS | 4=2CSPR | 1000 |
| Los Angeles International Airport, Los Angeles, California | LAX | 4=2CSPR | 700 |
| Orlando International Airport, Orlando, Florida | MCO | 3=CSPR+SGL | 1600 |
| Midway Airport, Chicago, Illinois | MDW | 5=2CSPR+SGL | 1000 |
| Minneapolis-Saint Paul International Airport, Minneapolis-Saint Paul, Minnesota | MSP | 3=PR+INT+NEWSGL | |
| Portland International Airport, Portland, Oregon | PDX | 3=PR+INT | |
| Phoenix Sky Harbor International Airport, Phoenix, Arizona | PHX | 2=PR | |
| Pittsburgh International Airport, Pittsburgh, Pennsylvania | PIT | 4=CSPR+INT_SGL | 1200 |
| Lindbergh Field, San Diego, California | SAN | 1=SGL | |
| Salt Lake City International Airport, Utah | SLC | 3=PR+SGL | |
| Tampa International Airport, Florida | TPA | 3=PR+INT | |

**Table 1 FAA Benchmark Airports Data Set**

Key: CSPR – Closely Spaced Parallel Runway, PR – Parallel Runway, SGL – Single Runway, INT – Intersecting runway, NEW – New runway by 2010

| Airport | Code | Runways (Number, Type) | CSPR Spacing (ft) |
|---|---|---|---|
| Albuquerque | ABQ | 4=4INT | |
| Albany | ALB | 2=INT | |
| Anchorage | ANC | 3=CSPR+SGL | 750 |
| Austin | AUS | 2=PR | |
| Seattle | BFI | 1=SGL | |
| Birmingham | BHM | 2=2INT | |
| Nashville | BNA | 4=2INT+2SGL | |
| Port Columbus | CMH | 2=CSPR | 2900 |
| Dallas | DAL | 3=CSPR+INT | 3000 |
| Dayton | DAY | 3=PR+SGL | |
| Des Moines | DSM | 2=2INT | |
| Gerald Ford | GRR | 3=PR+INT | |
| Greensboro | GSO | 2=2SGL | |
| Houston | HOU | 4=CSPR+2INT | 750 |
| Westchester County | HPN | 2=2INT | |
| Indianapolis | IND | 3=PR+SGL | |
| Kansas City | MCI | 3=2SGL+INT | |
| General Mitchell | MKE | 3=3INT | |
| New Orleans | MSY | 2=2SGL | |
| Oakland | OAK | 3=CSPR+2INT | 1000 |
| Eppley | OMA | 3=CSPR+INT | 1000 |
| Ontario, CA | ONT | 2=CSPR | 750 |
| Norfolk | ORF | 3=CSPR+SGL | 750 |
| Palm Beach | PBI | 2=SGL+INT | |
| Raleigh Durham | RDU | 2=CSPR | 3400 |
| Richmond | RIC | 3=2SGL+INT | |
| Southwest Florida | RSW | 1=SGL | |
| San Antonio | SAT | 3=CSPR+SGL | 1000 |
| San Jose | SJC | 2=CSPR | 900 |
| Sacramento | SMF | 2=PR | |
| John Wayne | SNA | 1=SGL | |
| Teterboro | TEB | 2=SGL+INT | |

**Table 2 Highest Operations Non-Benchmark Airports**

Key: CSPR – Closely Spaced Parallel Runway, PR – Parallel Runway, SGL – Single Runway, INT – Intersecting runway, NEW – New runway by 2010

| Airport | Dep. VFR | Arr. VFR | Total VFR | Dep. IFR | Arr. IFR | Total IFR |
|---|---|---|---|---|---|---|
| **ATL** | 104 | 103 | 200 | 91 | 90 | 174 |
| **BOS** | 69 | 65 | 126 | 48 | 46 | 88 |
| **CLE** | 59 | 59 | 105 | 33 | 33 | 59 |
| **CLT** | 80 | 73 | 140 | 66 | 60 | 116 |
| **DFW** | 132 | 141 | 270 | 91 | 97 | 185 |
| **DTW** | 80 | 77 | 146 | 76 | 73 | 138 |
| **EWR** | 63 | 59 | 108 | 45 | 43 | 78 |
| **IAH** | 65 | 68 | 123 | 60 | 63 | 113 |
| **JFK** | 60 | 67 | 98 | 43 | 48 | 71 |
| **LAX** | 84 | 86 | 150 | 72 | 73 | 128 |
| **LGA** | 43 | 43 | 81 | 34 | 34 | 64 |
| **MEM** | 86 | 86 | 152 | 68 | 68 | 120 |
| **MIA** | 76 | 76 | 134 | 61 | 61 | 108 |
| **ORD** | 110 | 109 | 202 | 87 | 87 | 160 |
| **PHL** | 61 | 64 | 110 | 53 | 56 | 96 |
| **SDF** | 63 | 63 | 111 | 59 | 59 | 105 |
| **SEA** | 56 | 53 | 91 | 50 | 47 | 81 |
| **SFO** | 55 | 55 | 99 | 40 | 40 | 72 |
| **STL** | 62 | 63 | 112 | 36 | 36 | 65 |

**Table 3 Current Airport Capacity (operations per hour)**

| Airport | Dep. VFR | Arr. VFR | Total VFR | Dep. IFR | Arr. IFR | Total IFR |
|---|---|---|---|---|---|---|
| **ATL** | 139 | 138 | 269 | 120 | 119 | 231 |
| **BOS** | 71 | 67 | 131 | 49 | 47 | 91 |
| **CLE** | 59 | 59 | 105 | 33 | 33 | 59 |
| **CLT** | 102 | 93 | 179 | 80 | 73 | 142 |
| **DFW** | 137 | 146 | 281 | 110 | 117 | 224 |
| **DTW** | 104 | 100 | 191 | 93 | 89 | 170 |
| **EWR** | 68 | 63 | 117 | 47 | 45 | 83 |
| **IAH** | 91 | 95 | 173 | 84 | 88 | 159 |
| **JFK** | 61 | 68 | 100 | 44 | 49 | 73 |
| **LAX** | 98 | 100 | 175 | 74 | 75 | 133 |
| **LGA** | 47 | 47 | 89 | 35 | 35 | 66 |
| **MEM** | 88 | 88 | 157 | 70 | 70 | 124 |
| **MIA** | 93 | 93 | 164 | 75 | 75 | 134 |
| **ORD** | 115 | 114 | 213 | 97 | 97 | 179 |
| **PHL** | 70 | 73 | 127 | 58 | 61 | 106 |
| **SDF** | 63 | 63 | 111 | 59 | 59 | 105 |
| **SEA** | 87 | 82 | 142 | 74 | 70 | 121 |
| **SFO** | 55 | 55 | 99 | 41 | 41 | 74 |
| **STL** | 77 | 78 | 140 | 67 | 67 | 122 |

**Table 4 OEP 2010 Enhanced Airport Capacity (operations per hour)**

# 3. Demand Sets

The demand data sets used for this analysis are derived from an ACES data set based on ETMS recorded data from 17 May 2002. This original set contained 62,589 flights, from which 2,480 military flights were removed leaving a baseline of 60,109 flights.

A demand set containing approximately 1.4 times the passenger enplanements of 17 May 2002 traffic was created, which represents the likely traffic load in the 2012 time frame. This demand set was generated using demographic-based models of future air traffic growth and a schedule generation code, references 6, 7.

A demand set supplied with ACES containing approximately 2 times the 2002 traffic was evaluated for use in this analysis but the 2X level of demand severely overloads the airports and generates excessive delays when using the OEP 2010 airport capacities as the basis for capacity, even with WakeVAS capacity improvements. A detailed analysis of delay versus demand and capacity is contained in section 7.

All flights which departed from or arrived at any of the airports for analysis were extracted and used for the ACES simulation runs. The entire demand set could not be used because ACES is a computationally intensive simulation and computing resources limited the total number of flights that could be included. The actual load on each of the study airports is correct, however, since all airports which are not part of the study set, but have flights departing to, or arriving from one of the study airports are included in the simulation. This analysis assumed unlimited airspace capacity, since the purpose of this study is to investigate the benefits of increased airport capacity.

The total number of flights included in each demand set is shown in Table 5. The 1.4X, 19 Airport demand set was used to evaluate the benefits of WakeVAS capacity improvements using the OEP 2010 airport capacities as the basis for comparison. Table 6 shows the 24 hour total demand for the 1.4X data set and traffic mix at each of the 19 study airports. Demand data was also generated for the additional airports evaluated for the Phase I rule change ConOps.

| Demand Set | Total Flights |
|---|---|
| 17 May 2002 All Airports | 60,109 |
| 17 May 2002, 19 Airports | 21,984 |
| 1.4X All Airports | 85,221 |
| 1.4X 19 Airports | 32,280 |

**Table 5 Demand Set Flight Totals**

| Airport | Total Operations | %small | %large | %b757 | %heavy |
|---|---|---|---|---|---|
| **ATL** | 4032 | 3.2 | 72.4 | 13.3 | 11.1 |
| **BOS** | 1815 | 5.3 | 76.1 | 10.1 | 8.5 |
| **CLE** | 1049 | 5.2 | 93.6 | 0.2 | 1.0 |
| **CLT** | 2290 | 6.9 | 86.9 | 4.1 | 2.1 |
| **DFW** | 3230 | 8.2 | 77.3 | 10.0 | 4.5 |
| **DTW** | 2096 | 3.6 | 86.1 | 6.9 | 3.4 |
| **EWR** | 1746 | 1.9 | 76.8 | 10.1 | 11.2 |
| **IAH** | 1957 | 2.8 | 89.3 | 4.6 | 3.3 |
| **JFK** | 871 | 2.0 | 45.1 | 8.3 | 44.7 |
| **LAX** | 2376 | 1.1 | 68.1 | 13.8 | 16.9 |
| **LGA** | 1410 | 2.7 | 88.2 | 7.6 | 1.5 |
| **MEM** | 1814 | 11.4 | 68.4 | 0.9 | 19.3 |
| **MIA** | 1611 | 3.8 | 66.0 | 11.7 | 18.5 |
| **ORD** | 4052 | 8.1 | 78.3 | 6.5 | 7.1 |
| **PHL** | 1837 | 6.8 | 83.5 | 5.1 | 4.6 |
| **SDF** | 631 | 7.3 | 58.6 | 8.6 | 25.5 |
| **SEA** | 1314 | 2.1 | 82.4 | 9.1 | 6.3 |
| **SFO** | 1284 | 3.4 | 65.0 | 15.6 | 16.0 |
| **STL** | 1910 | 6.9 | 84.6 | 6.5 | 2.0 |

**Table 6 Number of Operations and Traffic Mix for 1.4X Demand at 19 Airports**

# 4. WakeVAS Capacity Improvements

### *Single Runway using Wake Transport and Demise (Phase III ConOps)*

The expected capacity improvements from the use of a Wake Vortex Advisory System to reduce separations between aircraft using the same runway have been estimated from a previous study, reference 3. The proposed WakeVAS system uses an algorithm to predict wake behaviour based on local meteorological conditions and measurement sensors to confirm the accuracy of the predictions. This system corresponds to a Phase III ConOps.

The mean runway arrival rate improvement for the 12 airports analyzed for the previous study, averaged over 6 days of differing weather data compared to the non-visual arrival rate varied between 4.5% and 19% for each airport runway, with an overall mean improvement of 10%, averaged over all of the runways for the 12 airports from the previous study.

Reduced departure time based spacing was also generated from the wake model, but analysis of the data showed a large variance in the spacing. For this reason an assumed runway departure rate improvement of 5% was used for this current analysis.

Figure 1 shows the strong correlation between the runway arrival rate improvement obtained from the Phase III single runway WakeVAS ConOps and the percentage of heavy + B757 aircraft. This confirms, as expected, that the greatest benefit from reduced wake spacing will be obtained at airports with significant percentages of heavy and/ or B757 aircraft, since these categories of aircraft generate the largest wakes. A regression analysis of the dependence of runway arrival rate improvement on percentage of heavy + B757 aircraft gave the equation shown on the chart with an $R^2 = 0.8$, indicating that approximately 80% of the systematic variance of the runway arrival rate improvement can be estimated from the percentage of heavy + B757 aircraft within the bounds of the data analyzed. Note that it is important not to extrapolate the regression line fit much beyond the bounds of the data analyzed; for the 19 airport data set, the maximum percentage of heavy + B757 aircraft is 53% at JFK. This is a reasonable extrapolation beyond the bounds of the regression analysis. All other airports are within bounds.

The regression equation of Figure 1 was used to predict the improvement that might be expected for each of the 19 airports used in this current study, based on the traffic mix at each airport in the demand set. The arrival rate improvement was only applied under non-visual conditions, since using visual approach procedures pilots are responsible for wake separation. As previously stated a 5% improvement in departure rate was assumed, and this was applied under both IMC and VMC since departure wake separation rules between heavy and B757 aircraft and smaller aircraft are applied at all times. Table 7 shows the estimated improvement factors. Table 8 shows the corresponding enhanced airport capacities, calculated by applying the improvement factors to the OEP airport capacities from Table 4.

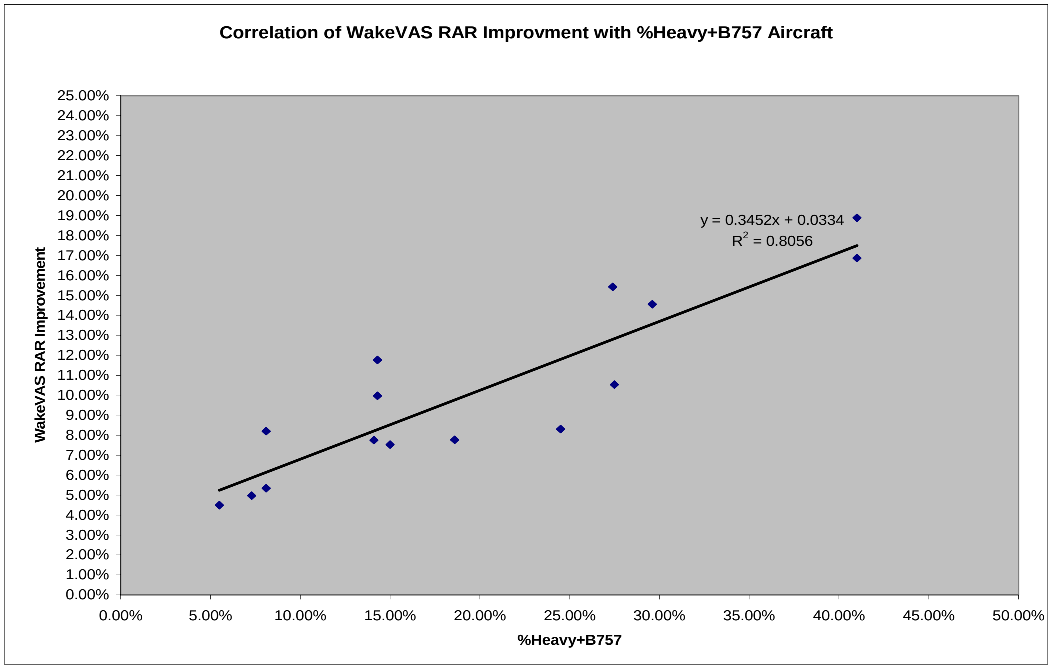

**Figure 1 Single Runway Non-Visual Arrivals Improvement (Phase III) Correlation with Traffic Mix**

| **Airport** | **Visual Departures Increase%** | **Visual Arrivals Increase%** | **Non-Visual Departures Increase%** | **Non-Visual Arrivals Increase%** |
|---|---|---|---|---|
| **ATL** | 5.0 | 0.0 | 5.0 | 12.0 |
| **BOS** | 5.0 | 0.0 | 5.0 | 9.6 |
| **CLE** | 5.0 | 0.0 | 5.0 | 3.8 |
| **CLT** | 5.0 | 0.0 | 5.0 | 5.6 |
| **DFW** | 5.0 | 0.0 | 5.0 | 8.5 |
| **DTW** | 5.0 | 0.0 | 5.0 | 6.7 |
| **EWR** | 5.0 | 0.0 | 5.0 | 10.7 |
| **IAH** | 5.0 | 0.0 | 5.0 | 6.3 |
| **JFK** | 5.0 | 0.0 | 5.0 | 21.4 |
| **LAX** | 5.0 | 0.0 | 5.0 | 13.9 |
| **LGA** | 5.0 | 0.0 | 5.0 | 6.5 |
| **MEM** | 5.0 | 0.0 | 5.0 | 11.3 |
| **MIA** | 5.0 | 0.0 | 5.0 | 14.1 |
| **ORD** | 5.0 | 0.0 | 5.0 | 8.2 |
| **PHL** | 5.0 | 0.0 | 5.0 | 6.8 |
| **SDF** | 5.0 | 0.0 | 5.0 | 14.8 |
| **SEA** | 5.0 | 0.0 | 5.0 | 8.5 |
| **SFO** | 5.0 | 0.0 | 5.0 | 14.2 |
| **STL** | 5.0 | 0.0 | 5.0 | 6.4 |
| **Mean** | **5.0** | **0.0** | **5.0** | **10.0** |

**Table 7 Single Runway Arrival and Departure Rates Improvement (Phase III) *(estimated from regression analysis)***

| Airport | Dep. VFR | Arr. VFR | Total VFR | Dep. IFR | Arr. IFR | Total IFR |
|---|---|---|---|---|---|---|
| **ATL** | 146 | 138 | 276 | 126 | 133 | 251 |
| **BOS** | 75 | 67 | 135 | 51 | 51 | 97 |
| **CLE** | 62 | 59 | 108 | 35 | 34 | 62 |
| **CLT** | 107 | 93 | 184 | 84 | 77 | 150 |
| **DFW** | 144 | 146 | 288 | 116 | 127 | 240 |
| **DTW** | 109 | 100 | 196 | 98 | 95 | 181 |
| **EWR** | 71 | 63 | 120 | 49 | 50 | 90 |
| **IAH** | 96 | 95 | 178 | 88 | 93 | 168 |
| **JFK** | 64 | 68 | 103 | 46 | 59 | 85 |
| **LAX** | 103 | 100 | 180 | 78 | 85 | 147 |
| **LGA** | 49 | 47 | 91 | 37 | 37 | 70 |
| **MEM** | 92 | 88 | 161 | 74 | 78 | 136 |
| **MIA** | 98 | 93 | 169 | 79 | 86 | 149 |
| **ORD** | 121 | 114 | 219 | 102 | 105 | 192 |
| **PHL** | 74 | 73 | 131 | 61 | 65 | 113 |
| **SDF** | 66 | 63 | 114 | 62 | 63 | 112 |
| **SEA** | 91 | 82 | 146 | 78 | 76 | 131 |
| **SFO** | 58 | 55 | 102 | 43 | 47 | 82 |
| **STL** | 81 | 78 | 144 | 70 | 71 | 129 |

**Table 8 Airport Capacities with WakeVAS Single Runway Arrivals and Departure Rates Improvement (Phase III)**

### *Single Runway and Closely Spaced Parallel Runways using Wind Dependant Wake Transport (Phase II ConOps)*

MITRE-CAASD performed a study to analyse WakeVAS procedures for potential benefits, development and implementation risks, see reference 4. Data from this report, summarised in Tables 9, 10, were used to estimate the capacity improvements that might be obtained at each of the 19 airports analysed in this current study.

Since the data from reference 4 does not provide a complete set for all of the airports of interest, a regression analysis was performed on the available data to determine if a strong correlation between the traffic mix and capacity benefit could be determined as was done in the NASA Langley study, reference 3. The use of a regression equation to predict the capacity improvement also has other advantages, it smoothes the experimental variation found in the results from different airports and it allows for a change in traffic mix to be taken into account since the current study uses a different demand data set from the MITRE-CAASD study.

Figures 2 to 7 show the correlation between capacity improvement and traffic mix for the single runway and CSPR arrival and departure ConOps. There is a high degree of correlation for all except the CSPR arrival ConOps (Figure 5) where there is no evidence of any correlation. The CSPR arrival ConOps allows independent operation of the runways under non-visual conditions. The main effect of this ConOps is to allow two arrival streams whereas for the single runway and CSPR departure ConOps the main effect is to allow reduced spacing between aircraft in the same arrival/ departure stream. This would explain the lack of dependence on traffic mix for the CSPR arrivals ConOps. For this ConOps only, the actual improvement value obtained by MITRE-CAASD is used where available and the mean value used for airports with CSPRs not included in the MITRE-CAASD study. For all other ConOps the appropriate regression equation is used to estimate the improvement factors, shown in Tables 11, 12. The corresponding airport capacity values are shown in Tables 13, 14.

| AIRPORT | PHASE II SINGLE RUNWAY ARRIVALS STRAIGHT OUT | PHASE II SINGLE RUNWAY DEPARTURES STRAIGHT OUT | |
|---|---|---|---|
| | NON-VISUAL (Arrivals per hr) %Increase | VISUAL (Dept. per hr) %Increase | NON-VISUAL (Dept. per hr) %Increase |
| **ATL** | (3.5) 11.0% | (3.0) 5.5% | (2.0) 5.0% |
| **BOS** | (4.0) 13.0% | (3.0) 5.5% | (2.0) 5.0% |
| **CLE** | | | |
| **CLT** | (2.0) 6.0% | (1.0) 2.0% | (1.0) 2.5% |
| **DFW** | (2.0) 6.0% | (1.0) 2.0% | (1.0) 2.5% |
| **DTW** | | | |
| **EWR** | (2.5) 8.0% | (5.0) 10.0% | (2.0) 5.0% |
| **IAH** | | | |
| **JFK** | (4.5) 16.0% | (6.0) 13.5% | (6.0) 15.5% |
| **LAX** | (6.0) 20.0% | (5.0) 10.5% | (4.0) 10.5% |
| **LGA** | (2.0) 6.0% | (1.0) 2.0% | (1.0) 2.5% |
| **MEM** | | | |
| **MIA** | | | |
| **ORD** | (2.0) 6.0% | (2.0) 3.5% | (1.0) 2.5% |
| **PHL** | | | |
| **SDF** | (6.0) 20.0% | (5.0) 10.5% | (3.0) 7.5% |
| **SEA** | | | |
| **SFO** | | | |
| **STL** | | | |
| **Mean** | **11%** | **6.5%** | **5.8%** |

**Table 9 Single Runway Arrival and Departure Rates Improvement (Phase II)**
*(From MITRE-CAASD reference 4, Figure 3-4, straight in arrivals from FAF, Figures 3-8a, 3-8b straight out departures.)*

| AIRPORT | PHASE II CSPR ARRIVALS UPWIND WAKE-FREE | PHASE II CSPR DEPARTURES STRAIGHT OUT | |
|---|---|---|---|
| | NON-VISUAL (Arrivals per hr) %Increase | VISUAL (Dept. per hr) %Increase | NON-VISUAL (Dept. per hr) %Increase |
| **ATL** | | | |
| **BOS** | (6.5) 14% | (3.0) 4.5% | (1.0) 2.0% |
| **CLE** | (6) 18% | (0.5) 1.0% | (0.0) 0.0% |
| **CLT** | | | |
| **DFW** | | (2.0) 1.5% | (0.5) 0.5% |
| **DTW** | (6) 8% | (2.0) 2.5% | (0.5) 0.5% |
| **EWR** | (7.5) 17.5 | (4.0) 6.5% | (1.5) 3.5% |
| **IAH** | | | |
| **JFK** | | (2.0) 3.0% | (0.5) 1.0% |
| **LAX** | (7.0) 9.5% | (5.0) 6.0% | (2.0) 2.5% |
| **LGA** | | | |
| **MEM** | | (4.0) 4.5% | (1.5) 2.0% |
| **MIA** | | (5.0) 6.5% | (2.0) 3.0% |
| **ORD** | | | |
| **PHL** | (6.0) 10.5% | (2.5) 4.0% | (0.5) 1.0% |
| **SDF** | | | |
| **SEA** | (6.0) 12.5% | (2.5) 4.5% | (0.5) 1.0% |
| **SFO** | (8.0) 20% | (5.0) 9% | (2.0) 5.0% |
| **STL** | (6.0) 16.5% | (0.5) 1% | (0.0) 0.0% |
| **Mean** | **14%** | **4.2%** | **1.7%** |

**Table 10 CSPR Arrival and Departure Rates Improvement (Phase II)**
*(From MITRE-CAASD reference 4, Figure 3-7, upwind wake-free arrivals, Figure 3-13, straight out departures.)*

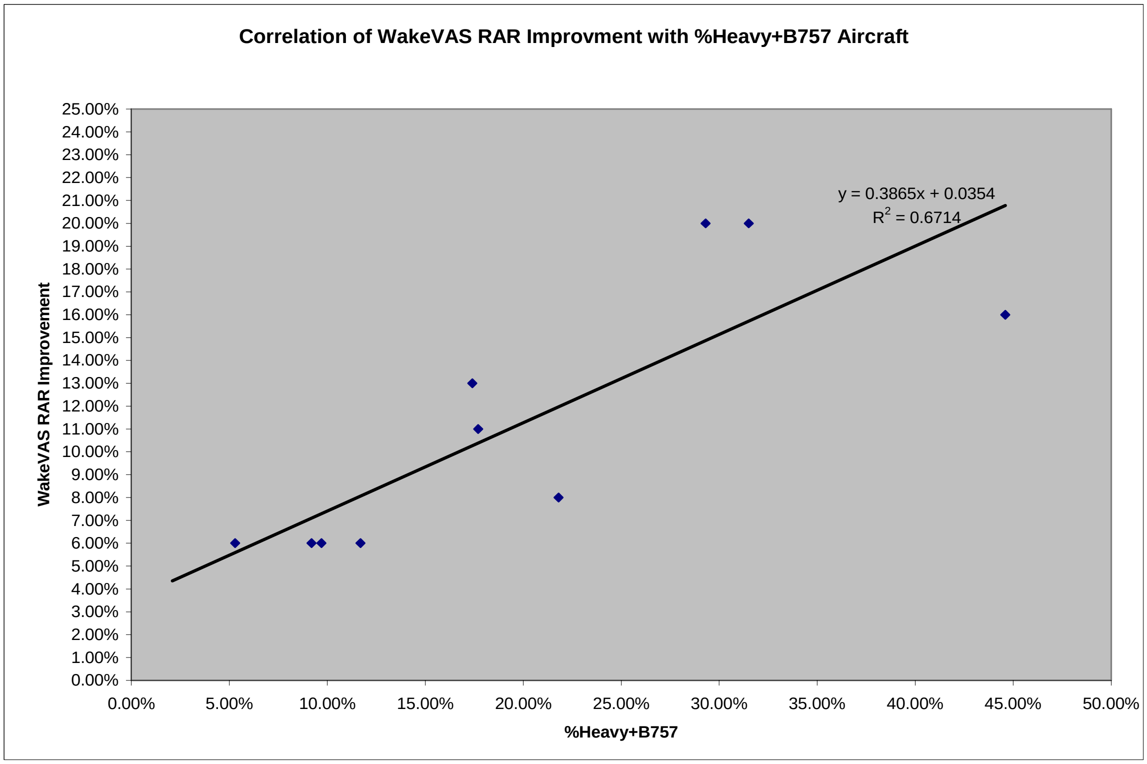

Figure 2 Single Runway Non-Visual Arrivals Improvement (Phase II) Correlation with Traffic Mix

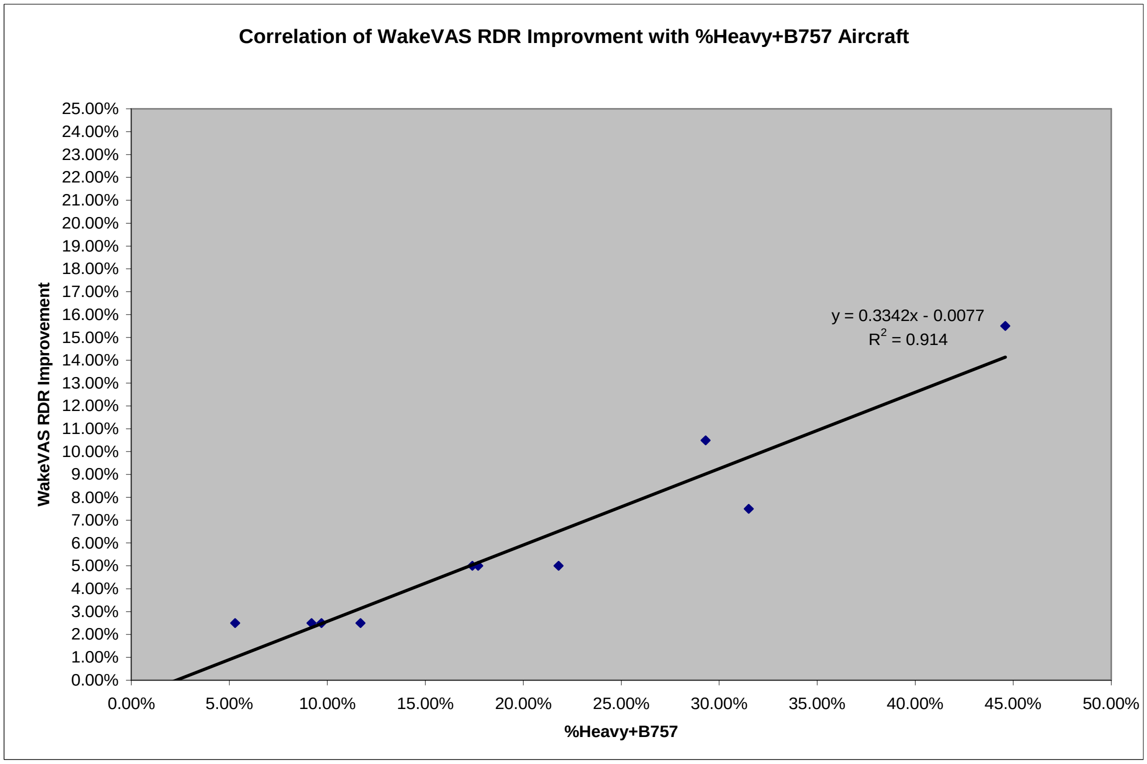

Figure 3 Single Runway Non-Visual Departure Improvement (Phase II) Correlation with Traffic Mix

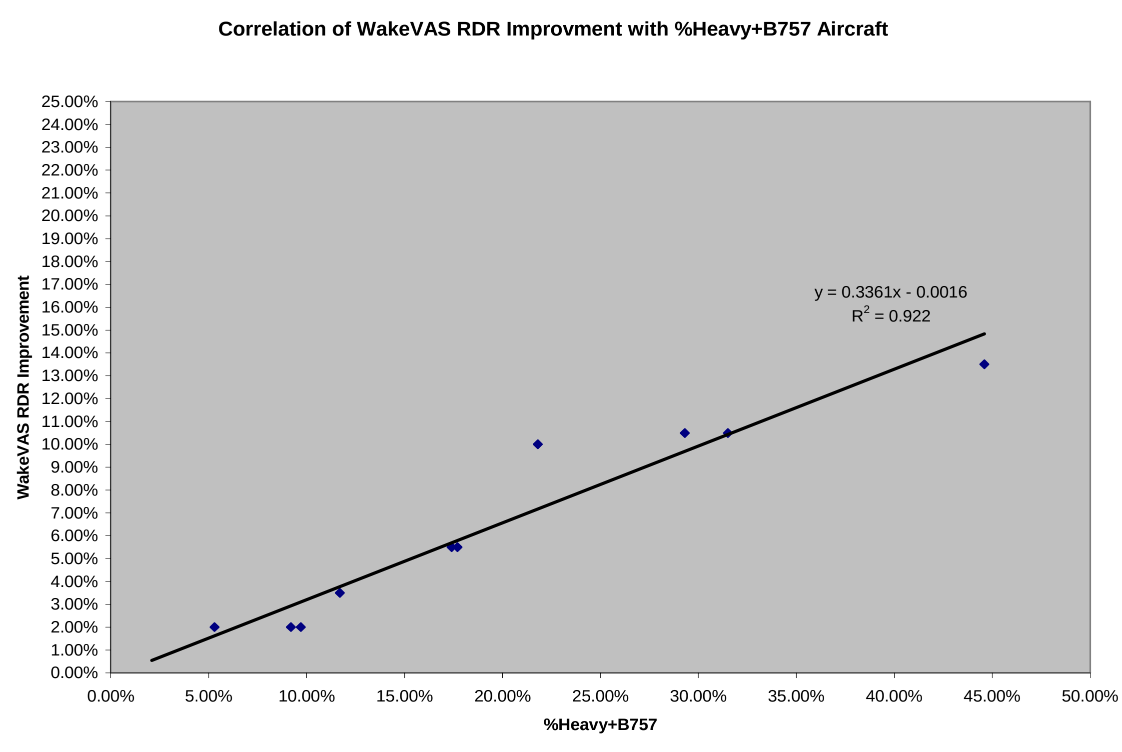

**Figure 4 Single Runway Visual Departure Improvement (Phase II) Correlation with Traffic Mix**

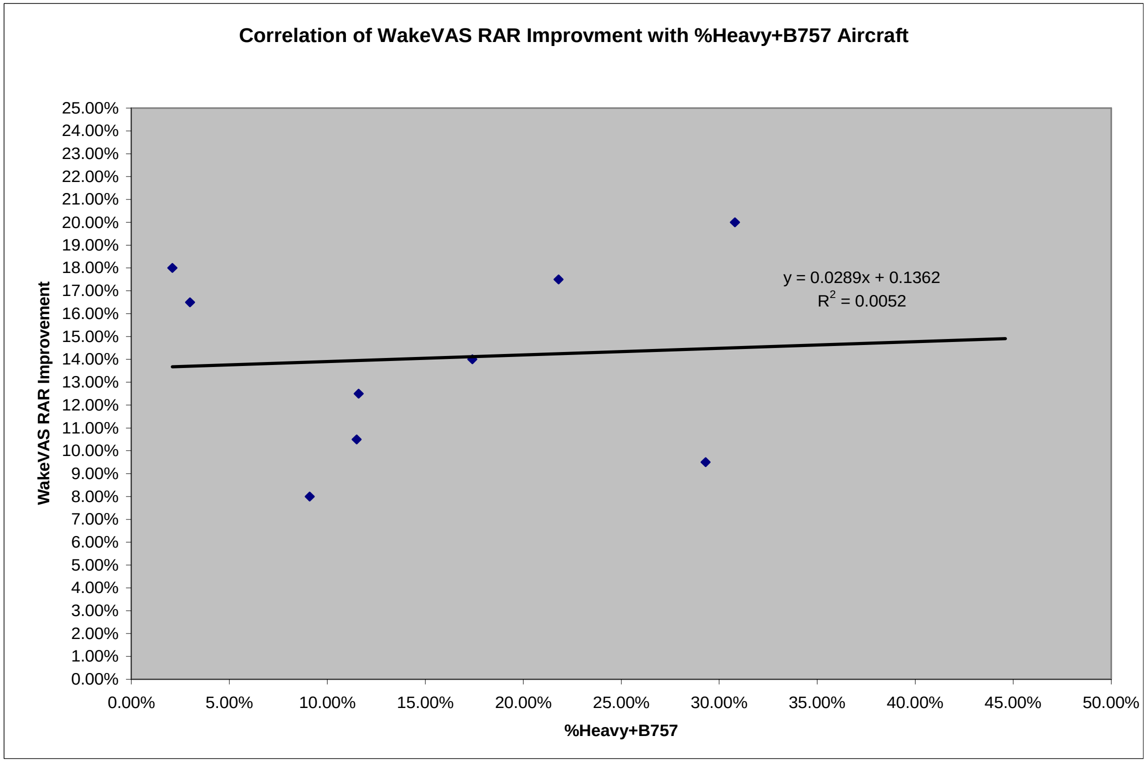

**Figure 5 CSPR Upwind Wake-Free Non-Visual Arrivals Improvement (Phase II) Correlation with Traffic Mix**

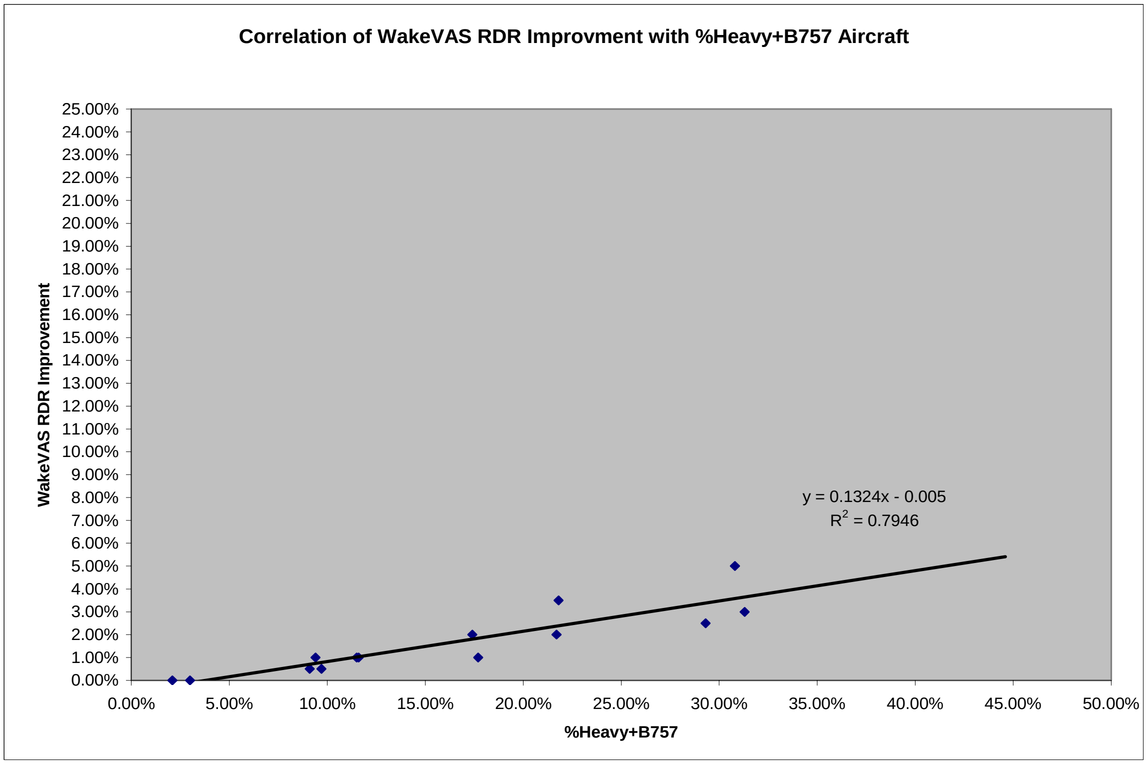

Figure 6 CSPR Non-Visual Departures Improvement (Phase II) Correlation with Traffic Mix

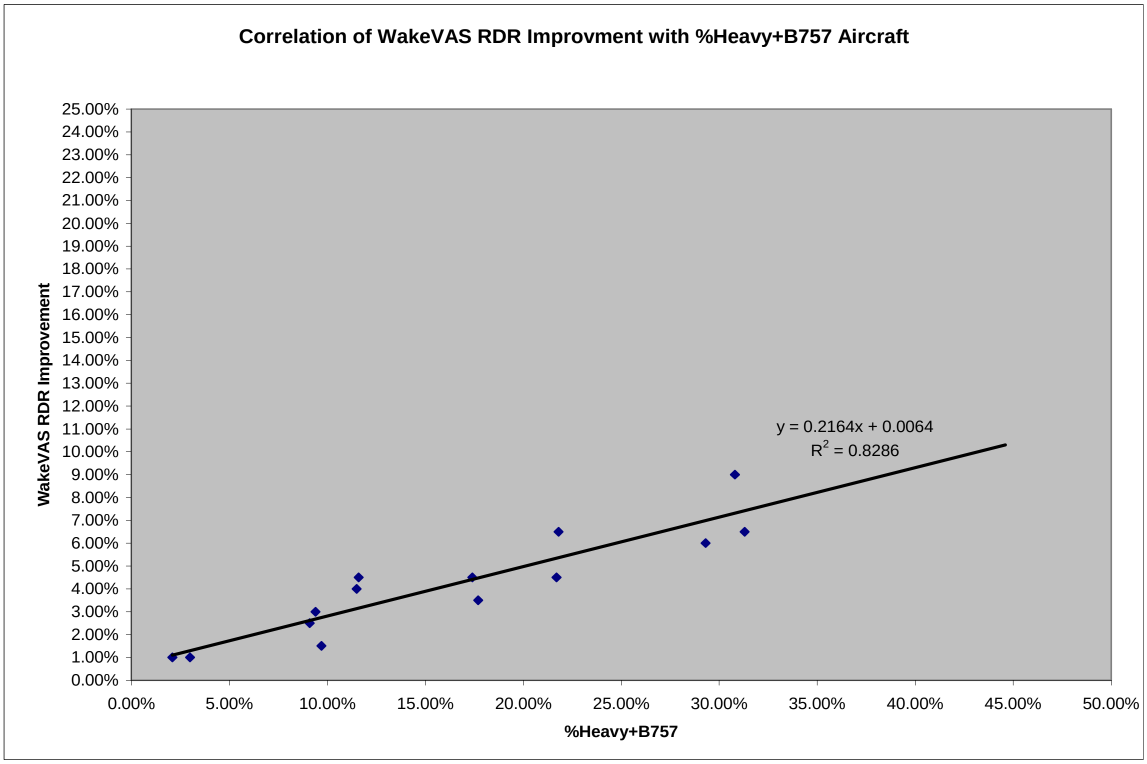

Figure 7 CSPR Visual Departures Improvement (Phase II) Correlation with Traffic Mix

| **Airport** | **Visual Departures Increase%** | **Visual Arrivals Increase%** | **Non-Visual Departures Increase%** | **Non-Visual Arrivals Increase%** |
|---|---|---|---|---|
| **ATL** | 8.3 | 0.0 | 7.7 | 13.3 |
| **BOS** | 5.9 | 0.0 | 5.3 | 10.5 |
| **CLE** | 0.3 | 0.0 | 0.0 | 4.0 |
| **CLT** | 2.1 | 0.0 | 1.4 | 6.1 |
| **DFW** | 4.9 | 0.0 | 4.2 | 9.3 |
| **DTW** | 3.1 | 0.0 | 2.5 | 7.3 |
| **EWR** | 7.0 | 0.0 | 6.4 | 11.8 |
| **IAH** | 2.7 | 0.0 | 2.0 | 6.8 |
| **JFK** | 17.4 | 0.0 | 16.7 | 23.7 |
| **LAX** | 10.1 | 0.0 | 9.5 | 15.4 |
| **LGA** | 2.9 | 0.0 | 2.3 | 7.1 |
| **MEM** | 7.6 | 0.0 | 6.9 | 12.4 |
| **MIA** | 10.4 | 0.0 | 9.7 | 15.6 |
| **ORD** | 4.6 | 0.0 | 3.9 | 9.0 |
| **PHL** | 3.2 | 0.0 | 2.6 | 7.4 |
| **SDF** | 11.0 | 0.0 | 10.3 | 16.3 |
| **SEA** | 4.9 | 0.0 | 4.3 | 9.4 |
| **SFO** | 10.4 | 0.0 | 9.7 | 15.7 |
| **STL** | 2.8 | 0.0 | 2.1 | 6.9 |
| **Mean** | **6.3** | **0.0** | **5.6** | **10.9** |

**Table 11 Single Runway Arrival and Departure Rates Improvement (Phase II)** ***(estimated from regression analysis)***

| **Airport** | **Visual Departures Increase%** | **Visual Arrivals Increase%** | **Non-Visual Departures Increase%** | **Non-Visual Arrivals Increase%** |
|---|---:|---:|---:|---:|
| **ATL** | N/A | N/A | N/A | N/A |
| **BOS** | 4.6 | 0.0 | 1.9 | 14.0 |
| **CLE** | 0.9 | 0.0 | 0.0 | 18.0 |
| **CLT** | N/A | N/A | N/A | N/A |
| **DFW** | 3.9 | 0.0 | 1.5 | 14.0 |
| **DTW** | 2.8 | 0.0 | 0.8 | 8.0 |
| **EWR** | 5.3 | 0.0 | 2.3 | 17.5 |
| **IAH** | 2.5 | 0.0 | 0.6 | 14.0 |
| **JFK** | N/A | N/A | N/A | N/A |
| **LAX** | 7.3 | 0.0 | 3.6 | 9.5 |
| **LGA** | N/A | N/A | N/A | N/A |
| **MEM** | 5.6 | 0.0 | 2.5 | 14.0 |
| **MIA** | 7.4 | 0.0 | 3.6 | 14.0 |
| **ORD** | N/A | N/A | N/A | N/A |
| **PHL** | 2.8 | 0.0 | 0.8 | 10.5 |
| **SDF** | N/A | N/A | N/A | N/A |
| **SEA** | 3.9 | 0.0 | 1.5 | 12.5 |
| **SFO** | 7.4 | 0.0 | 3.7 | 20.0 |
| **STL** | 2.5 | 0.0 | 0.7 | 16.5 |
| **Mean** | **4.4** | **0.0** | **1.8** | **14.0** |

**Table 12 CSPR Arrival and Departure Rate Improvement (Phase II)** ***(estimated from regression analysis)***
*(Except non-visual arrivals used actual or mean values from reference 4.)*

| Airport | Dep. VFR | Arr. VFR | Total VFR | Dep. IFR | Arr. IFR | Total IFR |
|---|---|---|---|---|---|---|
| **ATL** | 151 | 138 | 281 | 129 | 135 | 256 |
| **BOS** | 75 | 67 | 135 | 52 | 52 | 99 |
| **CLE** | 59 | 59 | 105 | 33 | 34 | 60 |
| **CLT** | 104 | 93 | 181 | 81 | 77 | 147 |
| **DFW** | 144 | 146 | 288 | 115 | 128 | 240 |
| **DTW** | 107 | 100 | 194 | 95 | 96 | 179 |
| **EWR** | 73 | 63 | 122 | 50 | 50 | 91 |
| **IAH** | 93 | 95 | 175 | 86 | 94 | 167 |
| **JFK** | 72 | 68 | 111 | 51 | 61 | 92 |
| **LAX** | 108 | 100 | 185 | 81 | 87 | 152 |
| **LGA** | 48 | 47 | 90 | 36 | 37 | 69 |
| **MEM** | 95 | 88 | 164 | 75 | 79 | 138 |
| **MIA** | 103 | 93 | 174 | 82 | 87 | 153 |
| **ORD** | 120 | 114 | 218 | 101 | 106 | 192 |
| **PHL** | 72 | 73 | 129 | 59 | 66 | 112 |
| **SDF** | 70 | 63 | 118 | 65 | 63 | 115 |
| **SEA** | 91 | 82 | 146 | 77 | 77 | 131 |
| **SFO** | 61 | 55 | 105 | 45 | 47 | 84 |
| **STL** | 79 | 78 | 142 | 68 | 72 | 128 |

**Table 13 Airport Capacities with WakeVAS Single Runway Arrivals and Departure Rates Improvement (Phase II)**

| Airport | Dep. VFR | Arr. VFR | Total VFR | Dep. IFR | Arr. IFR | Total IFR |
|---|---|---|---|---|---|---|
| **ATL** | 139 | 138 | 269 | 120 | 119 | 231 |
| **BOS** | 74 | 67 | 134 | 50 | 54 | 99 |
| **CLE** | 60 | 59 | 106 | 33 | 39 | 65 |
| **CLT** | 102 | 93 | 179 | 80 | 73 | 142 |
| **DFW** | 142 | 146 | 286 | 112 | 133 | 242 |
| **DTW** | 107 | 100 | 194 | 94 | 96 | 178 |
| **EWR** | 72 | 63 | 121 | 48 | 53 | 92 |
| **IAH** | 93 | 95 | 175 | 85 | 95 | 167 |
| **JFK** | 61 | 68 | 100 | 44 | 49 | 73 |
| **LAX** | 105 | 100 | 182 | 77 | 82 | 143 |
| **LGA** | 47 | 47 | 89 | 35 | 35 | 66 |
| **MEM** | 93 | 88 | 162 | 72 | 80 | 136 |
| **MIA** | 100 | 93 | 171 | 78 | 86 | 148 |
| **ORD** | 115 | 114 | 213 | 97 | 97 | 179 |
| **PHL** | 72 | 73 | 129 | 58 | 67 | 112 |
| **SDF** | 63 | 63 | 111 | 59 | 59 | 105 |
| **SEA** | 90 | 82 | 145 | 75 | 79 | 131 |
| **SFO** | 59 | 55 | 103 | 43 | 49 | 84 |
| **STL** | 79 | 78 | 142 | 67 | 78 | 133 |

**Table 14 Airport Capacities with WakeVAS CSPR Upwind Wake-Free Arrivals and Departure Rates Improvement (Phase II)**

### *Closely Spaced Parallel Runways using Rule Change (Phase I ConOps)*

For the Phase I ConOps, an estimate was made of the arrivals rate increase that could be obtained by relaxation of the FAA rule that CSPRs with spacing between runways of less than 2500 ft must be treated as a single runway under Instrument Flight Rules conditions for separation purposes. The rule change would allow 1.5 nm diagonal separations between aircraft on adjacent runways down to 1000 ft spacing as currently used for runways spaced between 2500 ft – 4300 ft laterally.

Two variations of the ConOps were analysed. First, any category of aircraft was allowed to use 1.5nm diagonal spacing if following a large or small category aircraft (unrestricted rule change). Secondly, restrictions were added to allow small and large aircraft to only follow small when using the rule change (restricted rule change).

A third variation was considered, restricting small aircraft to follow small only, but still allowing large to follow large with 1.5nm separation. This case was not used for simulation since the capacity improvements are very similar to the unrestricted case.

### *Calculation of Phase I Rule Change Improvement Factors from Traffic Mix Analysis*

The ACES simulation results for this study make use of the ACES nodal representation of airports. The nodal model of airports represents the airport capacity under VFR and IFR as a boundary for each operating state, generated from a triplet of values representing hourly capacity for arrivals only, departures only and maximum total mixed departures and arrivals.

ACES Build 3.2.1 also has an enhanced terminal area model which can include a higher fidelity representation of the specific runway system at individual airports. This was not used for this study, since few airports have currently been modelled at the higher level of detail (only ORD, EWR). However, use was made of the data tables that are supplied.

The enhanced model makes use of runway spacing tables which determine the time separation between aircraft that needs to be applied at the final approach fix in order to meet wake separation rules. The time separation values take into account differences in typical approach speeds of the categories of aircraft. The separation tables do not take into account position and speed uncertainties of the aircraft, separate buffer spacing tables are provided within ACES for this purpose. A typical value for the buffer spacing is 20 secs or about 1 nm at an approach speed of 185 kts. Using the arrival spacing tables plus the buffer spacing, the arrival rate for any lead/ follower pair can be calculated. Weighting this by traffic mix, assuming independent arrival of various categories of aircraft gives the approximate runway arrival rate for any particular airport.

Tables 15 and 16 are taken from the ACES simulator database and show the time separations used for a minimum allowed separation of 3 nm and 2.5 nm (some airports are permitted to use 2.5 nm minimum separations). Table 17 shows the time separation required for 1.5 nm diagonal separations between aircraft on adjacent CSPRs with spacing between 2500 ft – 4300 ft. The Phase 1 Rule change ConOps proposes the use of this diagonal spacing for runways down to 1000 ft lateral spacing for certain leader/ follower categories. At 1000 ft lateral spacing the time separation required to ensure 1.5 nm diagonal separations between aircraft is approximately 30 secs for a 185 kts approach speed. This is in-line with Table 17.

Substituting a 30 second spacing for the appropriate leader/ follower categories in tables 15 and 16 adding the 20 second uncertainty buffer spacing and weighting by traffic mix at an airport allows the theoretical capacity increase due to the Phase 1 rule change to be calculated.

The estimated improvement factors are shown in Table 18 and the corresponding airport capacity values are shown in Table 19.

The improvement due to the unrestricted rule change variation 1 as defined above is estimated to average about 60%. Variation 2 of the rule change gives a much smaller capacity benefit of about 11%. At the busiest airports, large category aircraft (with the exception of JFK) make up the majority of the traffic (70% to 90%) so not allowing large aircraft following large to use the rule change leads to a significant loss in benefit. Variation 3 of the rule change reduces the average improvement slightly to 57%. The busiest airports have a relatively low percentage (10% or less) of small category aircraft in the traffic mix so restrictions on small aircraft make little difference.

| Lead\Follow | Small | Large | B757 | Heavy |
|---|---|---|---|---|
| **Small** | 90 | 86 | 86 | 80 |
| **Large** | 130 | 86 | 86 | 80 |
| **B757** | 158 | 116 | 116 | 106 |
| **Heavy** | 200 | 158 | 158 | 106 |

**Table 15 IFR In-Trail Arrival Spacing for 3 nm Separation at Runway Threshold (seconds)**

| Lead\Follow | Small | Large | B757 | Heavy |
|---|---|---|---|---|
| **Small** | 76 | 72 | 72 | 66 |
| **Large** | 130 | 72 | 72 | 66 |
| **B757** | 158 | 116 | 116 | 106 |
| **Heavy** | 200 | 158 | 158 | 106 |

**Table 16 IFR In-Trail Arrival Spacing for 2.5 nm Separation at Runway Threshold (seconds)**

| Lead\Follow | Small | Large | B757 | Heavy |
|---|---|---|---|---|
| **Small** | 29.8 | 29.7 | 29.7 | 27.5 |
| **Large** | 29.2 | 29.7 | 29.7 | 28.1 |
| **B757** | 29.2 | 29.7 | 29.7 | 28.1 |
| **Heavy** | 26.5 | 27.3 | 27.3 | 27 |

**Table 17 IFR Adjacent Flights Arrival Spacing for 1.5 nm Diagonal Separation for CSPRs 2500 ft – 4300 ft (seconds)**

| Airport | Variation 1 Unrestricted Non-Visual Arrivals Increase% | Variation 2 Restricted Large/ Small Non-Visual Arrivals Increase% | Variation 3 Restricted Small Non-Visual Arrivals Increase% |
|---|---|---|---|
| **19 Apt Set** | | | |
| **ATL** | N/A | N/A | N/A |
| **BOS** | 56.5 | 13.8 | 54.5 |
| **CLE** | 64.2 | 4.2 | 61.9 |
| **CLT** | N/A | N/A | N/A |
| **DFW** | 58.4 | 13.6 | 55.2 |
| **DTW** | 60.1 | 8.5 | 58.6 |
| **EWR** | 57.4 | 13.5 | 56.5 |
| **IAH** | 64.4 | 7.0 | 63.0 |
| **JFK** | N/A | N/A | N/A |
| **LAX** | N/A | N/A | N/A |
| **LGA** | N/A | N/A | N/A |
| **MEM** | 56.5 | 18.6 | 52.4 |
| **MIA** | N/A | 17.7 | 49.5 |
| **ORD** | N/A | N/A | N/A |
| **PHL** | 60.7 | 10.3 | 57.9 |
| **SDF** | N/A | N/A | N/A |
| **SEA** | N/A | N/A | N/A |
| **SFO** | N/A | N/A | N/A |
| **STL** | 61.1 | 9.6 | 58.2 |
| **Mean** | **59.9** | **11.0** | **57.6** |
| **Additional Benchmark** | | | |
| **LAS** | 58.0 | 15.5 | 55.1 |
| **MCO** | 54.8 | 16.8 | 52.9 |
| **MDW** | 64.7 | 16.7 | 57.3 |
| **PIT** | 64.7 | 5.8 | 64.0 |
| **Mean** | **61.6** | **13.7** | **57.3** |
| **Additional Non-Benchmark** | | | |
| **OAK** | 62.8 | 20.5 | 55.4 |
| **OMA** | 68.5 | 22.7 | 56.9 |
| **SAT** | 67.7 | 25.1 | 55.8 |
| **SJC** | 64.6 | 14.6 | 58.6 |
| **Mean** | **65.9** | **20.7** | **56.7** |

**Table 18 CSPR IFR Arrival Rate Improvement (Phase I)**

| Airport | Variation 1<br>Unrestricted | | | Variation 2<br>Restricted Large/Small | | |
|---|---|---|---|---|---|---|
| | Dep. IFR | Arr. IFR | Total IFR | Dep. IFR | Arr. IFR | Total IFR |
| **19 Apt Set** | | | | | | |
| **ATL** | 120 | 119 | 231 | 120 | 119 | 231 |
| **BOS** | 49 | 67 | 111 | 49 | 52 | 96 |
| **CLE** | 33 | 58 | 84 | 33 | 35 | 61 |
| **CLT** | 80 | 73 | 142 | 80 | 73 | 142 |
| **DFW** | 110 | 138 | 245 | 110 | 122 | 229 |
| **DTW** | 93 | 100 | 181 | 93 | 92 | 173 |
| **EWR** | 47 | 63 | 101 | 47 | 49 | 87 |
| **IAH** | 84 | 95 | 166 | 84 | 90 | 161 |
| **JFK** | 44 | 49 | 73 | 44 | 49 | 73 |
| **LAX** | 74 | 75 | 133 | 74 | 75 | 133 |
| **LGA** | 35 | 35 | 66 | 35 | 35 | 66 |
| **MEM** | 70 | 88 | 142 | 70 | 76 | 130 |
| **MIA** | 75 | 75 | 134 | 75 | 75 | 134 |
| **ORD** | 97 | 97 | 179 | 97 | 97 | 179 |
| **PHL** | 58 | 73 | 118 | 58 | 65 | 110 |
| **SDF** | 59 | 59 | 105 | 59 | 59 | 105 |
| **SEA** | 74 | 70 | 121 | 74 | 70 | 121 |
| **SFO** | 41 | 41 | 74 | 41 | 41 | 74 |
| **STL** | 67 | 78 | 133 | 67 | 71 | 126 |
| **Additional Benchmark** | | | | | | |
| **LAS** | 35 | 47 | 75 | 35 | 40 | 68 |
| **MCO** | 82 | 105 | 168 | 82 | 93 | 156 |
| **MDW** | 33 | 54 | 80 | 33 | 38 | 64 |
| **PIT** | 87 | 106 | 153 | 87 | 87 | 134 |
| **Additional Non-Benchmark** | | | | | | |
| **OAK** | 30 | 31 | 54 | 30 | 31 | 54 |
| **OMA** | 39 | 61 | 92 | 39 | 46 | 77 |
| **SAT** | 33 | 43 | 69 | 33 | 41 | 67 |
| **SJC** | 33 | 54 | 80 | 33 | 38 | 64 |

**Table 19 Airport Capacities with WakeVAS CSPR Rule Change IFR Arrival Rates Improvement (Phase I)**

# 5. Availability of WakeVAS ConOps

The overall benefit that will be obtained from any WakeVAS is a product of the capacity improvement and the time that the system is able to provide that capacity improvement.

The single runway Phase III ConOps is able to provide at least some improvement under nearly all meteorological conditions since several meteorological factors are used by the wake prediction model. The improvement factors used in this study were obtained from an analysis of 6 days of weather data at 12 different airports and represent the average improvement obtained over many hours of data collected during diverse conditions, see reference 3. For this current study, it is assumed that these improvement factors are representative of the mean improvement that would be obtained over a complete year. The single runway Phase III arrival ConOps will be available to provide a capacity gain whenever non-visual conditions exist. The departure ConOps will be available to provide a capacity gain at all times. The availability factors used are just the annual percentage IFR/VFR shown in Table 20.

The CSPR Phase I Arrivals Rule Change ConOps is available at all times but only provides improvement during IFR since the wake separation rules which are being changed only apply during IFR conditions. The availability factors are the annual percentage IFR shown in Table 20.

The wind dependant ConOps are available for a lesser proportion of time. The availability is a product of the percentage of time that wind conditions meet the specific criteria for the ConOps from Table 21 and for non-visual improvements the percentage of time in IFR from Table 20. (This makes the assumption that wind conditions are not correlated with visual/ non-visual conditions.)

MITRE-CAASD analysed wind conditions required for each WakeVAS wind dependant ConOps variant and documented the results in reference 4. This current study makes use of the MITRE-CAASD analysis in estimating the availability of the ConOps. The data shown in Table 21 was selected from a larger data set contained in reference 4 and certain assumptions were made as documented below.

1. The single runway arrival ConOps wind data used is from II-B-2(c), Table 4.2, of reference 4 which is for an approach angled 3 degrees to the final approach fix. This is not actually the correct criteria for the ConOps analysed here, which is for a straight in approach. However the percentage availability for a straight in approach is given a very low value in Table 4.2, of reference 4. This is based on MITRE-CAASD calculating that a minimum 16 knot cross-wind would be required all the way out to 20 nm from the runway for a straight in approach (Table 2.6, reference 4). The requirement for the angled approach is for an 8 knot wind out to 5 nm from the runway. The actual benefits for the angled 3 degrees to final approach fix ConOps were not analysed by MITRE-CAASD but it is

assumed they would be similar to the straight approach ConOps. (Only the angled approaches to the missed approach point were analyzed.)

2. The CSPR arrival ConOps wind data used is from II-B-1(C), Table 4.1, of reference 4 which is for an approach angled 3 degrees to final approach fix. The straight in CSPR approach was not considered because it has very low availability for several airports. The capacity improvements obtained in the MITRE-CAASD analysis for CSPR arrivals do not depend on which approach is used, so can be used with any of the wind data.

3. The CSPR arrival ConOps wind data used was from II-A-3(d)1, Table 4.1, of reference 4 which is for a 5 nm diverging departure path. The ConOps evaluated for this current study is for a straight out CSPR departure, but wind data are not given for this ConOps. It is assumed that the availability would be similar; in any case the capacity improvements from a straight out and 5 nm diverging path are similar.

4. The CSPR ConOps considered were all for upwind runway wake-free since the availability of the ConOps with both runways wake-free is very small for several of the airports analysed, see Table 4.3 of reference 4.

The annual percentage availability of a wind dependant ConOps is a product of the values in Table 21 and the percentage of time that an airport is under visual or non-visual conditions from Table 20. The total annual availability is shown in Table 22. The departures column represents the availability of visual departures procedures. The arrivals column represents the availability of non-visual arrivals procedures, since the arrivals ConOps evaluated here only provide a capacity benefit under non-visual conditions. As a simplification, it is assumed that non-visual departures procedures would have been available at the same time as non-visual arrivals procedures, so both arrivals and departures improvements are used during non-visual conditions in the ACES simulation. This is not necessarily the case, but any discrepancy will be small since the contribution of non-visual departures ConOps to overall capacity gains is small compared to the non-visual arrivals capacity gains. The availability factors in Table 22 are the values used in the benefits assessment.

| **Airport** | **%IFR** | **Airport** | **%IFR** |
|---|---:|---|---:|
| ATL | 23% | MCO | 5% |
| BOS | 18% | MDW | 15% |
| BWI | 13% | MEM | 21% |
| CLE | 15% | MIA | 3% |
| CLT | 18% | MSP | 31% |
| CVG | 43% | ORD | 15% |
| DCA | 14% | PDX | 18% |
| DEN | 7% | PHL | 15% |
| DFW | 17% | PHX | 1% |
| DTW | 23% | PIT | 14% |
| EWR | 19% | SAN | 30% |
| FLL | 5% | SDF | 20% |
| IAD | 20% | SEA | 29% |
| IAH | 24% | SFO | 26% |
| JFK | 14% | SLC | 15% |
| LAS | 1% | STL | 23% |
| LAX | 18% | TPA | 4% |
| LGA | 20% | | |

**Table 20 Annual Percentages of IFR Conditions at FAA Benchmark Airports**
*(From reference 8.)*

| | **CSPR** | | **SINGLE RUNWAY** | |
|---|---|---|---|---|
| | **DEP** | **ARR** | **DEP** | **ARR** |
| **Airport** | **II-A-3(d)1** | **II-B-1(C)** | **II-A-3(a)** | **II-B-2(c)** |
| **ATL** | N/A | N/A | 0.9 | 2.3 |
| **BOS** | 56.6 | 75.1 | 8.6 | 14.0 |
| **CLE** | 35.8 | 63.9 | 4.7 | 10.5 |
| **CLT** | N/A | N/A | 0.4 | 1.4 |
| **DFW** | 36.0 | 71.3 | 1.9 | 3.5 |
| **DTW** | 70.7 | 78.6 | 4.2 | 8.0 |
| **EWR** | 36.0 | 71.3 | 6.5 | 10.5 |
| **IAH** | 36.0 | 71.3 | 4.2 | 8.0 |
| **JFK** | N/A | N/A | 9.1 | 14.2 |
| **LAX** | 36.0 | 71.3 | 0.1 | 0.4 |
| **LGA** | N/A | N/A | 6.8 | 11.0 |
| **MEM** | 29.9 | 71.3 | 4.2 | 8.0 |
| **MIA** | 24.1 | 71.3 | 4.2 | 8.0 |
| **ORD** | N/A | N/A | 5.3 | 11.9 |
| **PHL** | 26.2 | 78.4 | 3.2 | 6.4 |
| **SDF** | N/A | N/A | 2.8 | 6.9 |
| **SEA** | 10.1 | 51.6 | 4.2 | 8.0 |
| **SFO** | 21.1 | 57.7 | 4.2 | 8.0 |
| **STL** | 49.2 | 93.8 | 4.6 | 10.7 |
| **Mean** | **36.0** | **71.3** | **4.2** | **8.0** |

**Table 21 Percentage of Time wind conditions are met for ConOps**
*(From MITRE-CAASD, reference 4, Tables 4.2, 4.4.)*

| | **LANGLEY SINGLE** | | **MITRE SINGLE** | | **CSPR upwind** | **CSPR upwind** |
|---|---|---|---|---|---|---|
| **Airport** | **DEP** | **ARR** | **DEP** | **ARR** | **DEP** | **ARR** |
| **ATL** | 77.0 | 23.0 | 0.7 | 0.5 | N/A | N/A |
| **BOS** | 82.0 | 18.0 | 7.0 | 2.5 | 46.4 | 13.5 |
| **CLE** | 85.0 | 15.0 | 4.0 | 1.6 | 30.4 | 9.6 |
| **CLT** | 82.0 | 18.0 | 0.3 | 0.3 | N/A | N/A |
| **DFW** | 83.0 | 17.0 | 1.6 | 0.6 | 29.9 | 12.1 |
| **DTW** | 77.0 | 23.0 | 3.2 | 1.8 | 54.4 | 18.1 |
| **EWR** | 81.0 | 19.0 | 5.3 | 2.0 | 29.2 | 13.6 |
| **IAH** | 76.0 | 24.0 | 3.2 | 1.9 | 27.4 | 17.1 |
| **JFK** | 86.0 | 14.0 | 7.8 | 2.0 | N/A | N/A |
| **LAX** | 82.0 | 18.0 | 0.1 | 0.1 | 29.5 | 12.8 |
| **LGA** | 80.0 | 20.0 | 5.4 | 2.2 | N/A | N/A |
| **MEM** | 79.0 | 21.0 | 3.3 | 1.7 | 23.6 | 15.0 |
| **MIA** | 97.0 | 3.0 | 4.1 | 0.2 | 23.4 | 2.1 |
| **ORD** | 85.0 | 15.0 | 4.5 | 1.8 | N/A | N/A |
| **PHL** | 85.0 | 15.0 | 2.7 | 1.0 | 22.3 | 11.8 |
| **SDF** | 80.0 | 20.0 | 2.2 | 1.4 | N/A | N/A |
| **SEA** | 71.0 | 29.0 | 3.0 | 2.3 | 7.2 | 15.0 |
| **SFO** | 74.0 | 26.0 | 3.1 | 2.1 | 15.6 | 15.0 |
| **STL** | 77.0 | 23.0 | 3.5 | 2.5 | 37.9 | 21.6 |
| **Mean** | **81.0** | **19.0** | **3.0** | **1.0** | **29.0** | **14.0** |

**Table 22 Annual Percentage Availability of ConOps**

# 6. Delay Reduction and Airline Cost Savings

### *Delay Reduction*

Delay reductions from ACES simulation results and the corresponding estimated cost savings for each of the WakeVAS ConOps analyzed are presented for the 19 study airports. Also presented are total delay reduction and cost savings for the network wide airport set that includes all airports with flights departing to or arriving from any of the 19 airports. Each simulation run assumed either IFR or VFR conditions for all airports.

An additional 4 FAA benchmark airports (LAS, MCO, MDW, PIT) and 4 airports within the next 32 busiest category (OAK, OMA, SAT, SJC) were identified as having existing parallel runways with lateral spacing between 1000 ft – 2500 ft. These were analysed for benefits due to the Phase 1 Rule Change ConOps in addition to the 19 other airports.

ACES logs data during the simulation which allows calculation of total delay (defined as the difference between actual gate arrival time and scheduled gate arrival time) and delay by flight leg, for each flight in the simulation. For this analysis delay was categorised as ground hold, ground or airborne delay. All flights delayed on departure by more than 5 hours were deemed to be cancelled and 5 hours of delay included in the ground hold delay estimate for the cancelled flight.

For brevity, only total delays are presented in this report, but the airline cost savings estimates are calculated using delay by category. Ground hold delay is least expensive, since the aircraft main engines are not operating; ground delay is incurred during taxi-in or taxi-out with engines operating; airborne delay is most expensive to the airlines.

Table 23 shows minutes of delay for 24 hours of flight operations at each of the 19 study airports, and Table 24 shows the number of cancellations. The corresponding delay reductions obtained using each of the Wake(

which have flights departing to, or arriving from the WakeVAS equipped airports. Table 26 show the network wide total delays and the delays per flight for the OEP baseline airport capacities and for the WakeVAS ConOps increased capacities.

The reduction in delay obtained from ACES simulation using the improvement factors from section 4 of this report were for a single day of simulated operations. The single day results are multiplied by the number of days in a year and weighted by the annual percentage availability of the ConOps as calculated in section 5 to obtain the annualized values for each of the 19 airports, shown in Table 27.

The Phase II single runway and CSPR ConOps give less annual delay reduction than the Phase III ConOps due to lower availability even though the improvement factor obtained is greater for the Phase II CSPR ConOps and about the same for the Phase II single runway ConOps, see tables in section 4. The CSPR Phase II ConOps was only applicable to 13 out of 19 airports studied, which reduces the potential for delay reduction.

The Phase I CSPR arrival ConOps *potentially* gives a larger annual delay reduction than the Phase II CSPR Conops due to large improvement factors and high availability, since it is applicable in IFR conditions and is not wind-dependant. However this large benefit is only realisable if it is feasible to allow large aircraft to follow large aircraft using the 1.5 nm diagonal separation rule. If this has to be restricted to only allow heavy and B757 aircraft to follow large with the rule change then the benefits are much less. An alternative to restricting large following large for all runway separations would be to allow the unrestricted rule for runways with lateral spacing greater than a certain limit, otherwise use the restricted version. For the benchmark airports, using a runway lateral spacing requirement of 1500 ft minimum would only allow the unrestricted rule change to be used at BOS, DTW and MCO which would greatly reduce the benefit. However, using a 1200 ft minimum would allow the unrestricted rule change at 8 of the benchmark airports, still providing a substantial benefit.

### *Airline Cost Savings*

The airline cost savings calculated in this analysis are based on the fleet and operations weighted air carrier costs contained in reference 9. 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 28. These values are used to calculate the estimated cost savings due to Wake VAS delay reduction, according to the flight segment where the delay occurred

The estimated annual airline cost savings that results from the use of the WakeVAS ConOps at each airport analysed are shown in Table 29. The total cost savings at the 19 airports and network wide total savings, which includes airports having flights departing to, or arriving from any of the 19 study airports is shown in Table 30.

The largest annual network wide saving of **$687 million** occurs with use of the Phase III single runway ConOps, due to applicability to all of the 19 airports studied and high availability obtained from the use of wake behaviour prediction using multiple meteorological factors, not just wind dependence.

The CSPR Phase I rule change for arrivals ConOps potentially saves **$213 million** for the unrestricted rule change, but this reduces to **$73 million** for the restricted case. Increasing the runway lateral spacing requirement to 1200 ft for the unrestricted case and allowing the use of the restricted rule down to 1000 ft gives a saving of **$145 million**. Further increasing the spacing requirement to 1500 ft essentially reduces the benefit to that of the restricted case.

The CSPR Phase II wind dependant ConOps saves an estimated **$130 million**, with the single runway Phase II wind dependant ConOps saving a lesser amount of **$41 million** due to low availability.

Included in the single runway ConOps savings are the savings due to substantial delay reductions at Chicago O'Hare (ORD). For the Phase III ConOps the ORD cost savings amount to **$129 million** of the total savings. This result should be interpreted with caution, since the savings result from a 1.4X flight demand at ORD that imposes a delay of 81 minutes per flight operation using the OEP 2010 airport capacities. This excessive delay would not be tolerable in practice, so the benefits obtained from WakeVAS would likely be less at ORD, since the baseline delay without WakeVAS would be less. However, the overall network wide savings would still be substantial.

The 19 airports analysed in this study were identified as having most potential for WakeVAS deployment from previous studies. WakeVAS single runway ConOps could be deployed at all of the 35 FAA benchmark airports. WakeVAS CSPR ConOps could be deployed at an additional 4 or 5 benchmark airports ((LAS, MCO, MDW, PIT) and possibly ATL. *(ATL is operated primarily as if the parallel runways were not closely spaced since the departures are from the 2 inner runways and arrivals from 2 outer runways; separation between the pairs is approx 4500 ft. A new single runway is due to become operational in 2006.)* In addition there are airports not in the benchmark list which could have sufficient demand in the future to warrant deployment of WakeVAS.

An additional set of test cases analysed the benefits of using the Phase I ConOps rule change at the additional benchmark airports (LAS, MCO, MDW, PIT) and airports within the next 32 busiest category (OAK, OMA, SAT, SJC) with existing runways spaced between 1000 ft – 2500 ft. For the benchmark airports, the additional network wide cost saving was **$54 million** for the unrestricted case and **$21 million** for the restricted case. The additional saving for the non-benchmark airports was negligible, since the airports analysed are not capacity constrained at the future 1.4X demand level used for this study. However, if a higher demand level, for example 2X current operations, is reached in the farther term then the busiest of the non-benchmark airports could benefit from WakeVAS deployment.

### *Additional Runways*

Consideration was also given to adding additional runways between existing parallel runways where lateral spacing would permit, given the rule change to allow independent operation of runways spaced down to 1000 ft. This would require a minimum of approximately 2500 ft between existing runways. An analysis of the benchmark airports in the FAA Operational Evolution Plan determined that where it is feasible to add runways, many airports already plan to do so (11 airports) and of these 5 are CSPRs. Where space between runways would allow an additional, the airport often has terminal buildings between the existing parallel runways or has an intersecting runway between the existing parallels. An example is PHX where there is 3500 ft between existing parallel runways, but the terminal buildings and control tower are sited between them. Other airports with parallel runways spaced more than 2500 ft, but with terminal buildings between them are DFW, DTW, FLL, JFK, LAX, MEM, PHX. An examination of the layout at all of the FAA benchmark where new runways are not currently planned did not indicate any obvious opportunity to insert a third between existing parallels because of obstructions, either terminal buildings, towers or intersecting runways.

The airports not included in the benchmark list do not have sufficient demand at the 1.4X level to warrant additional runways. In the farther term as demand increases this could change and there may well be airports that could benefit from a rule change plus additional runway.

### *WakeVAS Installation, Operating and Support Costs*

The Logistics Management Institute published a business case analysis, reference 10 that contains an estimate of the costs for a Phase III WakeVAS including the wake vortex hardware and software and operating and support costs. The LMI report contains detailed cost estimates for SFO, DFW and STL only.

From reference 10, the cost to equip SFO or DFW is estimated to be $1.6 million for hardware and software and $280,000 per year for operation and support. For STL the costs estimates are $3.1 million for hardware and software and $690,000 per year for operation and support.

The costs for implementing a wind dependant ConOps are not addressed in reference 10, but would presumably be less than that for a Phase III system, since a wake sensing system is not needed.

Using these cost values, the savings that could be obtained by deployment of the WakeVAS Phase III single runway ConOps would yield a substantial overall benefit within the first year of operation at 16 of the 19 study airports, see Table 29. Assuming the cost of a Phase II wind dependent system is the same or less than for the Phase III system the CSPR ConOps would also yield a positive cost saving within the first year of operation at 11 of the 13 applicable airports.

| | **OEP 2010 AIRPORT CAPACITIES** | | **LANGLEY PHASE III SINGLE RUNWAY ARRIVALS & DEPARTURES** | | **MITRE-CAASD PHASE II SINGLE RUNWAY ARRIVALS & DEPARTURES** | | **MITRE-CAASD PHASE II CSPR ARRIVALS & DEPARTURES** | | **RULE CHANGE PHASE I CSPR ARRIVALS** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | **Unrest-ricted** | **Restricted Large/ Small** |
| **Airport** | **IFR** | **VFR** | **IFR** | **VFR** | **IFR** | **VFR** | **IFR** | **VFR** | **IFR** | **IFR** |
| **ATL** | 38,187 | 15,147 | 26,041 | 14,585 | 24,326 | 14,272 | 39,007 | 15,806 | 34,788 | 34,571 |
| **BOS** | 41,246 | 8,778 | 33,139 | 9,135 | 32,268 | 9,113 | 36,641 | 8,771 | 34,273 | 38,567 |
| **CLE** | 27,231 | 6,832 | 17,848 | 6,859 | 26,785 | 7,494 | 19,759 | 6,970 | 15,914 | 25,546 |
| **CLT** | 17,778 | 9,106 | 15,205 | 9,020 | 15,234 | 8,419 | 16,950 | 8,862 | 14,942 | 18,317 |
| **DFW** | 26,759 | 14,805 | 22,501 | 12,613 | 21,824 | 12,279 | 25,470 | 13,627 | 25,373 | 25,791 |
| **DTW** | 16,004 | 8,479 | 11,844 | 8,154 | 12,505 | 7,814 | 14,000 | 8,288 | 11,437 | 15,529 |
| **EWR** | 57,564 | 8,938 | 42,935 | 8,876 | 34,041 | 8,561 | 46,192 | 8,319 | 47,517 | 58,379 |
| **IAH** | 11,062 | 6,881 | 8,141 | 6,357 | 8,272 | 6,629 | 9,893 | 6,543 | 9,521 | 10,323 |
| **JFK** | 4,489 | 3,920 | 4,730 | 4,019 | 4,514 | 3,831 | 4,527 | 3,855 | 3,681 | 4,664 |
| **LAX** | 7,430 | 4,112 | 5,595 | 4,525 | 4,855 | 4,090 | 6,172 | 4,258 | 7,570 | 7,235 |
| **LGA** | 68,070 | 10,486 | 51,688 | 9,590 | 59,411 | 9,656 | 69,714 | 10,224 | 72,996 | 68,896 |
| **MEM** | 19,896 | 9,283 | 14,366 | 8,548 | 13,662 | 8,021 | 16,397 | 8,447 | 16,665 | 18,141 |
| **MIA** | 5,666 | 2,790 | 4,016 | 2,794 | 3,730 | 2,648 | 5,303 | 2,784 | 4,621 | 5,824 |
| **ORD** | 253,407 | 131,114 | 265,451 | 88,143 | 263,020 | 99,296 | 249,000 | 131,609 | 247,062 | 247,028 |
| **PHL** | 23,767 | 12,754 | 18,701 | 13,211 | 20,649 | 13,052 | 21,128 | 13,293 | 19,261 | 21,713 |
| **SDF** | 3,915 | 2,827 | 3,273 | 2,580 | 3,247 | 2,992 | 3,824 | 2,809 | 3,276 | 3,451 |
| **SEA** | 1,529 | 1,195 | 1,188 | 1,152 | 1,132 | 1,153 | 1,072 | 1,144 | 1,594 | 1,441 |
| **SFO** | 8,271 | 2,653 | 5,027 | 2,441 | 3,991 | 2,341 | 4,664 | 2,343 | 8,558 | 7,683 |
| **STL** | 17,651 | 10,883 | 14,689 | 9,662 | 15,357 | 10,773 | 15,660 | 10,683 | 14,467 | 17,302 |
| **Total** | **649,924** | **270,981** | **566,377** | **222,263** | **568,823** | **232,436** | **605,371** | **268,635** | **593,516** | **630,401** |

**Table 23 Minutes of Delay for 24 Hours of Operations**

| | **OEP 2010 AIRPORT CAPACITIES** | | **LANGLEY PHASE III SINGLE RUNWAY ARRIVALS & DEPARTURES** | | **MITRE-CAASD PHASE II SINGLE RUNWAY ARRIVALS & DEPARTURES** | | **MITRE-CAASD PHASE II CSPR ARRIVALS & DEPARTURES** | | **RULE CHANGE PHASE I CSPR ARRIVALS** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | **Unrest-ricted** | **Restricted Large/ Small** |
| **Airport** | **IFR** | **VFR** | **IFR** | **VFR** | **IFR** | **VFR** | **IFR** | **VFR** | **IFR** | **IFR** |
| **ATL** | 14 | 4 | 21 | 5 | 21 | 4 | 10 | 2 | 9 | 20 |
| **BOS** | 41 | 30 | 39 | 30 | 39 | 29 | 35 | 29 | 30 | 37 |
| **CLE** | 17 | 4 | 14 | 3 | 13 | 1 | 16 | 3 | 15 | 18 |
| **CLT** | 19 | 4 | 11 | 2 | 14 | 4 | 9 | 5 | 8 | 8 |
| **DFW** | 1 | 0 | 0 | 1 | 1 | 2 | 1 | 0 | 1 | 1 |
| **DTW** | 22 | 6 | 18 | 4 | 14 | 6 | 17 | 5 | 16 | 17 |
| **EWR** | 15 | 5 | 7 | 4 | 4 | 6 | 9 | 4 | 6 | 13 |
| **IAH** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **JFK** | 11 | 3 | 8 | 3 | 7 | 3 | 7 | 3 | 6 | 9 |
| **LAX** | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| **LGA** | 20 | 2 | 13 | 3 | 13 | 2 | 14 | 2 | 7 | 18 |
| **MEM** | 1 | 3 | 7 | 4 | 7 | 2 | 0 | 3 | 0 | 1 |
| **MIA** | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 4 | 2 |
| **ORD** | 337 | 0 | 52 | 0 | 54 | 0 | 359 | 0 | 356 | 357 |
| **PHL** | 17 | 8 | 16 | 6 | 17 | 7 | 16 | 6 | 9 | 16 |
| **SDF** | 9 | 3 | 6 | 3 | 5 | 1 | 7 | 3 | 7 | 8 |
| **SEA** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **SFO** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **STL** | 16 | 7 | 11 | 8 | 10 | 5 | 15 | 7 | 15 | 16 |
| **Total** | **542** | **80** | **224** | **76** | **220** | **72** | **516** | **72** | **489** | **542** |

**Table 24 Cancellations for 24 Hours of Operations**

*(Flight departure delayed by more than 5 hours.)*

| Airport | Langley PHASE III SINGLE RUNWAY ARRIVALS & DEPARTURES | | MITRE-CAASD PHASE II SINGLE RUNWAY ARRIVALS & DEPARTURES | | MITRE-CAASD PHASE II CSPR ARRIVALS & DEPARTURES | | RULE CHANGE PHASE I CSPR ARRIVALS | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Unrest-ricted | Restricted Large/ Small |
| | IFR | VFR | IFR | VFR | IFR | VFR | IFR | IFR |
| **ATL** | 167 | 4 | 196 | 15 | | | | |
| **BOS** | 145 | -6 | 160 | -1 | 107 | 5 | 171 | 65 |
| **CLE** | 171 | 5 | 27 | 4 | 130 | 3 | 199 | 23 |
| **CLT** | 83 | 11 | 67 | 11 | | | | |
| **DFW** | 76 | 32 | 82 | 32 | 21 | 20 | 23 | 16 |
| **DTW** | 89 | 15 | 98 | 11 | 58 | 8 | 106 | 33 |
| **EWR** | 284 | 6 | 447 | 1 | 220 | 15 | 212 | -4 |
| **IAH** | 49 | 9 | 47 | 4 | 19 | 6 | 26 | 12 |
| **JFK** | 11 | -2 | 20 | 1 | | | | |
| **LAX** | 36 | -2 | 48 | 5 | 26 | 3 | | |
| **LGA** | 308 | 10 | 179 | 14 | 73 | 0 | | |
| **MEM** | 62 | 7 | 74 | 26 | 63 | 14 | 59 | 29 |
| **MIA** | 27 | 0 | 32 | 2 | 6 | 0.1 | | |
| **ORD** | 1,224 | 716 | 1,255 | 530 | | | | |
| **PHL** | 89 | 2 | 52 | 0 | 49 | 1 | 115 | 39 |
| **SDF** | 26 | 4 | 31 | 7 | | | | |
| **SEA** | 6 | 1 | 7 | 1 | 8 | 1 | | |
| **SFO** | 54 | 4 | 71 | 5 | 60 | 5 | | |
| **STL** | 74 | 15 | 68 | 12 | 38 | 3 | 58 | 6 |
| **Total** | **2,982** | **832** | **2,962** | **682** | **878** | **84** | **969** | **220** |

**Table 25 Hours of Delay Reduction due to WakeVAS for 24 Hours of Operations**

| | OEP 2010 AIRPORT CAPACITIES | | LANGLEY PHASE III SINGLE RUNWAY ARRIVALS & DEPARTURES | | MITRE-CAASD PHASE II SINGLE RUNWAY ARRIVALS & DEPARTURES | | MITRE-CAASD PHASE II CSPR ARRIVALS & DEPARTURES | | RULE CHANGE PHASE I CSPR ARRIVALS | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Unrest-ricted | Restricted Large/ Small |
| | IFR | VFR | IFR | VFR | IFR | VFR | IFR | VFR | IFR | IFR |
| **Flown** | 28,324 | 29,191 | 28,789 | 29,227 | 28,797 | 29,221 | 28,460 | 29,212 | 28,528 | 28,407 |
| **Cancelled** | 1,185 | 318 | 720 | 282 | 712 | 288 | 1,049 | 297 | 981 | 1102 |
| **Total Delay** | 971,885 | 442,621 | 814,369 | 405,985 | 807,105 | 410,130 | 872,940 | 442,138 | 833,443 | 931,747 |
| **Delay per Flight** | **34.3** | **15.2** | **28.3** | **13.9** | **28.0** | **14.0** | **30.7** | **15.1** | **29.2** | **32.8** |

**Table 26 Network Wide Total Minutes of Delay**

| | Langley PHASE III SINGLE RUNWAY ARRIVALS & DEPARTURES | | MITRE-CAASD PHASE II SINGLE RUNWAY ARRIVALS & DEPARTURES | | MITRE-CAASD PHASE II CSPR ARRIVALS & DEPARTURES | | RULE CHANGE PHASE I CSPR ARRIVALS | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Unrestricted | Restricted Large/ Small |
| **Airport** | **IFR** | **VFR** | **IFR** | **VFR** | **IFR** | **VFR** | **IFR** | **IFR** |
| **ATL** | 14,057 | 366 | 378 | 37 | | | | |
| **BOS** | 9,534 | -391 | 1,468 | -15 | 5,267 | 866 | 11,248 | 4,247 |
| **CLE** | 9,383 | 249 | 158 | 58 | 4,532 | 299 | 10,875 | 1,264 |
| **CLT** | 5,446 | 750 | 62 | 14 | | | | |
| **DFW** | 4,714 | 1,957 | 179 | 185 | 951 | 2,141 | 1,433 | 1,002 |
| **DTW** | 7,500 | 1,294 | 660 | 131 | 3,854 | 1,626 | 8,909 | 2,763 |
| **EWR** | 19,683 | 418 | 3,255 | 24 | 10,856 | 1,630 | 14,734 | -248 |
| **IAH** | 4,265 | 765 | 326 | 49 | 1,217 | 561 | 2,250 | 1,079 |
| **JFK** | 561 | -84 | 142 | 43 | | | | |
| **LAX** | 2,338 | -124 | 13 | 2 | 1,217 | 277 | | |
| **LGA** | 22,487 | 726 | 1,440 | 275 | | | | |
| **MEM** | 4,766 | 555 | 453 | 315 | 3,461 | 1,201 | 4,512 | 2,242 |
| **MIA** | 301 | -1 | 28 | 35 | 47 | 9 | | |
| **ORD** | 67,028 | 39,211 | 8,175 | 8,720 | | | | |
| **PHL** | 4,896 | 131 | 182 | 0 | 2,102 | 83 | 6,301 | 2,148 |
| **SDF** | 1,876 | 301 | 157 | 59 | | | | |
| **SEA** | 602 | 76 | 56 | 8 | 416 | 22 | | |
| **SFO** | 5,131 | 335 | 542 | 59 | 3,292 | 294 | | |
| **STL** | 6,244 | 1,289 | 613 | 153 | 3,008 | 462 | 4,876 | 489 |
| **Total** | **190,811** | **47,823** | **18,287** | **10,150** | **40,220** | **9,471** | **65,138** | **14,986** |

**Table 27 Annual Hours of Delay Reduction due to WakeVAS**

| Cost per hr | Airborne | Ground | Ground Hold |
|---|---|---|---|
| **Aircraft Average** | $2,209 | $1,702 | $852 |

**Table 28 Airlines Operating Costs**

| Airport | Langley PHASE III SINGLE RUNWAY ARRIVALS & DEPARTURES | MITRE-CAASD PHASE II SINGLE RUNWAY ARRIVALS & DEPARTURES | MITRE-CAASD PHASE II CSPR ARRIVALS & DEPARTURES | RULE CHANGE PHASE I CSPR ARRIVALS | |
|---|---|---|---|---|---|
| | | | | Unrest-ricted | Restricted Large/ Small |
| **ATL** | $24,111,646 | $696,322 | N/A | N/A | N/A |
| **BOS** | $12,667,659 | $1,996,761 | $7,348,340 | $12,609,883 | $4,240,382 |
| **CLE** | $13,984,405 | $24,168 | $7,345,251 | $16,888,045 | $1,343,758 |
| **CLT** | $5,675,142 | $62,829 | N/A | N/A | N/A |
| **DFW** | $9,119,217 | $524,639 | $4,763,442 | $1,752,708 | $1,465,894 |
| **DTW** | $9,068,384 | $777,083 | $5,767,712 | $7,339,580 | $2,256,190 |
| **EWR** | $31,843,313 | $5,227,462 | $19,980,580 | $21,779,339 | -$241,437 |
| **IAH** | $6,301,571 | $445,804 | $2,688,616 | $2,577,800 | $1,418,928 |
| **JFK** | $893,763 | $319,432 | N/A | N/A | N/A |
| **LAX** | $3,388,650 | $22,645 | $2,077,168 | N/A | N/A |
| **LGA** | $36,676,937 | $2,369,719 | N/A | N/A | N/A |
| **MEM** | $8,219,484 | $1,232,744 | $6,243,858 | $4,452,361 | $2,298,827 |
| **MIA** | $307,176 | $88,169 | $249,868 | N/A | N/A |
| **ORD** | $129,647,936 | $22,868,596 | N/A | N/A | N/A |
| **PHL** | $5,643,009 | $64,425 | $2,406,546 | $6,798,213 | $2,683,479 |
| **SDF** | $2,003,205 | $232,104 | N/A | N/A | N/A |
| **SEA** | $616,641 | $59,238 | $469,775 | N/A | N/A |
| **SFO** | $9,217,359 | $1,003,619 | $6,102,265 | N/A | N/A |
| **STL** | $9,505,847 | $892,718 | $4,391,278 | $5,407,157 | $955,660 |
| **Total** | **$318,891,344** | **$38,908,477** | **$69,834,699** | **$79,605,086** | **$16,421,681** |

Table 29 Annual Airline Cost Savings Due to WakeVAS

| Total Annual Cost Savings | 19 AIRPORTS | NETWORK WIDE |
|---|---|---|
| **SINGLE RUNWAY (Phase III)** | $318,891,344 | $687,368,298 |
| **CSPR (Phase II)** | $69,834,699 | $130,517,693 |
| **SINGLE RUNWAY (Phase II)** | $38,908,477 | $41,004,465 |
| **CSPR Arrivals Unrestricted (Phase I)** | $79,605,086 | $213,232,574 |
| **CSPR Arrivals Unrestricted > 1200 ft lateral runway spacing (Phase I)** | | |

# 7. Dependence of Delay on Demand and Airport Capacity

ACES Build 3.2.1 has a simple nodal model of airports which represents the airport capacity under VFR and IFR as a boundary for each operating state, generated from a triplet of values representing hourly capacity for arrivals only, departures only and maximum total mixed departures and arrivals. This nodal model keeps track of arrival and departure queues of aircraft and attempts to adjust the allowed departure and arrival rates within the capacity limits to favour departures, arrivals or give equal weight depending on the demand. All queuing models exhibit rapid growth in delay when the average demand approaches some fraction of the capacity and exhibit an exponential trend in delay. In reality, delays would not be allowed to reach extreme levels before action would be taken, so caution must be used to ensure the demand/capacity ratio at the airport is not so large as to create unrealistic delays, if the results from an analysis of a capacity enhancing concept are to be meaningful.

ACES Build 3.2.1 also has an enhanced terminal model which can include a higher fidelity representation of the specific runway system at individual airports. This was not used for this study, since few airports have currently been modelled at the higher level of detail. (The enhanced model for ORD was initially used, but did not agree well with nodal model results, so was discounted for this study). The use of the enhanced model will be investigated for a future study and may possibly exhibit less rapidly increasing levels of delay as demand increases.

The results from multiple simulation runs are shown in Figure 8. The demand/capacity ratio used is the total demand in 24 hours divided by the total airport capacity in 24 hours; this is the average demand and does not capture peak demand periods.

It is clear from the figure that there is an exponential increase in delay as the demand/capacity ratio increases, with a very large level of delay occurring once the demand/capacity ratio exceeds 0.7. If 15 minutes of delay on average are considered the maximum acceptable then the average demand to capacity ratio needs to be kept below about 0.63.

The demand set generated for this analysis was approximately 1.4X the enplanements of the baseline 2002 May 19 demand set. Table 31 shows the number of operations and demand/capacity ratio based on OEP 2010 airport capacities for each of the 19 study airports for the 1.4X demand and for the ACES supplied 2X demand. Even with 1.4X the demand/capacity ratio exceeds 0.63 for many airports under IFR. With the 2X demand, the demand/capacity ratio exceeds 0.63 for nearly all of the airports under both IFR and VFR conditions. For 2X at many airports the 24hr *average* demand/capacity ratio exceeds one, which means a 2X demand set would not be feasible with airport capacities based on OEP 2010 capacity enhancements (this is the case even with WakeVAS improvements).

A limitation of this current study is that the airports were all operated under either VFR or IFR conditions at the same time, whereas in reality a mix of VFR and IFR conditions would occur, changing throughout the day. This was done for simplicity and because there is currently only a limited set of weather dependent airport state data for ACES, with no clear agreement on how to annualize results obtained. If the airports were operated in a more realistic way, then it is likely that a higher level of demand could be accommodated without excessive delay.

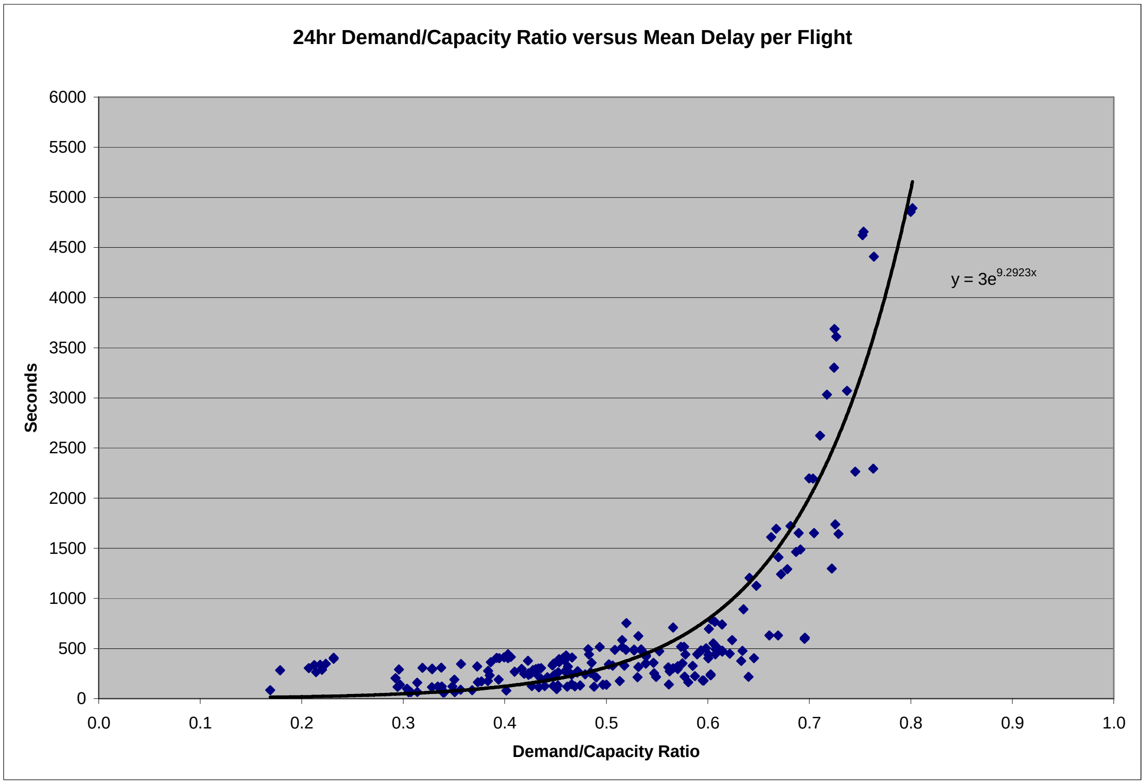

**Figure 8 Demand/Capacity Ratios versus Mean Delay per Flight**

| **Airport** | **OEP 2010 VFR Capacity** | **OEP 2010 IFR Capacity** | **Total Operations ACES 2X** | **24hr DEMAND /CAPACITY** | | **Total Operations LANGLEY 1.4X** | **24hr DEMAND /CAPACITY** | |
|---|---|---|---|---|---|---|---|---|
| | | | | **VFR** | **IFR** | | **VFR** | **IFR** |
| **ATL** | 269 | 231 | 6558 | 1.02 | 1.18 | 4032 | 0.62 | 0.73 |
| **BOS** | 131 | 91 | 2309 | 0.73 | 1.06 | 1815 | 0.58 | 0.83 |
| **CLE** | 105 | 59 | 1426 | 0.57 | 1.01 | 1049 | 0.42 | 0.74 |
| **CLT** | 179 | 142 | 2895 | 0.67 | 0.85 | 2290 | 0.53 | 0.67 |
| **DFW** | 281 | 224 | 3832 | 0.57 | 0.71 | 3230 | 0.48 | 0.60 |
| **DTW** | 191 | 170 | 4238 | 0.92 | 1.04 | 2096 | 0.46 | 0.51 |
| **EWR** | 117 | 83 | 2920 | 1.04 | 1.47 | 1746 | 0.62 | 0.88 |
| **IAH** | 173 | 159 | 4891 | 1.18 | 1.28 | 1957 | 0.47 | 0.51 |
| **JFK** | 100 | 73 | 2739 | 1.14 | 1.56 | 871 | 0.36 | 0.50 |
| **LAX** | 175 | 133 | 4400 | 1.05 | 1.38 | 2376 | 0.57 | 0.74 |
| **LGA** | 89 | 66 | 1566 | 0.73 | 0.99 | 1410 | 0.66 | 0.89 |
| **MEM** | 157 | 124 | 2919 | 0.77 | 0.98 | 1814 | 0.48 | 0.61 |
| **MIA** | 164 | 134 | 1637 | 0.42 | 0.51 | 1611 | 0.41 | 0.50 |
| **ORD** | 213 | 179 | 5770 | 1.13 | 1.34 | 4052 | 0.79 | 0.94 |
| **PHL** | 127 | 106 | 3715 | 1.22 | 1.46 | 1837 | 0.60 | 0.72 |
| **SDF** | 111 | 105 | 840 | 0.32 | 0.33 | 631 | 0.24 | 0.25 |
| **SEA** | 142 | 121 | 2309 | 0.68 | 0.80 | 1314 | 0.39 | 0.45 |
| **SFO** | 99 | 74 | 2250 | 0.95 | 1.27 | 1284 | 0.54 | 0.72 |
| **STL** | 140 | 122 | 1482 | 0.44 | 0.51 | 1910 | 0.57 | 0.65 |

**Table 31 Demand/Capacity Ratio for 1.4X and 2X Demand Sets**

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**14. ABSTRACT**

The FAA and NASA are currently engaged in a Wake Turbulence Research Program to revise wake turbulence separation standards, procedures, and criteria to increase airport capacity while maintaining or increasing safety. The research program is divided into three phases: Phase I – near term procedural enhancements; Phase II – wind dependant Wake Vortex Advisory System (WakeVAS) Concepts of Operations (ConOps); and Phase III – farther term ConOps based on wake prediction and sensing. This report contains an analysis that evaluates the benefits of a closely spaced parallel runway (CSPR) Phase I ConOps, a single runway and CSPR Phase II ConOps and a single runway Phase III ConOps. A series of simulation runs were performed using the Airspace Concepts Evaluation System (ACES) Build 3.21 air traffic simulator to provide an initial assessment of the reduction in delay and cost savings obtained by the use of a WakeVAS at selected U.S. airports. The ACES simulator is being developed by NASA Ames Research Center as part of the Virtual Airspace Modelling and Simulation (VAMS) program.

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