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Impact of Airport Capacity Constraints on National Airspace System Delays

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This paper develops a method for understanding the system-wide impact, measured in delay, of arrival and departure capacity constraints at 34 major airports in the United States. Capacity constraints at airports limit departures and arrivals, consequently delays accrue. Baseline arrival and departure rates at these airports were determined by analyzing four months of data. In addition to the most often used arrival and departure rates, reduced arrival and departure rates were also obtained from the four months of data. Both the baseline and the reduced airport arrival and departure rates were used as constraints for computing system-wide delays. Airport arrival and departure rates were changed at each airport, one at a time, to determine the effect of such changes on the arrival and departure delays at the other airports. Results of one hundred and three simulations are given as sensitivity matrices. These matrices describe the impact of arrival or departure capacity reduction at each of these airports on the arrival and departure delays at other major airports in the continental United States.

I. Introduction

As departure and arrival capacities are reduced at an airport, fewer aircraft depart and arrive at that airport. Aircraft are delayed prior to takeoff both due to departure restrictions at the airports of origin and due to arrival restrictions at the airports of destination. For example, air traffic management initiatives such as ground delay programs moderate arrival demand in response to reduced landing capacity at an airport by delaying in-bound flights at their airports of origin. In addition, airlines operate a hub-and-spoke network in which flights arriving from one airport are flown out to different destinations. This connectivity between flights causes departure or arrival delays at one airport to impact delays at other airports.

An approach similar to the one used for studying the sensitivity of delays at one airport on another, discussed in this paper, is described in Ref. 1. The study in Ref. 1 determined the benefits of airport capacity enhancing technologies. The benefits were measured in terms of delay savings using a simulation in which the airports and sectors were modeled as nodes of a node-link network. Ref. 1 did not attempt to determine how airport capacity changes at one airport affect delays at the other airports.

This paper is devoted to quantifying how delay at one of the 34 major airports in the United States affects the departure and arrival delays at the other major airports in the United States. The method for determining the impact of capacity reduction at one airport on the other airports consists of using the National Aeronautics and Space Administration's (NASA) Airspace Concept Evaluation System (ACES). Baseline and reduced airport departure and arrival capacities were obtained by analyzing four-months of Aviation System Performance Metrics (ASPM) data. A series of ACES simulations with baseline and reduced capacities were performed that showed the effect of capacity reduction at one airport on the other major airports.

The paper is organized as follows. Section II describes the method for determining the affect of capacity reduction at one airport on the delays at the other airports. Section III presents the inputs needed for conducting ACES simulations. This includes determination of baseline and reduced airport departure and arrival capacities, and data conditioning steps. Results obtained using the baseline and reduced airport capacities via 103 ACES simulations are discussed in Section IV. The paper is summarized in Section V.

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II. Sensitivity Study Method

This section describes the sensitivity analysis method used for determining the affect that departure and arrival capacity reduction at one major airport has on the departure and arrival delays at the other 33 major airports in the continental United States. The 34 airports considered in this study are tracked in the Operational Evolution Plan (OEP) of the Federal Aviation Administration (FAA) and are referred to as OEP airports.

The sensitivity determination method consists of conducting an ACES simulation with the 34 airport departure and arrival capacities set at their most common settings for establishing the baseline delays. Then, performing a series of ACES runs with airport departure and arrival capacities reduced at each airport one at a time, while maintaining baseline capacity value at the other airports, to determine the change in arrival and departure delays at each of the 34 airports.

The Airspace Concept Evaluation System (ACES) was used to do the simulations. ACES is a comprehensive computational model of the national airspace system consisting of air traffic control and traffic flow management models of air route traffic control centers, terminal radar approach controls (TRACON), airports and the air traffic control system command center (ATCSCC).[2] It simulates flight trajectories through the enroute-phase of flights, where the enroute-phase for piston-props is 6,000 feet, for turboprops is 8,000 feet and for jet aircraft is 10,000 feet. A queuing model simulates the surface movement and flight through the terminal airspace. Thus, with continuous aircraft dynamics and discrete air traffic control and traffic flow management events, ACES is a hybrid-system. The traffic flow management and air traffic control models in ACES use airport and sector capacity thresholds for delaying flights while they are on the ground and during their enroute phase to ensure that these capacity thresholds are not exceeded. Some of the ACES outputs are arrival and departure counts at airports, traffic counts in sectors and air traffic system performance metrics including arrival, departure, enroute and total delays. Validation studies in Refs. 3 and 4 have shown that ACES generates realistic delays and airport operational metrics similar to those observed in the real-world. Due to these capabilities, ACES was chosen as the system for conducting the airport departure and arrival rate sensitivity study discussed in this paper.

III. Simulation Inputs and Outputs

Input for ACES simulations consists of scenario files containing capacity data (airport arrival and departure capacities, and sector capacities), traffic data (scheduled departure times and flight-plans), and adaptation data (sector/center geometric data). These inputs are described below. Delay metrics, the outputs of ACES, are defined in this section.

A. Airport Capacities

To determine airport departure and arrival capacities, four-months of data spanning the period from March 1, 2006 through June 30, 2006 reported in the FAA's Aviation System Performance Metrics (ASPM) database were collected. This database can be accessed via the web site: http://www.apo.data.faa.gov/. Airport capacity data for a particular airport can be obtained by selecting the *Analysis* tab and choosing *Airport*, *Weather* and *Hourly* radio buttons on the graphical user interface. Table 1 shows the airport capacity data for Hartsfield-Jackson Atlanta International airport during each hour of March 17, 2006. The first column shows the local hour and the second column lists the landing and takeoff conditions at that hour. Instrument approach condition is indicated by IA and visual approach condition by VA. The airport departure rate (ADR), which is the number of takeoffs per hour, is tabulated in the third column. The airport arrival rate (AAR), which is the number of landings per hour, is listed in the fourth column of the table. Finally, the total capacity of the airport, which is the sum of the ADR and AAR, is given in the last column of the table. In addition to the items in Table 1, the airport capacity data contain the actual number of arrivals and departures during the hour, cloud-ceiling, visibility, temperature, windspeed, wind-angle and arrival and departure runway configurations.

1. Baseline Capacities

The data of the type listed in Table 1 were analyzed via scripts written in the *Matlab* language[5] to determine the most frequently used total capacities, along with the associated arrival and departure capacities, for each of the 74 ASPM airports including the 34 OEP airports. Honolulu International airport, which is one of the 35 OEP airports, was excluded from analysis because this study is devoted to airports within the continental United States.

After obtaining the most frequently assigned total capacity - mode capacity from the entire dataset, instances with total capacities equal to the selected mode capacity were placed in a subset. Departure and arrival capacities were then selected from this subset based on the minimum of the cost function given in Eq. (1):

$$J = (C_{ADR} - C_{AAR})^2 \tag{1}$$

C_{ADR} is the airport departure rate and C_{AAR} is the airport arrival rate. Observe that a minimum value of the function is obtained when the ADR is equal to the AAR. Table 2 lists the selected ADR and AAR values corresponding to the mode value of total capacities. The first and the seventh columns list the International Civil Aviation Organization codes for the airports. The second and the eighth columns indicate whether the airport is included in the OEP or not. Mode values of the total capacities are given in columns five and eleven. The frequency of occurrence of the mode value of the total capacity for each of the 74 airports is given as a percentage of the total of 2928 (24 hours $\times$122 days) possible instances in columns six and twelve. The ADR and AAR values listed in this table were used in the ACES simulation for generating the baseline delay values.

Table 1. Hartsfield-Jackson Atlanta International airport capacity on March 17, 2006.

Local Hour	Weather	ADR	AAR	Total
0	IA	96	96	192
1	IA	96	96	192
2	IA	96	96	192
3	IA	96	96	192
4	IA	96	96	192
5	IA	96	96	192
6	IA	96	78	174
7	IA	96	82	178
8	VA	96	94	190
9	VA	96	94	190
10	VA	96	94	190
11	VA	96	94	190
12	VA	96	94	190
13	VA	96	94	190
14	VA	96	94	190
15	VA	96	94	190
16	VA	96	94	190
17	VA	96	94	190
18	VA	96	94	190
19	VA	96	94	190
20	VA	96	94	190
21	VA	96	94	190
22	VA	96	94	190
23	VA	96	94	190

2. Reduced Capacities

Matlab scripts were also used to identify instances where total capacities, C_{Total} , were close to 50% of the baseline capacities, C_{Mode} , listed in Table 2. The desire was to identify instances in real data when ADR and AAR were severely reduced. The ADR and AAR values corresponding to 50% capacities were obtained based on the minimum of Eq. (2):

$$J = (C_{ADR} - C_{AAR})^2 + (0.5C_{Mode} - C_{Total})^2 \tag{2}$$

These ADR and AAR values for the 34 OEP airports are listed in Table 3. This second set consists of the reduced airport departure and arrival capacities that were used in ACES simulations for comparisons against the baseline capacities listed in Table 2. Note that the reduced total capacities are not exactly 50% of the mode capacity; they are as close to 50% as possible based on the actual four-months of airport capacity data that were analyzed. For example, the reduced total capacity of Cincinnati/Northern Kentucky International Airport (KCVG) in Table 3 is 69% of the baseline total capacity of 156 aircraft/hour in Table 2.

B. Flight-Plans and Adaptation Data

Flight-plans for the simulations were derived from the Aircraft Situation Display to Industry (ASDI) data, which is provided via the FAA's Enhanced Traffic Management System (ETMS)[6], spanning the period from zero Coordinated Universal Time (UTC) on 17 March 2006 to zero UTC on 19 March 2006. These days were selected because 1) they were within the March 1, 2006 to June 30, 2006 time period and 2) they had experienced high traffic-volume, low weather impact and low delays. There were 48,258 departures on the 17th (a Friday) and 35,394 departures on the 18th (a Saturday) according to the *Centers: Summary of Domestic Operations Report* in the FAA's

Table 2. Baseline capacities for the 74 ASPM airports.

Airport	Type	ADR	AAR	Total	% Occur.	Airport	Type	ADR	AAR	Total	% Occur.
KABQ	ASPM	40	50	90	62	KTEB	ASPM	25	25	50	42
KANC	ASPM	24	24	48	82	KTUS	ASPM	32	35	67	66
KAUS	ASPM	60	80	140	100	KVNY	ASPM	50	50	100	70
KBDL	ASPM	37	37	74	33	KATL	OEP	96	96	192	21
KBHM	ASPM	42	42	84	44	KBOS	OEP	52	63	112	18
KBNA	ASPM	60	74	134	64	KBWI	OEP	45	45	90	75
KBUF	ASPM	56	56	112	33	KCLE	OEP	56	56	112	40
KBUR	ASPM	36	36	72	51	KCLT	OEP	60	60	120	35
KDAL	ASPM	30	30	60	48	KCVG	OEP	72	84	156	35
KDAY	ASPM	47	58	105	75	KDCA	OEP	36	36	72	46
KGYY	ASPM	50	50	100	100	KDEN	OEP	120	120	240	74
KHOU	ASPM	28	28	56	51	KDFW	OEP	100	126	226	25
KHPN	ASPM	30	30	60	46	KDTW	OEP	92	72	164	37
KIND	ASPM	72	72	144	80	KEWR	OEP	44	48	92	26
KISP	ASPM	28	28	56	65	KFLL	OEP	40	42	82	47
KJAX	ASPM	48	40	88	44	KIAD	OEP	68	57	125	33
KLGB	ASPM	24	24	48	94	KIAH	OEP	56	120	176	25
KMCI	ASPM	52	52	104	68	KJFK	OEP	42	35	77	27
KMHT	ASPM	26	26	52	78	KLAS	OEP	50	54	104	54
KMKE	ASPM	35	32	67	100	KLAX	OEP	64	68	132	21
KMSY	ASPM	35	40	75	62	KLGA	OEP	40	40	80	59
KOAK	ASPM	80	45	125	69	KMCO	OEP	72	72	144	48
KOGG	ASPM	32	32	64	99	KMDW	OEP	36	36	72	56
KOMA	ASPM	36	36	72	98	KMEM	OEP	60	92	152	51
KONT	ASPM	20	25	45	72	KMIA	OEP	60	72	132	69
KOXR	ASPM	45	45	90	99	KMSP	OEP	60	60	120	33
KPBI	ASPM	36	36	72	70	KORD	OEP	100	100	200	40
KPVD	ASPM	27	27	54	91	KPDX	OEP	60	60	120	52
KRDU	ASPM	45	45	90	98	KPHL	OEP	52	52	104	59
KRFD	ASPM	45	45	90	71	KPHX	OEP	60	76	136	63
KRSW	ASPM	18	18	36	35	KPIT	OEP	80	80	160	96
KSAT	ASPM	30	25	55	72	KSAN	OEP	30	30	60	94
KSDF	ASPM	60	60	120	57	KSEA	OEP	50	40	90	35
KSJC	ASPM	20	22	42	28	KSFO	OEP	40	32	72	36
KSJU	ASPM	35	35	70	100	KSLC	OEP	68	84	152	67
KSNA	ASPM	22	27	49	99	KSTL	OEP	52	52	104	70
KSWF	ASPM	30	30	60	95	KTPA	OEP	35	35	70	25

Air Traffic Operations Network (OPSNET) database.[7] Delay data obtained from the OPSNET database for these days are provided in Table 4. The second row of the table lists the total number of aircraft delayed by fifteen-minutes or more. The third and the fourth rows show the number of aircraft delayed due to weather and due to traffic-volume. Total delay is given in the fifth row. Average delay given in the sixth row is obtained as the ratio of the total delay to the total number of aircraft delayed by fifteen-minutes or more. It can be verified that these two days are low delay days by comparing the total time delay values in Table 4 with those in Table 8 of Ref. 8.

Along with the flight-plan data, adaptation data and capacity data are required for ACES simulation. Sector and center geometry definitions in the January 1, 2005 adaptation data obtained from ETMS have been used to generate the results in this paper. Baseline sector capacity values are also derived from January 1, 2005 ETMS data tables.

C. Flight Schedule and Connectivity

The flight connectivity data, data conditioning steps and delay metrics are described in this section.

1. Flight Connectivity Data

Flight connectivity data relating the same physical aircraft to two or more flights segments were obtained from the Bureau of Transportation Statistics (BTS) for the two days. Airline flight-numbers were used as tail-numbers for flights not found in the BTS data. The airline flight-numbers, aircraft tail-numbers and the associated flight-plans for all the flights were then included in the Flight Data Set (FDS) file.

The subsequent step consists of assigning a departure time to the flights in the FDS file. Scheduled departure times derived from the BTS data are assigned to the flights in the FDS file found in the BTS data. For flights that are not in the BTS data, proposed departure times from flight-plan messages in the ASDI data are assigned as scheduled departure times. In instances when the route of flight is available but the departure time is not, average taxi times reported in the FAA's Aviation System Performance Metrics (ASPM) database are subtracted from the departure message times reported in the ASDI data to estimate the gate departure times. Scheduled departure times are then set to these gate departure times.

Table 3. Reduced capacities for the 34 OEP airports.

Airport	ADR	AAR	Total	Airport	ADR	AAR	Total
KATL	48	48	96	KLGA	25	25	50
KBOS	26	26	52	KMCO	36	36	72
KBWI	28	28	56	KMDW	24	24	48
KCLE	28	28	56	KMEM	60	56	116
KCLT	30	30	60	KMIA	30	32	62
KCVG	51	57	108	KMSP	26	26	52
KDCA	26	26	52	KORD	50	50	100
KDEN	62	62	124	KPDX	32	32	64
KDFW	56	59	115	KPHL	28	26	54
KDTW	60	48	108	KPHX	60	48	108
KEWR	30	30	60	KPIT	40	40	80
KFLL	18	18	36	KSAN	28	28	56
KIAD	30	32	62	KSEA	28	28	56
KIAH	48	48	96	KSFO	25	27	52
KJFK	20	20	40	KSLC	40	40	80
KLAS	30	34	64	KSTL	32	32	64
KLAX	53	57	110	KTPA	20	19	39

Table 4. OPSNET delay data.

Date	3/17/2006	3/18/2006	3/19/2006
# Aircraft Delayed	783	476	1441
Weather	166	264	1199
Volume	396	144	129
Total Delay (min.)	22,054	14,210	70,119
Average Delay (min.)	28.17	29.85	48.66

After assigning a scheduled departure time for every flight, an ACES simulation is run without airport and sector capacity constraints to compute the unconstrained arrival time of each flight at its destination airport. These computed arrival times are then used as scheduled arrival times at the destination airports of the flights.

2. Data Conditioning

Data conditioning steps are needed to compensate for missing and incomplete data. Although the data conditioning steps taken introduce some errors in the simulation, they help keep most flights in the simulation. Errors are due to discrepancies between the airline flight schedule and the simulated flight schedule

Although departure schedules are provided as ACES input, arrival schedules for the flights are created during the configuration step of ACES. These computed arrival times need to be earlier than the scheduled departure times of the next segment of the flights. Data in the initial FDS file are therefore processed further to ensure that flight connectivity is preserved and that the arrival and departure schedules linked to the same physical aircraft account for the turn-around-time.

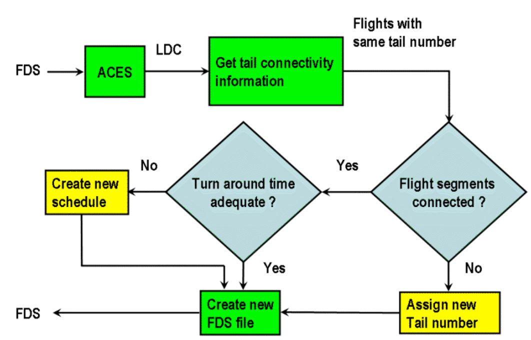

Figure 1. Block diagram of the process for checking flight connectivity and turn-around-times.

Turn-around-time is defined as the time required for unloading the aircraft after arrival at the gate and preparing it for departure. Turn-around-time was assumed to be 40-minutes irrespective of the size of the aircraft. The procedure for checking flight connectivity and turn-around-times is summarized in Fig. 1. The process is begun by running an ACES simulation with the initial FDS file and storing the results in the output database.

The output database is examined to retrieve flights with a common tail-number. These flights are sorted in time and then a check is performed to determine if the destination airport of the previous flight segment is the same as the origin of the next segment. If the check fails, a new tail-number is assigned to the subsequent flight segments. For example, consider the four flight segments in Table 5. Since the first segment of the flight ends at Los Angles International (KLAX) and the next segment begins at KLAX, these two segments are proper. The third segment starts at Chicago O'Hare International (KORD) which indicates that the flight connectivity between the second and the third leg is broken. A new tail-number, N12345-1, is assigned in the FDS file to associate this flight with a different aircraft. Tail-numbers of the subsequent segments are also altered. This means that the tail-number of the fourth segment in Table 5 is also altered to N12345-1 because it shares its airport of origin with the airport of destination of segment three.

Table 5. Flight segments operated by the same physical aircraft.

Segment	Tail-number	Origin	Destination
1	N12345	KSFO	KLAX
2	N12345	KLAX	KDEN
3	N12345	KORD	KIAD
4	N12345	KIAD	KORD

Next, the scheduled arrival and departure times of the flight segments are examined to determine if there is adequate turn-around-time between the segments. If t_{sa} is the scheduled arrival time of the previous segment, t_{sd} is the scheduled departure time of the next segment and t_{tat} is the required turn-around-time, it is expected that

$$t_{sd} \geq t_{sa} + t_{tat} \tag{3}$$

If it is determined that the condition described by Eq. (3) is not met, the scheduled departure time is altered to meet the condition. The amount of change in the departure time also appears in the scheduled time of arrival of this flight segment at the next airport. Since the unimpeded flight time between a pair of origin-destination airports is a constant, a change in departure schedule alters the arrival schedule by the same amount. Once the schedule of a flight segment is altered, schedules of subsequent flight segments are also altered to ensure that the turn-around-time requirement is met.

The process summarized in Fig. 1 was applied to the initial FDS file that contained data for 98,674 flights operating out of 2,669 U. S. and foreign airports that were operated during the 48-hour period from March 17th to the 18th. Flight schedules and tail-numbers were altered for 37,638 flights to create the modified FDS file.

D. Selection of Time Periods for Capacity Reduction

Since the system-wide impact is a function of the time of day when ADR or AAR is reduced, peak-demand times were identified for each airport. A three-hour period around the peak demand time was identified as the time for ADR and AAR reduction at each airport. These times are provided in Table 6. The second and seventh columns list the two dates – 3/17/2006 and 3/18/2006 associated with start-times and end-times for reduction of the ADR and AAR values.

E. Delay Metrics

The delay metrics described below are ACES outputs that have been used for the study described in this paper. Scheduled times are employed in the simulation to provide the datum for computation of delays. Delays associated with the departure and arrival, which are defined below, are computed as those in Ref. 3. Scheduled takeoff time, t_{stt}, is defined as:

$$t_{stt} = t_{sgdt} + t_{utot}, \tag{4}$$

Table 6. Time periods for reduced ADR and AAR values at the 34 OEP airports.

Airport	Start-date	Start-time (UTC)	End-date	End-time (UTC)	Airport	Start-date	Start-time (UTC)	End-date	End-time (UTC)
KATL	3/17	13:00	03/17	16:00	KLGA	03/17	19:00	03/17	22:00
KBOS	3/17	23:00	03/18	2:00	KMCO	03/17	20:00	03/17	23:00
KBWI	3/17	20:00	03/17	23:00	KMDW	03/17	23:00	03/18	2:00
KCLE	3/17	23:00	03/18	2:00	KMEM	03/17	13:00	03/17	16:00
KCLT	3/17	23:00	03/18	2:00	KMIA	03/17	23:00	03/18	2:00
KCVG	3/17	23:00	03/18	2:00	KMSP	03/17	23:00	03/18	2:00
KDCA	3/17	23:00	03/18	2:00	KORD	03/18	0:00	03/18	3:00
KDEN	3/17	16:00	03/17	19:00	KPDX	03/17	14:00	03/17	17:00
KDFW	3/17	23:00	03/18	2:00	KPHL	03/17	23:00	03/18	2:00
KDTW	3/17	22:00	03/18	1:00	KPHX	03/17	16:00	03/17	19:00
KEWR	3/17	23:00	03/18	2:00	KPIT	03/17	19:00	03/17	22:00
KFLL	3/17	21:00	03/18	0:00	KSAN	03/17	15:00	03/17	18:00
KIAD	3/17	20:00	03/17	23:00	KSEA	03/18	1:00	03/18	4:00
KIAH	3/17	18:00	03/17	21:00	KSFO	03/17	18:00	03/17	21:00
KJFK	3/17	21:00	03/18	0:00	KSLC	03/17	16:00	03/17	19:00
KLAS	3/17	23:00	03/18	2:00	KSTL	03/17	18:00	03/17	21:00
KLAX	3/18	3:00	03/18	6:00	KTPA	03/17	21:00	03/18	0:00

where t_{sgdt} is the scheduled gate departure time and t_{utot} is the unimpeded (assuming it is the only aircraft) taxi-out time. Recollect that the scheduled gate departure time is available in the FDS file and that the unimpeded taxi times for the airports are obtained from the ASPM database. The actual takeoff time, t_{att}, is similarly defined as:

$$t_{att} = t_{agdt} + t_{atot}, \tag{5}$$

where t_{agdt} is the actual gate departure time and t_{atot} is the actual taxi-out time. Actual times are not real ones but simulated times. Departure delay is then obtained as:

$$t_{dd} = t_{att} - t_{stt}. \tag{6}$$

Scheduled gate arrival time, t_{sgat}, is defined as:

$$t_{sgat} = t_{stt} + t_{uft} + t_{utit}, \tag{7}$$

where t_{stt} is the scheduled takeoff time (wheels-off time), t_{uft} is the unimpeded flight time and t_{utit} is the unimpeded taxi-in time. Actual gate arrival time, t_{agat}, is similarly defined is terms of the actual takeoff time, t_{att}, actual flight time, t_{aft}, and the actual taxi-in time, t_{atit}, as:

$$t_{agat} = t_{att} + t_{aft} + t_{atit}. \tag{8}$$

The gate arrival delay, t_{gad}, is obtained as:

$$t_{gad} = t_{agat} - t_{sgat} . \tag{9}$$

Substituting Eqs. (7) and (8) in Eq. (9) and using the definition in Eq. (6), it is seen that

$$t_{gad} = t_{dd} + (t_{aft} - t_{uft}) + (t_{atit} - t_{utit}) . \tag{10}$$

Equation (10) shows that the departure delay is accounted as part of the arrival delay. Arrival delay can be reduced by absorbing a part of the departure delay in flight. These metrics were computed with the baseline and reduced airport capacities to study the system-wide impact of capacity reduction at the 34 OEP airports. Results of this study are discussed in the next section.

IV. Results

Results obtained via ACES simulations with baseline capacities are described in Subsection A and those obtained using reduced capacities are discussed in Subsection B.

A. Baseline Capacity Results

A simulation was conducted with the conditioned FDS file, baseline sector capacities and baseline airport departure and arrival capacities listed in Table 2.

Aircraft-counts in each sector resulting from the baseline ACES simulation were retrieved from the output database and added together to compute the total number of aircraft in the continental United States above 10,000 feet altitude at one-minute intervals. This time history of aircraft count was then compared with the time history of the actual number of flights, above 10,000 feet altitude. Actual flights for those days, recorded in the ASDI data, were processed using NASA's Future ATM Concepts Evaluation Tool (FACET).[9] The two time histories are shown in Fig. 2. Observe that the ACES simulation starts with all aircraft on the ground, whereas in the actual air traffic system there are always flights that are airborne. Figure 2 shows that the simulated traffic catches up with the actual traffic around four UTC. The general trend of the simulated traffic is similar to the actual traffic for the twenty-four hours between eight UTC on 17 March 2006 and eight UTC on 18 March 2006 (location marked 32 UTC in Fig. 2).

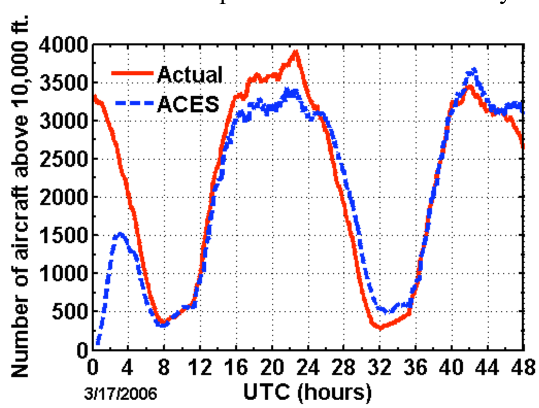

Figure 2. ACES simulated aircraft counts and actual aircraft counts comparison.

Differences between the time histories are both due to issues with the actual flight data and with the simulation. Several issues related to the quality of ASDI data are described in Ref. 10. These issues make it difficult to exactly determine how many flights are in the airspace at a given instant of time. Flight-plan amendments, cancellations and pop-up flights are not included in the simulation. Flights with track information but missing flight-plans in ASDI data are not included in the simulation. Additionally, the trajectory flown by the real aircraft can be different than the one synthesized in the simulation.

During the simulation, aircraft were delayed on the ground and in the air to ensure that the airport and sector capacities were not exceeded. Figure 3 shows the baseline ADR value of 96, scheduled takeoff demand and the achieved takeoff rate at the Hartsfield-Jackson Atlanta airport as a function of time. The time along the abscissa is with respect to 17 March 2006, 0:00 UTC. The dashed line shows the baseline ADR value. The scheduled demand is shown with a solid-line marked with crosses (x) and the achieved departure rate, measured as the number of aircraft that departed in one-hour time period, is shown with another solid-line marked with circles (o). Observe that the scheduled demand was greater than the ADR value, whereas the achieved ('actual') departure rate is close to the ADR value. Comparing the scheduled demand and the achieved rate graphs in Fig. 3 between the locations marked as 28 UTC and 32 UTC, it is seen that the excess demand is modulated by shifting the flights to later times. Actual departure rates beyond 44:00 UTC should be ignored because departed flights that did not reach their destination airports prior to termination of the simulation were not counted.

The arrival rate was also controlled in ACES to guarantee that the baseline AAR capacities are not exceeded. Figure 4 shows the baseline AAR value of 96, scheduled arrival demand and the achieved arrival rate at the Hartsfield-Jackson Atlanta airport. Observe that the arrival rate constraint was also met by delaying flights, which is reflected in the duration of the achieved arrival rate being close to the AAR value.

It should be noted that most of the arrival delays are realized prior to departure at the departure airport and minimally in the airborne phase. In this sense, delays are mostly realized (imposed) at airports of origin both for ADR constraints at airports of origin and AAR constraints at the airports of destination. This is also the way most of the delays occur in the real air traffic system. For example, controlled departure times are issued at airports of origin during a Ground Delay Program at a destination airport.

The values of t_{dd} and t_{gad} for each of the 34 OEP airports were obtained from the ACES baseline simulation. Table 7 lists these values along with the number of aircraft that departed from and arrived at each airport and the number of aircraft that landed at each airport during the twenty-four hour period spanning from eight UTC on 17 March 2006 to eight UTC on 18 March 2006 (location marked as 32 UTC in Fig. 2). Columns one and six list the airports. Departure-counts are listed in columns two and seven, and the total departure delays in minutes obtained by summing the departure delays of aircraft delayed by 15-minutes or more are given in columns three and eight. This 15-minutes delay metric is commonly used by the FAA for assessing the performance of the air traffic system. Arrival-counts are provided in columns four and nine, and the total arrival delays in minutes obtained as the sum of arrival delays of aircraft delayed by 15-minutes or more are listed in columns five and ten.

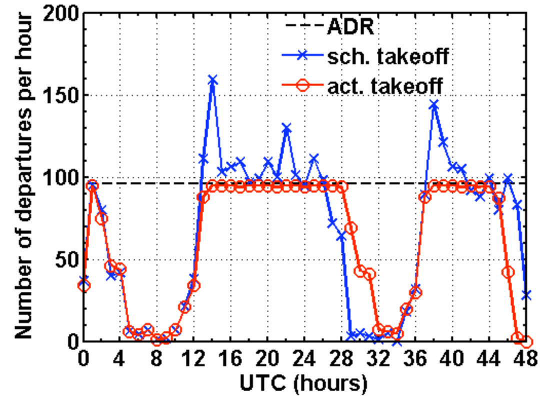

Figure 3. Departure rate achieved at Hartsfield-Jackson Atlanta airport with baseline airport and sector capacities.

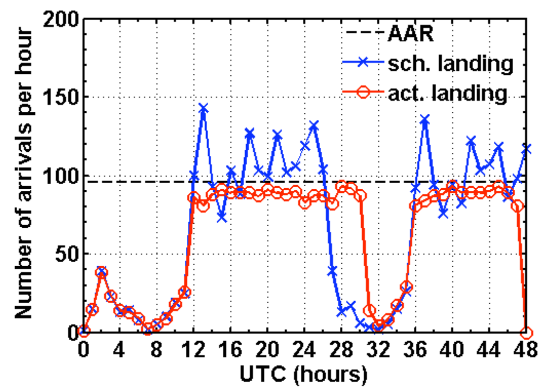

Figure 4. Arrival rate achieved at Hartsfield-Jackson Atlanta airport with baseline airport and sector capacities.

It should be noted that the delays in Table 7 cannot be compared with the OPSNET delays given in Table 4 because of their definitions. Delays in ACES are compared against schedule, whereas delays in OPSNET are compared with respect to the time when pilot requests permission to depart. In ACES, once a flight incurs departure delay, it can continue to incur departure delays as it arrives and departs from other airports. In the real system, it is possible that departure delay is only accounted once. Delays would not accrue in subsequent flight segments, if the air traffic controller permits the flight to depart soon after departure request is made by the pilot.

Departure delay per flight is obtained as the ratio of the total departure delays to the departure-counts and the arrival delay per flight is obtained as the ratio of the total arrival delays to the arrival-counts. These ratios, obtained using the data in Table 7, are shown in Fig. 5. This figure shows that Hartsfield-Jackson Atlanta International (KATL) flights experience the most departure and arrival delays. One of the reasons is apparent from Fig. 3, which shows that the ratio of peak departure demand to departure capacity is 1.7. For comparison, Chicago O'Hare (KORD), which has similar ADR and AAR values as Atlanta, has a peak departure demand to capacity ratio of 1.1. Flights departing from George Bush Intercontinental/Houston Airport (KIAH) and flights arriving at Fort Lauderdale/Hollywood International (KFLL) also experience significant delays. The large difference between

Table 7. Baseline delay results for 34 OEP airports.

Airport	Dep. count	Dep. Delay ≥ 15 min.	Arr. count	Arr. Delay ≥ 15 min.	Airport	Dep. count	Dep. Delay ≥ 15 min.	Arr. count	Arr. Delay ≥ 15min.
KATL	1,761	151,897	1,787	166,517	KLGA	647	14,717	642	18,934
KBOS	633	12,139	568	13,336	KMCO	560	17,178	567	20,659
KBWI	418	12,558	426	9,586	KMDW	454	4,194	448	5,509
KCLE	418	4,170	408	3,707	KMEM	613	7,996	618	3,278
KCLT	735	10,104	735	6,940	KMIA	589	7,130	549	11,928
KCVG	721	6,653	606	3,368	KMSP	749	3,942	767	5,657
KDCA	428	10,876	433	6,157	KORD	1,558	11,015	1,552	15,074
KDEN	875	3,174	877	5,233	KPDX	372	1,619	375	2,506
KDFW	1,035	4,508	1,001	6,009	KPHL	802	21,182	785	10,715
KDTW	751	4,860	727	5,714	KPHX	953	28,812	935	17,893
KEWR	760	21,316	713	14,047	KPIT	357	3,561	356	3,524
KFLL	448	11,499	487	20,481	KSAN	337	2,474	336	3,617
KIAD	596	8,025	610	7,532	KSEA	499	2,196	476	3,184
KIAH	930	45,942	843	12,642	KSFO	592	8,746	565	19,072
KJFK	574	12,620	508	7,847	KSLC	699	2,934	604	3,610
KLAS	935	17,496	826	16,825	KSTL	420	2,798	434	4,258
KLAX	1,013	6,176	860	7,700	KTPA	406	5,734	416	6,431

departure delay and arrival delay at KIAH is due to low ADR of 56 aircraft per hour compared to the high AAR of 120 aircraft per hour (see Table 2).

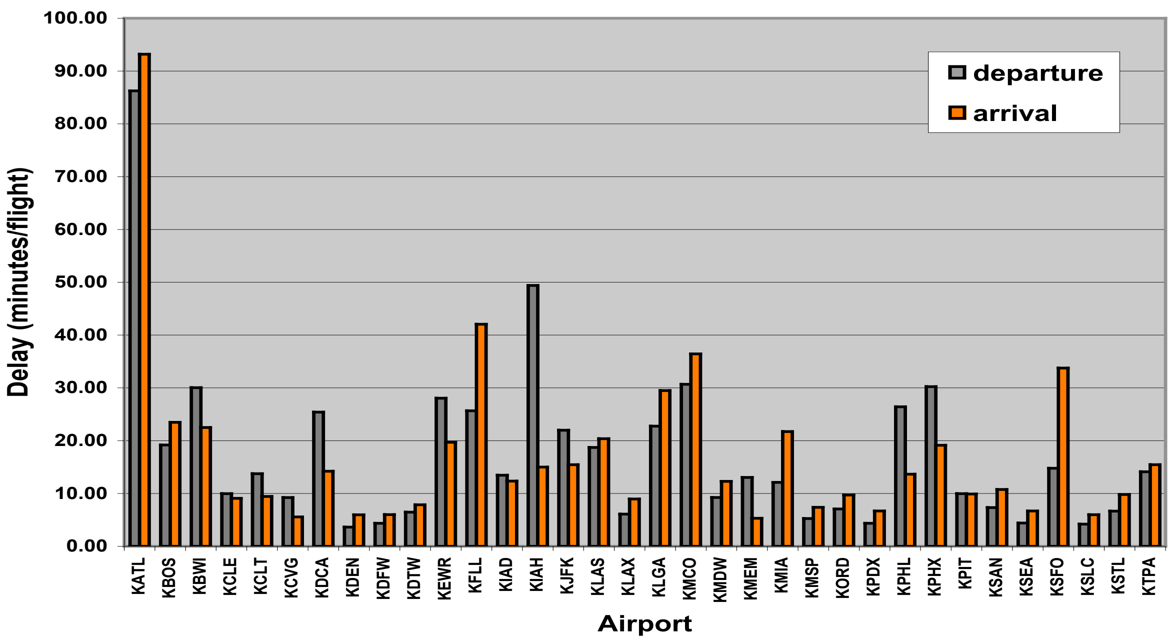

Figure 5. Baseline departure and arrival delays at the 34 OEP airports.

B. Reduced Capacity Results

One-hundred-and-two ACES simulations were conducted with reduced ADR and AAR capacities listed in Table 3 for the time-durations given in Table 6. The baseline ADR and AAR values for the non-OEP airports listed in Table 2 were kept for all the simulations, only the values for OEP airports were altered for the sensitivity study. The first set of 34 ACES simulations were conducted by changing the ADR value for each OEP airport one at a time, while keeping the baseline ADR values for the other airports. The baseline AAR values for all OEP airports were kept for this set of simulations. Figure 6 shows an example of the achieved departure rate in response to ADR reduction at the Hartsfield-Jackson Atlanta airport from the baseline rate of 96 aircraft per hour to 48 aircraft per hour during 13:00 UTC through 16:00 UTC. The dashed-line in the graph shows the ADR value and the solid-line marked with circles shows the achieved rate. The scheduled departure demand is shown by the solid-line marked with crosses.

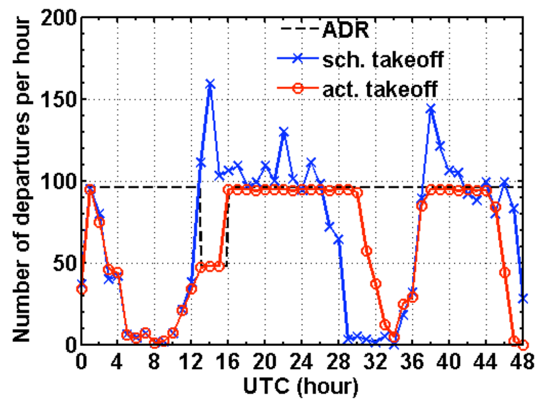

Figure 6. Departure rate achieved at Hartsfield-Jackson Atlanta airport with reduced ADR.

The impact of the ADR reduction at Atlanta airport on the departure and arrival delays at the other airports is shown in Fig. 7. This figure shows the percentage increase or decrease in the delay values compared to the baseline delay values at those airports, which are given in columns three, five, eight and ten of Table 7. A key observation is that as departure delays at Atlanta increase, arrival delays at the other airports also increase. This is an expected result based on Eq. (10); it is interesting that the departure delays at some of the airports increase. This effect is explained by the fact that departures from these airports are connected to arrivals from Atlanta. The same physical aircraft arriving from Atlanta is flown out of these airports to other out-bound destinations. An arrival delay associated with these flights shows up as departure delay for the connected out-bound flights. Finally, one observes that the arrival delays also increase at Atlanta although the AAR values were not changed. This again is due to delayed departures from airports that depart aircraft for Atlanta.

The impact of ADR reduction at each of the 34 OEP airports on the departure delays at other OEP airports is summarized in Table 8. The first column of this table lists the airport whose ADR was reduced and the header row indicates the impacted airport. A value of 89 in the first element of the first row states that total departure delay of flights delayed by 15-minutes or more at Atlanta increased by 89% compared to the baseline departure delay value of 151,897 minutes (see Table 7) due to reduced ADR at Atlanta. Similarly, the second element of the second row shows that the departure delay increased by 57% at Boston Logan airport due to reduced ADR at the Boston Logan airport. Note that the percentage values in the table have been rounded. Viewing Table 8 as a matrix, it is seen that the diagonal elements have a higher value compared to the off-diagonal terms. This is an expected result because ADR reduction at the airport directly affects departures from that airport. Closer examination reveals that for some of the airports, departure delays do not increase significantly with reduced ADR values. It was determined that for these airports, the departure demand is either lower or only slightly greater than the reduced ADR values. The only two airports - KMEM and KPHX for which the reduced ADR values were found to be same as the baseline values in the four months of operational data (see Tables 2 and 3), additional departure delays were not expected.

The effect of ADR reduction on the arrival delays is shown in Table 9. Viewing the data in Table 9 as a matrix, it is seen that the values of diagonal elements are low, which indicates that reduced ADR at an airport does not significantly increase arrival delays at that airport. Some airports – Atlanta (KATL), Houston (KIAH), John F. Kennedy (KJFK), San Francisco (KSFO) and Salt Lake City (KSLC) did not follow this trend. Reduced ADR at these airports had the effect of increasing arrival delays at these airports. Examining the rows of Table 9, it is seen that the off-diagonal terms are large for some airports. For example, the value of 41 in the first row under the KDFW heading means that total delays of flights arriving at Dallas/Fort Worth (KDFW) that were delayed by fifteen-minutes or more increased by 41% compared to the baseline value in Table 7 due to reduced ADR at Atlanta. Increase in arrival delay should be expected because the delay caused by ADR reduction at the airports of origin can be expected to be propagated to the airports of destination. The significance of increase in delay should be judged by comparing the baseline delay value for the airport against the baseline delay values of other airports, which are given

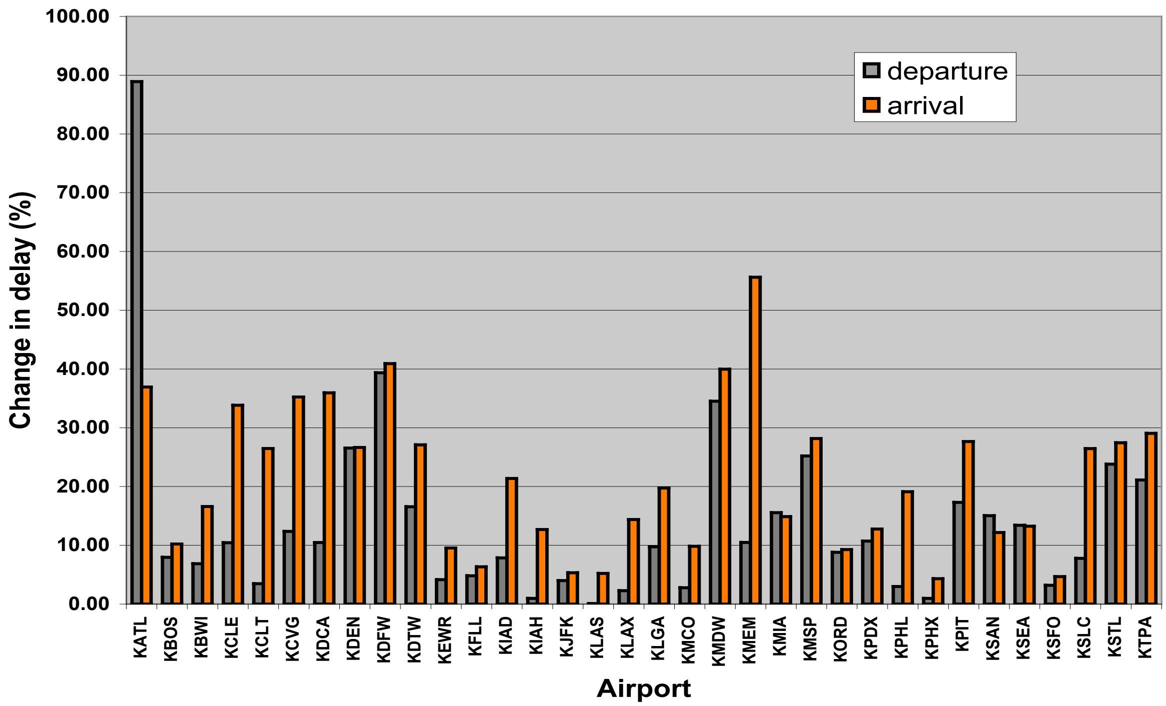

Figure 7. Impact of ADR reduction at Hartsfield-Jackson Atlanta airport on delays at other OEP airports.

in Table 7. For example, an increase of 50% in delays at Atlanta is considerably more significant compared to the same increase at Salt Lake City.

The next set of 34 ACES simulations were conducted with reduced AAR values at each of the 34 OEP airports. Baseline ADR values were kept for all the airports. Figure 8 shows the impact of AAR reduction at Atlanta on the other OEP airports. The bar-graphs show that the total arrival delay due to flights arriving late by fifteen-minutes or more increases by more than 90% compared to the baseline arrival delay in Table 7. The figure shows that departure delays at several airports increase due to reduced AAR at Atlanta. This is to be expected because the arrival constraint at Atlanta is met by delaying the out-bound flights to Atlanta at their airports of origin. Arrival delay at Atlanta also contributes to departure delay at Atlanta due to in-bound out-bound flight connectivity. This departure delay then propagates as arrival delay at other airports. In some instances, the departure and arrival delays are reduced slightly at other airports. This is essentially due to shifting of the departure and arrival times of the affected flights to times of lower demand at these airports.

The results shown in both Figs. 7 and 8 demonstrate that the impact of capacity reduction at one airport on the delays at another airport is complicated because of network (flight-connectivity) effects. Mathematical modeling of these effects is difficult, and therefore, a simulation capability like ACES is required for such an analysis.

The impact of reduction of AAR at each airport on the departure delays at 34 OEP airports is summarized in Table 10. Data trends in this table are similar to those seen in Fig. 8. It should be noted that departure delays at La Guardia (KLGA), Minneapolis-Saint Paul (KMSP), Chicago O'Hare (KORD), San Francisco (KSFO) and Salt Lake City (KSLC) increase significantly due to their own reduced AAR rates.

The sensitivity of arrival delays at the 34 OEP airports to reduced AAR at other airports is summarized in Table 11. This table shows that the reducing AAR at the airports, increases arrival delays significantly. Delays increase by more than 100% at Cleveland-Hopkins (KCLE), Charlotte/Douglas (KCLT), Newark Liberty (KEWR), Washington Dulles (KIAD), John F Kennedy (KJFK), La Guardia (KLGA), Minneapolis-Saint Paul (KMSP), Chicago O'Hare (KORD), Philadelphia (KPHL), Phoenix Sky Harbor (KPHX) and Salt Lake City (KSLC). The off-diagonal terms show that arrival delays also increase considerably at some airports due to AAR reduction at other airports. Instances are also seen where arrival delays decrease by a small amount.

Table 8. Impact of ADR reduction at one airport on departure delays at other OEP airports.

Airport	KATL	KBOS	KBWI	KCLE	KCLT	KCVG	KDCA	KDEN	KDFW	KDTW	KEWR	KFLL	KIAD	KIAH	KJFK	KLAS	KLAX
KATL	89	8	7	10	3	12	10	27	39	17	4	5	8	1	4	0	2
KBOS	0	57	1	0	1	0	1	-2	0	0	0	1	1	0	1	1	0
KBWI	0	0	1	0	0	-1	0	0	0	0	0	0	-1	0	0	0	0
KCLE	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0	0	0
KCLT	0	0	0	0	49	0	1	0	0	0	0	0	2	0	0	0	0
KCVG	0	0	0	0	0	29	0	0	0	0	0	0	0	0	0	0	0
KDCA	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
KDEN	0	1	-2	0	2	0	2	82	2	2	1	-1	0	0	1	-1	3
KDFW	0	0	0	0	0	0	1	1	105	0	0	0	0	0	0	0	0
KDTW	0	0	0	0	0	0	0	-1	0	34	0	0	0	0	0	1	0
KEWR	0	0	0	0	0	1	1	-1	0	1	53	1	0	0	1	0	0
KFLL	0	0	0	0	0	-1	0	0	0	0	-1	22	1	0	1	0	0
KIAD	0	0	0	3	0	-1	0	0	0	1	0	0	51	0	0	0	-1
KIAH	0	0	-1	2	3	2	-1	3	5	3	0	1	1	30	0	-2	2
KJFK	0	1	1	0	0	-1	1	-1	0	0	1	3	2	0	99	0	2
KLAS	0	0	0	0	0	0	0	7	1	0	0	0	0	0	0	67	7
KLAX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
KLGA	0	3	0	0	4	-1	2	-1	1	0	0	5	1	0	1	-1	1
KMCO	0	0	-1	-1	0	-1	0	0	0	0	0	0	0	0	0	0	0
KMDW	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0
KMEM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KMIA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KMSP	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	1
KORD	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	1
KPDX	0	0	0	-1	-1	0	1	-1	-2	2	1	-2	0	0	1	-3	4
KPHL	0	0	1	1	0	0	0	0	0	0	0	3	1	0	0	0	1
KPHX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KPIT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KSAN	0	0	-1	-2	1	2	0	-1	1	1	0	-1	-1	0	1	2	-1
KSEA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KSFO	0	0	0	0	0	-1	0	6	2	-1	0	0	0	0	0	8	11
KSLC	0	0	-2	-2	-1	-1	0	4	2	1	0	-3	-1	0	1	3	0
KSTL	0	-1	-1	0	0	-1	0	0	0	0	0	-1	0	0	0	0	0
KTPA	0	0	1	0	0	0	0	-1	0	0	0	0	0	0	0	0	0

Airport	KLGA	KMCO	KMDW	KMEM	KMIA	KMSP	KORD	KPDX	KPHL	KPHX	KPIT	KSAN	KSEA	KSFO	KSLC	KSTL	KTPA
KATL	10	3	35	10	16	25	9	11	3	1	17	15	13	3	8	24	21
KBOS	0	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
KBWI	-1	0	1	0	-1	1	0	1	1	0	0	0	0	0	0	1	0
KCLE	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
KCLT	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
KCVG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
KDCA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KDEN	3	-1	1	-1	0	0	1	5	-2	-1	2	4	4	4	-3	1	3
KDFW	0	0	0	0	0	0	0	1	0	0	0	1	1	1	1	0	0
KDTW	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
KEWR	0	1	0	0	1	1	1	0	0	0	0	0	0	-1	0	0	0
KFLL	-1	1	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	1
KIAD	0	0	0	0	0	0	0	-3	0	0	0	0	0	-2	1	0	-1
KIAH	0	0	2	0	1	2	0	-1	0	1	2	2	3	-2	3	2	3
KJFK	0	1	0	0	0	1	0	-3	2	0	0	0	1	-1	-1	0	1
KLAS	0	0	1	0	0	0	0	2	0	1	0	15	3	1	4	1	0
KLAX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KLGA	95	2	1	0	2	2	-1	-2	2	0	3	0	1	-1	1	0	4
KMCO	0	2	-2	0	0	1	0	-4	1	0	-1	1	0	0	0	0	0
KMDW	0	0	48	0	0	0	0	0	0	0	0	0	0	0	0	2	0
KMEM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KMIA	0	0	0	0	56	0	0	0	0	0	0	0	0	0	0	0	1
KMSP	0	1	0	0	0	351	1	0	0	0	0	0	0	1	0	0	0
KORD	0	0	0	0	0	0	345	0	0	0	0	0	3	1	1	0	0
KPDX	0	-1	2	1	-2	1	0	148	0	0	0	4	3	3	-2	1	3
KPHL	0	2	2	0	1	0	0	0	80	0	2	1	0	-1	0	0	0
KPHX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KPIT	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
KSAN	1	-1	-1	0	0	2	-1	3	0	0	1	9	-6	3	-2	2	3
KSEA	0	0	0	0	0	0	0	1	0	0	0	0	36	0	1	0	0
KSFO	-1	-1	0	0	0	0	0	10	0	0	0	7	19	76	9	2	0
KSLC	0	-1	1	-1	-1	3	0	9	-2	0	-2	9	10	10	249	0	4
KSTL	0	-1	0	0	-1	2	0	0	-1	0	-1	0	0	0	0	19	2
KTPA	-1	0	1	0	-1	0	0	0	0	0	0	0	2	0	1	1	54

Table 9. Impact of ADR reduction at one airport on arrival delays at other OEP airports.

Airport	KATL	KBOS	KBWI	KCLE	KCLT	KCVG	KDCA	KDEN	KDFW	KDTW	KEWR	KFLL	KIAD	KIAH	KJFK	KLAS	KLAX
KATL	37	10	17	34	26	35	36	27	41	27	10	6	21	13	5	5	14
KBOS	0	2	3	1	1	0	6	0	0	2	2	1	2	0	6	-1	1
KBWI	0	0	-1	0	1	0	-1	1	0	0	0	0	1	0	0	-1	0
KCLE	0	0	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0
KCLT	0	0	1	1	2	1	1	1	1	1	1	0	1	0	0	1	1
KCVG	0	0	1	1	0	1	1	0	1	1	1	0	0	0	0	0	1
KDCA	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	-1	0
KDEN	0	0	-1	-1	2	1	5	4	2	2	2	-1	1	1	1	2	3
KDFW	0	1	0	2	0	0	0	3	1	1	1	0	1	0	0	0	2
KDTW	0	0	0	1	0	1	1	1	0	0	0	0	1	0	0	1	1
KEWR	0	2	2	3	5	2	3	0	2	4	3	2	3	2	2	1	2
KFLL	0	0	0	0	1	0	0	1	0	2	1	1	1	0	3	-2	1
KIAD	0	0	-1	2	1	0	0	0	0	1	0	0	8	0	1	0	2
KIAH	0	1	2	8	3	7	4	5	3	1	5	0	0	23	0	1	3
KJFK	0	4	1	2	1	3	2	1	0	1	1	3	2	0	11	0	10
KLAS	0	1	2	2	0	-1	0	13	6	3	1	0	0	1	4	8	10
KLAX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KLGA	0	10	2	6	6	3	18	2	4	6	2	4	5	1	2	0	1
KMCO	0	0	0	0	0	0	-1	1	-1	0	0	0	1	0	0	2	0
KMDW	0	0	1	2	0	0	0	3	2	1	0	0	0	0	0	0	0
KMEM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KMIA	0	1	0	2	1	0	1	1	1	0	0	0	1	1	1	1	0
KMSP	0	1	1	4	1	2	3	12	4	5	3	0	2	1	1	1	2
KORD	0	4	3	16	4	14	7	13	11	10	4	2	6	4	1	4	9
KPDX	0	0	1	3	1	2	0	-1	-2	1	1	-2	2	0	-2	0	4
KPHL	1	4	7	3	4	5	2	2	5	5	0	2	1	1	0	3	4
KPHX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KPIT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KSAN	0	0	0	2	2	0	-2	1	-1	1	-1	-1	0	1	1	2	1
KSEA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
KSFO	0	1	1	1	0	3	0	9	2	1	0	0	3	1	5	8	10
KSLC	0	0	0	4	0	1	-1	4	-1	0	0	-2	0	1	2	4	2
KSTL	0	0	0	0	0	0	-1	1	0	1	1	-1	1	0	0	1	0
KTPA	0	0	2	0	1	0	1	1	0	1	1	1	1	0	1	0	1

Airport	KLGA	KMCO	KMDW	KMEM	KMIA	KMSP	KORD	KPDX	KPHL	KPHX	KPIT	KSAN	KSEA	KSFO	KSLC	KSTL	KTPA
KATL	20	10	40	56	15	28	9	13	19	4	28	12	13	5	26	27	29
KBOS	2	2	1	2	1	0	2	1	2	0	2	0	2	0	0	1	1
KBWI	0	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0	1
KCLE	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0
KCLT	1	1	0	1	0	2	1	1	1	0	3	0	1	0	0	2	1
KCVG	0	0	0	0	0	1	0	1	0	0	0	1	0	0	1	0	0
KDCA	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
KDEN	5	-1	1	0	-1	2	3	0	0	1	1	3	5	4	3	1	-1
KDFW	0	0	1	1	0	1	2	1	1	1	1	3	3	2	2	0	0
KDTW	0	0	2	1	0	2	0	0	0	0	1	1	1	0	-1	0	0
KEWR	0	3	3	3	2	2	3	4	0	1	4	1	2	0	1	4	1
KFLL	0	1	1	1	0	0	1	0	0	0	2	1	0	0	1	1	2
KIAD	0	0	0	0	0	4	4	4	2	0	1	3	2	-1	0	1	0
KIAH	1	0	1	7	1	4	4	-1	2	2	4	5	4	-1	4	3	2
KJFK	0	3	0	1	2	3	2	4	0	1	1	4	10	1	2	4	4
KLAS	0	0	5	3	0	8	2	5	1	7	0	21	3	2	8	4	1
KLAX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KLGA	2	2	4	2	4	3	7	1	3	0	8	1	-1	1	-1	3	5
KMCO	0	0	1	1	0	1	1	0	1	0	0	0	0	0	0	-1	-1
KMDW	0	0	2	0	0	3	0	3	0	0	0	0	1	0	0	2	0
KMEM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KMIA	0	0	0	1	0	1	0	0	1	0	1	0	0	0	0	0	2
KMSP	1	1	4	4	1	5	6	4	1	3	2	8	5	2	5	6	2
KORD	4	1	0	8	3	11	2	10	5	3	8	13	13	3	5	13	6
KPDX	1	0	0	10	-1	-3	0	4	-1	1	4	5	13	2	-1	0	-1
KPHL	2	3	3	7	1	5	7	3	5	2	8	3	1	0	3	5	5
KPHX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KPIT	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
KSAN	1	-1	-2	0	0	0	0	1	1	2	0	4	1	0	2	1	-1
KSEA	0	0	0	1	0	1	0	3	0	0	0	0	1	0	1	0	0
KSFO	0	0	0	0	0	2	3	4	1	3	0	8	11	17	11	1	0
KSLC	0	-1	1	-3	0	1	-1	5	-1	4	0	7	8	5	77	2	-1
KSTL	-1	-1	0	0	-1	0	2	0	1	0	2	0	1	0	1	0	-1
KTPA	1	0	3	1	0	0	0	2	0	0	1	1	2	0	1	1	2

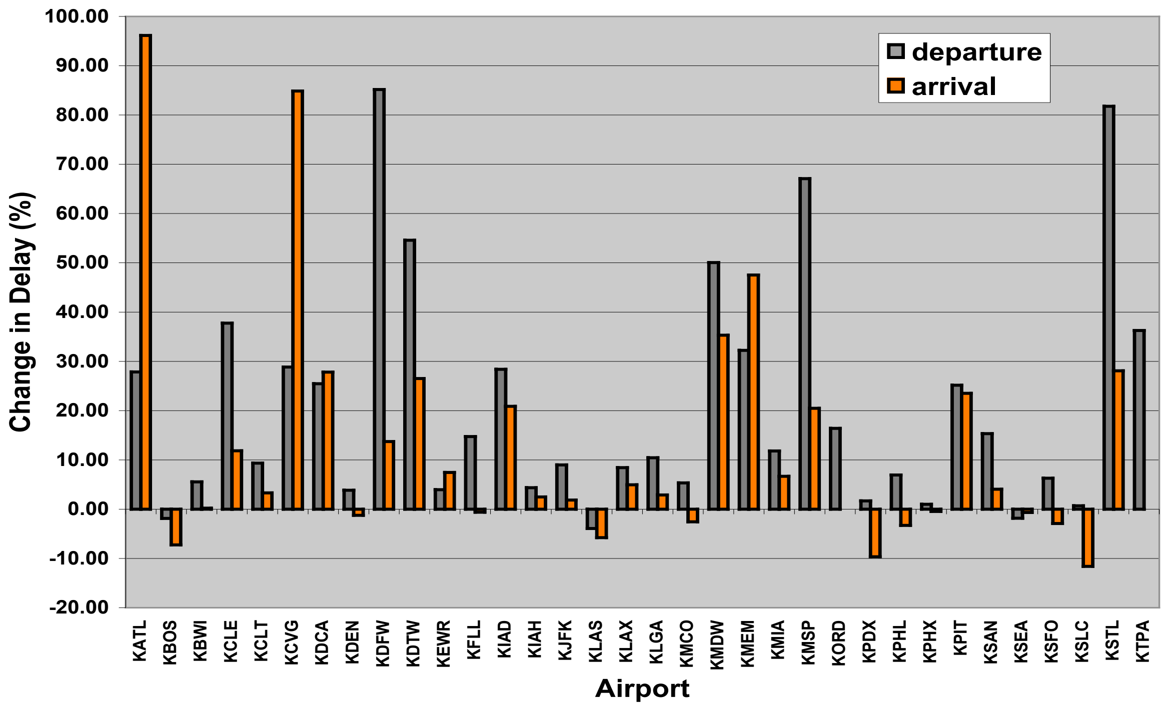

Figure 8. Impact of AAR reduction at Hartsfield-Jackson Atlanta airport on delays at other OEP airports.

The final set of 34 ACES simulations were conducted with both ADR and AAR reduced together at each airport, one at a time, while keeping baseline ADR and AAR values at the other airports to complete the sensitivity study. Tables 12 and 13 summarize these results. Table 12 presents the impact on departure delays at the 34 OEP airports and Table 13 shows the impact on arrival delays. Both these tables show that the departure and arrival delays increase substantially at the airports were capacity is reduced. Other observations made in the previous tables remain the same for these tables too.

The data presented in Tables 12 and 13 show that the percentage change in departure and arrival delays at the affected airports due to both reduced ADR and AAR capacities is close to the maximum of delay change due to reduced ADR capacities or AAR capacities given in Tables 8 through 11. For example, departure delay increase of 93% at Dallas Fort Worth (KDFW) due to both ADR and AAR reduction at Hartsfield-Jackson Atlanta (KATL) (see Table 12) is closer to 85% increase in departure delays due AAR reduction at KATL (see Table 10) compared to 39% increase in departure delays due ADR reduction at KATL (see Table 8). These initial results show that it might not be possible to simply add the impact due to ADR capacity reduction to that due to AAR reduction to derive the combined impact of both ADR and AAR capacity reduction. The utility of the sensitivity data in Tables 8 through 13 for developing delay forecasting models remains to be seen. The results also provide insight into flight demand between pairs of airports. For example, the impact of capacity reduction at Atlanta on delays at Dallas Fort Worth (KDFW) is much more compared to those at San Francisco International (KSFO). This insight can also be gained by analyzing origin-destination pairs in the ACES FDS file.

System-wide impact due to each airport is easily determined by first using the percent change in delays given in the rows of Tables 8 through 13 with the baseline delay values reported in Table 7 for determination of delay increase or decrease at each affected airport, and then adding these delay values. Figure 9 shows the increase in system-wide departure delays due to ADR and AAR reduction, obtained using the values in Table 12. Figure 10 depicts the impact on system-wide arrival delays obtained using values in Table 13. Both Figs. 9 and 10, show that capacity constraints at Atlanta, compared to constraints at other airports, have a significantly higher impact on the total system departure and arrival delays. One of the reasons is that there are significantly more flights with connected segments out of Atlanta compared to any other airport. Atlanta had 1,347 connected flights compared to 1,017 at Chicago, the airport with the next higher number of connected flights. In the real system the delays at

Table 10. Impact of AAR reduction at one airport on departure delays at other OEP airports.

Airport	KATL	KBOS	KBWI	KCLE	KCLT	KCVG	KDCA	KDEN	KDFW	KDTW	KEWR	KFLL	KIAD	KIAH	KJFK	KLAS	KLAX
KATL	28	-2	6	38	9	29	25	4	85	55	4	15	28	4	9	-4	8
KBOS	0	13	1	0	0	0	3	-2	0	2	0	0	1	0	3	0	0
KBWI	0	1	0	-2	1	-1	0	1	-2	2	1	-2	-2	0	1	-1	0
KCLE	0	1	1	29	1	2	1	-1	1	2	1	0	2	0	0	-1	0
KCLT	0	0	-1	-1	28	2	-1	-2	4	2	1	-1	-1	0	0	0	1
KCVG	0	0	0	0	0	6	0	0	0	1	0	0	0	0	0	-1	0
KDCA	0	1	-1	1	0	0	6	0	1	1	0	0	0	0	0	-1	0
KDEN	0	0	1	0	-1	1	2	20	-2	0	1	1	2	0	3	1	4
KDFW	0	0	0	1	0	0	1	3	38	0	0	0	0	0	0	0	0
KDTW	0	0	0	1	0	2	1	-1	-1	10	0	-1	1	0	0	0	0
KEWR	0	11	4	4	7	4	1	-2	0	19	14	1	8	0	1	0	-1
KFLL	0	-1	-2	-2	2	-1	0	-1	3	3	1	20	-1	0	1	-1	2
KIAD	0	1	-2	4	2	3	0	0	3	3	6	0	14	0	7	0	1
KIAH	0	0	-1	1	1	1	3	-2	6	2	-1	-1	1	0	0	0	1
KJFK	0	12	-1	8	1	7	1	1	0	5	-1	0	0	0	25	-1	0
KLAS	0	0	0	0	0	0	1	18	4	1	0	0	0	0	0	21	23
KLAX	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	1	11
KLGA	0	22	-2	17	8	6	27	4	8	46	-3	3	4	0	0	1	2
KMCO	0	0	0	-4	-2	0	-1	0	-1	0	0	1	-1	0	0	0	2
KMDW	0	0	1	3	0	0	0	-2	0	5	0	0	0	0	0	0	0
KMEM	0	0	1	2	0	2	1	-1	6	4	-2	0	2	0	1	-1	2
KMIA	0	-1	-1	0	0	-1	-1	-1	0	0	-1	-2	-1	0	0	0	0
KMSP	0	1	0	5	0	10	1	32	10	17	0	0	0	0	-1	0	2
KORD	0	1	1	25	3	26	6	25	16	25	-1	1	4	0	1	0	-1
KPDX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KPHL	0	4	-1	7	2	3	4	-2	1	12	0	1	5	0	1	-1	0
KPHX	-1	-1	6	5	1	-3	0	68	7	4	-2	0	-1	0	1	22	35
KPIT	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0
KSAN	0	0	1	0	-1	-1	0	-2	0	0	0	0	2	0	0	2	1
KSEA	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3
KSFO	0	0	-1	-1	-1	-1	-1	6	-2	-1	0	0	-2	0	0	-2	31
KSLC	0	-1	-2	0	-1	-3	1	11	5	-1	1	0	-1	0	1	0	7
KSTL	0	-1	-2	-2	0	-2	2	2	-2	1	0	-2	1	0	1	-2	-4
KTPA	0	0	-2	-1	2	0	-2	3	4	2	-1	2	-3	0	1	0	1

Airport	KLGA	KMCO	KMDW	KMEM	KMIA	KMSP	KORD	KPDX	KPHL	KPHX	KPIT	KSAN	KSEA	KSFO	KSLC	KSTL	KTPA
KATL	10	5	50	32	12	67	16	2	7	1	25	15	-2	6	1	82	36
KBOS	6	-1	0	0	-1	2	8	0	1	0	2	-1	0	-1	-1	0	0
KBWI	1	-1	1	-2	-1	3	-1	-1	-2	0	1	-1	2	0	1	1	4
KCLE	1	0	6	0	0	0	0	1	-1	0	2	0	0	-1	1	0	-1
KCLT	2	0	2	0	4	6	5	-2	0	0	2	1	0	-2	-3	2	2
KCVG	0	1	1	0	0	0	0	-3	0	0	0	1	0	0	0	1	0
KDCA	1	1	0	0	-1	1	2	-3	1	0	1	0	0	-1	0	1	3
KDEN	2	0	-1	1	-2	5	0	3	0	3	-5	15	-3	1	2	6	3
KDFW	0	0	0	1	0	0	4	-4	0	0	0	1	0	0	-1	3	0
KDTW	1	-1	1	-3	-1	2	1	0	0	0	1	2	0	-2	1	1	0
KEWR	1	2	1	1	4	5	16	-4	0	0	21	-1	0	-3	0	0	3
KFLL	1	4	2	-1	-1	1	0	-1	0	0	-1	1	2	-1	-4	0	14
KIAD	3	-1	1	2	-2	0	2	-2	-1	0	4	0	0	0	1	13	3
KIAH	1	-3	3	1	-2	5	0	-3	-1	1	-2	2	-3	3	6	3	3
KJFK	0	0	-2	-1	-1	4	2	-4	-1	-1	9	0	1	-1	1	-1	6
KLAS	0	0	3	0	0	6	2	7	0	5	0	48	15	2	23	2	0
KLAX	0	0	0	0	0	0	0	2	0	-1	0	8	3	1	3	0	0
KLGA	87	-2	15	2	4	3	5	-1	4	1	0	3	1	0	2	3	0
KMCO	-1	0	0	1	0	2	-1	-2	1	0	-1	1	3	-1	1	-1	2
KMDW	1	0	26	0	0	6	0	-3	1	0	1	1	0	0	0	2	0
KMEM	0	0	3	2	2	3	1	2	2	0	2	2	0	3	-1	3	5
KMIA	0	-1	0	0	5	1	0	0	-1	0	-1	0	0	0	0	0	3
KMSP	0	1	24	1	0	137	20	10	1	0	4	5	5	-1	4	21	0
KORD	3	0	-2	7	3	61	113	7	2	0	24	4	14	0	5	21	2
KPDX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KPHL	4	0	6	-2	4	3	10	-2	11	0	20	0	0	-1	-1	3	2
KPHX	2	0	18	5	0	8	1	44	0	7	3	43	17	2	22	11	1
KPIT	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
KSAN	-1	0	0	0	0	1	0	3	-1	0	-1	3	2	1	0	1	0
KSEA	0	0	0	0	0	0	0	27	0	0	0	1	28	0	5	0	0
KSFO	-1	-1	-5	3	-3	2	1	35	0	0	0	24	29	71	9	-1	2
KSLC	1	-3	-1	1	-1	5	5	18	-1	3	1	8	8	6	122	4	0
KSTL	0	-3	0	-1	0	1	0	-2	-2	0	-2	-2	0	1	-6	9	3
KTPA	0	-2	3	-1	4	1	0	-3	-1	0	-1	-1	2	-1	1	1	28

Table 11. Impact of AAR reduction at one airport on arrival delays at other OEP airports.

Airport	KATL	KBOS	KBWI	KCLE	KCLT	KCVG	KDCA	KDEN	KDFW	KDTW	KEWR	KFLL	KIAD	KIAH	KJFK	KLAS	KLAX
KATL	96	-7	0	12	3	85	28	-1	14	27	7	-1	21	2	2	-6	5
KBOS	0	47	1	-1	0	0	0	2	0	0	-1	-1	0	0	3	-1	0
KBWI	0	1	6	2	2	0	-1	0	-3	1	0	-2	0	0	-1	-1	0
KCLE	0	0	1	102	0	2	0	0	-1	1	0	-1	0	0	1	1	1
KCLT	0	0	1	5	177	0	1	-1	0	1	0	-1	0	-1	-1	1	1
KCVG	0	0	0	0	0	53	0	-1	-2	0	0	0	1	0	0	1	0
KDCA	0	1	0	0	0	-1	48	0	-2	0	-1	-1	0	0	0	0	-1
KDEN	0	0	1	2	1	2	3	58	1	1	-1	0	0	0	-1	-2	4
KDFW	0	1	0	0	0	0	-1	1	80	0	1	0	0	0	0	-1	0
KDTW	0	0	1	-1	0	0	0	-1	-2	51	0	-1	0	0	0	-1	1
KEWR	0	2	2	7	0	0	-1	0	-2	6	115	-1	3	0	2	-1	2
KFLL	0	-1	1	0	3	-3	3	0	-1	0	0	43	0	1	0	-2	2
KIAD	0	0	1	4	2	2	2	0	0	3	0	-1	115	0	2	1	3
KIAH	0	0	0	2	-1	-2	3	0	-2	1	-1	-1	0	53	0	2	0
KJFK	0	5	1	8	3	9	2	0	-3	-1	0	-2	0	0	124	1	1
KLAS	0	0	1	3	0	0	-1	-3	1	0	0	0	0	0	0	98	5
KLAX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28
KLGA	0	15	-2	11	12	-3	34	-1	0	30	-4	0	3	-1	-2	4	2
KMCO	0	0	1	1	1	0	0	0	-4	0	-1	0	0	0	-1	1	1
KMDW	0	0	1	3	0	0	0	1	-1	-1	0	0	0	0	0	1	0
KMEM	1	0	2	-2	3	-1	1	0	0	-2	0	0	0	0	-3	3	0
KMIA	0	-1	1	0	0	-1	0	0	-1	0	0	-1	0	0	0	-1	0
KMSP	0	-1	0	1	0	0	-1	5	-2	6	0	0	2	0	1	0	1
KORD	0	0	2	1	-1	2	0	-1	2	9	-1	-1	0	0	-1	-4	-2
KPDX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KPHL	0	1	-1	0	1	-1	0	0	-3	0	1	0	2	0	1	-2	0
KPHX	-1	-2	5	5	0	-2	-1	14	0	0	2	0	-1	-2	-3	13	4
KPIT	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	-1	0
KSAN	0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0	2
KSEA	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	1
KSFO	-1	0	2	-1	0	1	-3	2	1	-2	-3	-1	0	-1	0	4	17
KSLC	0	0	3	6	-1	0	1	-1	1	-3	-3	-2	-1	-1	-1	2	2
KSTL	0	-1	0	2	0	2	-3	-1	-6	1	-2	-2	0	0	0	-2	0
KTPA	0	-1	1	-1	-1	1	-2	2	-1	1	0	0	-1	0	0	-1	1

Airport	KLGA	KMCO	KMDW	KMEM	KMIA	KMSP	KORD	KPDX	KPHL	KPHX	KPIT	KSAN	KSEA	KSFO	KSLC	KSTL	KTPA
KATL	3	-3	35	48	7	20	0	-10	-3	0	24	4	-1	-3	-12	28	0
KBOS	0	-1	0	0	-1	0	-1	0	1	0	4	0	-1	0	-2	-1	0
KBWI	0	-1	-1	-6	-1	-1	0	0	-1	0	0	0	-1	1	1	0	-1
KCLE	0	0	1	0	0	1	-1	0	0	1	-1	-1	-1	0	1	0	0
KCLT	-1	-1	0	2	-1	1	-1	0	1	0	9	1	0	0	0	-2	0
KCVG	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	-1	0
KDCA	0	0	0	0	0	0	-1	2	0	0	0	1	-1	0	-1	-1	-1
KDEN	4	-1	-1	4	0	0	2	2	2	0	5	3	1	-1	3	1	-1
KDFW	0	0	0	0	0	2	0	-2	0	0	0	1	0	-1	1	0	0
KDTW	0	0	0	-6	-1	1	1	1	-1	0	1	1	0	-1	-1	1	-1
KEWR	0	-1	0	-1	-1	-1	2	-1	0	0	1	3	-1	-2	1	1	0
KFLL	2	2	0	0	-1	1	-1	-1	2	0	5	1	0	0	1	1	1
KIAD	0	-1	0	1	1	-1	0	1	-1	0	3	3	3	-2	2	0	2
KIAH	1	-1	-2	-2	-1	2	-1	-1	-1	1	1	0	3	-3	2	-1	-2
KJFK	-1	0	-1	0	-2	-2	1	-2	-1	1	-2	0	4	0	0	-2	1
KLAS	0	1	2	-2	1	0	0	1	1	1	3	10	4	-2	6	0	3
KLAX	0	0	0	0	0	0	0	0	0	1	0	2	0	0	1	0	0
KLGA	153	-2	9	1	-2	-2	5	-2	0	3	5	2	1	-2	1	0	0
KMCO	0	1	-1	1	0	0	-2	0	1	0	3	1	2	0	0	1	0
KMDW	0	1	48	0	0	0	0	2	0	0	-1	1	0	0	0	1	0
KMEM	2	-2	-1	65	0	-4	1	-1	0	2	4	2	3	-3	1	0	2
KMIA	0	-1	2	-1	16	0	0	0	1	0	0	1	0	-1	0	-1	1
KMSP	0	0	4	0	0	405	-2	1	0	0	4	1	-1	-1	-3	3	-1
KORD	0	-1	-1	2	-1	5	275	-2	0	0	3	12	-1	-1	-2	2	-1
KPDX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KPHL	0	1	3	-7	0	-1	0	0	141	0	8	6	0	0	-1	-1	4
KPHX	2	-3	9	-2	1	-7	7	26	2	124	11	7	8	-6	19	0	-6
KPIT	0	0	0	0	0	1	-1	0	0	0	1	0	0	0	0	0	0
KSAN	0	0	0	0	0	0	-1	1	0	0	0	2	2	2	1	0	0
KSEA	0	0	0	0	0	0	0	4	0	1	0	3	98	0	1	0	0
KSFO	-1	-1	-2	1	-1	7	2	9	0	0	1	7	15	50	10	5	-3
KSLC	1	-2	-1	-5	0	-4	1	8	-2	1	4	-1	2	2	229	4	3
KSTL	1	-1	-2	6	0	-1	0	-3	-2	1	1	1	0	0	2	23	-2
KTPA	0	-1	0	0	-1	-1	0	0	0	0	0	1	0	0	1	1	88

Table 12. Impact of ADR and AAR reduction at one airport on departure delays at other OEP airports.

Airport	KATL	KBOS	KBWI	KCLE	KCLT	KCVG	KDCA	KDEN	KDFW	KDTW	KEWR	KFLL	KIAD	KIAH	KJFK	KLAS	KLAX
KATL	100	9	15	56	17	41	35	27	93	87	9	24	32	5	13	0	12
KBOS	0	58	2	0	1	0	4	-3	0	2	0	1	1	0	3	1	0
KBWI	0	1	1	1	1	-1	0	0	-2	1	1	-2	-1	0	1	0	0
KCLE	0	1	1	34	1	2	1	0	1	2	0	0	2	0	0	-1	1
KCLT	0	0	0	0	61	2	1	-2	4	2	1	-1	-1	0	0	0	1
KCVG	0	0	0	0	0	28	0	0	0	1	0	0	1	0	0	-1	0
KDCA	0	1	-1	1	0	0	11	0	1	1	0	0	0	0	0	-1	0
KDEN	0	0	1	-1	-1	3	1	87	1	1	2	0	0	0	1	-1	4
KDFW	0	0	0	1	0	0	1	4	111	0	0	0	0	0	0	-1	0
KDTW	0	0	0	1	0	2	1	-1	-1	36	0	-1	1	0	0	0	0
KEWR	0	12	6	4	6	5	2	-2	0	19	56	2	8	0	2	0	0
KFLL	0	-1	-1	-1	2	-1	0	0	3	3	0	33	0	0	1	0	1
KIAD	0	2	-2	5	3	4	0	0	3	4	6	0	54	0	7	-1	0
KIAH	0	1	0	6	0	3	2	3	11	4	-1	0	1	30	0	-1	1
KJFK	0	14	1	8	2	7	1	1	0	5	-1	2	1	0	100	0	2
KLAS	0	0	0	0	0	0	1	24	4	1	0	0	0	0	0	77	27
KLAX	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	1	12
KLGA	0	23	-1	18	9	6	29	5	8	46	-3	5	6	0	1	1	2
KMCO	0	1	0	-1	-1	1	-1	1	-1	1	0	1	-1	0	0	0	2
KMDW	0	0	1	3	0	0	0	1	0	5	0	0	0	0	0	0	0
KMEM	0	0	1	2	0	2	1	-1	6	4	-2	0	2	0	1	-1	2
KMIA	0	-1	-1	0	0	-1	-1	-1	0	0	-1	-2	-1	0	0	0	-1
KMSP	0	1	0	5	0	10	1	33	11	17	0	0	0	0	-1	0	2
KORD	0	1	1	25	3	26	6	27	17	25	-1	1	4	0	1	1	0
KPDX	0	0	0	-1	-1	0	1	-1	-2	2	1	-2	0	0	1	-3	4
KPHL	0	6	1	8	3	3	4	-2	1	13	0	5	6	0	0	-1	0
KPHX	-1	-1	6	5	1	-3	0	68	7	4	-2	0	-1	0	1	22	35
KPIT	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0
KSAN	0	0	-1	-2	2	2	1	-3	1	1	0	0	-1	0	1	0	-2
KSEA	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3
KSFO	0	-1	-2	-3	-1	0	-1	13	0	-1	0	-1	-2	0	0	6	34
KSLC	-1	-1	-3	-1	-4	-1	0	10	7	0	-1	-1	-2	0	1	-1	8
KSTL	0	-1	-3	-3	-1	-2	1	2	-2	1	0	-2	-1	0	1	-2	-2
KTPA	0	1	-1	-1	2	-1	0	4	4	2	0	2	-3	0	1	0	0

Airport	KLGA	KMCO	KMDW	KMEM	KMIA	KMSP	KORD	KPDX	KPHL	KPHX	KPIT	KSAN	KSEA	KSFO	KSLC	KSTL	KTPA
KATL	18	13	78	34	27	79	26	0	12	1	44	19	4	6	-3	104	43
KBOS	6	0	0	0	0	2	8	-1	2	0	2	0	-1	0	-1	1	0
KBWI	1	-2	1	-2	-1	3	-1	2	-2	0	1	-1	2	-1	1	1	5
KCLE	1	0	6	0	0	0	0	1	-1	0	2	0	0	-1	2	0	-1
KCLT	2	0	2	0	4	6	5	-1	1	0	2	1	0	-2	-3	2	1
KCVG	0	1	1	0	0	0	1	-3	0	0	0	1	0	0	1	1	0
KDCA	1	1	0	0	-1	1	2	-3	1	0	1	-1	0	-1	0	1	3
KDEN	2	-1	1	0	0	3	5	2	-1	3	-5	17	-3	1	3	1	4
KDFW	0	0	0	1	0	0	4	-4	0	0	1	1	-1	0	-1	3	0
KDTW	1	-1	1	-3	-1	2	1	0	-1	0	1	2	1	-2	1	1	-1
KEWR	2	4	1	1	5	4	17	-5	1	0	23	-1	0	-3	0	0	3
KFLL	0	5	2	-1	-3	1	-1	-2	1	0	-1	1	2	-1	-1	1	15
KIAD	3	0	1	2	-2	0	1	0	0	0	5	0	0	0	2	13	4
KIAH	2	-2	4	2	-1	7	0	-1	-1	1	-2	3	-4	2	2	6	3
KJFK	2	2	-2	-1	1	4	2	-3	1	-1	9	-1	2	-2	1	-1	7
KLAS	0	0	4	0	0	6	3	5	0	5	0	55	17	3	24	3	0
KLAX	0	0	0	0	0	0	0	2	0	-1	0	8	3	1	3	0	0
KLGA	111	0	16	1	6	4	5	-1	6	1	2	3	3	0	2	1	1
KMCO	-1	2	-1	1	0	1	-1	-2	1	0	1	2	4	0	2	-1	2
KMDW	1	0	56	0	0	6	0	-3	1	0	1	1	0	0	0	5	0
KMEM	0	0	3	2	2	3	1	2	2	0	2	2	0	3	-1	3	5
KMIA	0	0	0	0	56	0	0	0	-1	0	-1	0	0	-1	0	0	5
KMSP	0	1	24	1	0	358	20	10	1	0	5	4	5	0	5	21	0
KORD	4	0	-2	7	3	62	360	7	3	0	24	5	18	1	6	21	3
KPDX	0	-1	2	1	-2	1	0	148	0	0	0	4	3	3	-2	1	3
KPHL	4	3	7	-2	4	2	10	-3	82	0	23	0	0	-1	-1	3	2
KPHX	2	0	18	5	0	8	1	44	0	7	3	43	17	2	22	11	1
KPIT	1	0	0	0	-1	0	0	0	0	0	2	0	0	0	0	-1	0
KSAN	1	-1	-1	0	0	1	-1	3	0	-1	0	6	-5	2	0	2	3
KSEA	0	0	0	0	0	0	0	28	0	0	0	1	56	1	5	0	0
KSFO	0	-2	-5	2	-2	4	1	40	-1	1	0	25	36	110	13	0	2
KSLC	-1	-3	0	0	-1	6	0	21	-2	3	-3	8	8	8	289	5	-2
KSTL	0	-4	1	-1	1	1	1	-1	-4	0	-2	0	1	1	0	18	2
KTPA	0	-1	3	-1	4	1	0	-3	-2	0	0	0	3	0	1	2	64

Table 13. Impact of ADR and AAR reduction at one airport on arrival delays at other OEP airports.

Airport	KATL	KBOS	KBWI	KCLE	KCLT	KCVG	KDCA	KDEN	KDFW	KDTW	KEWR	KFLL	KIAD	KIAH	KJFK	KLAS	KLAX
KATL	117	11	23	43	32	137	59	18	40	59	18	7	29	13	10	6	19
KBOS	0	49	2	0	1	0	5	1	1	2	2	1	2	0	8	-1	0
KBWI	0	0	6	2	2	0	-1	0	-2	0	1	-2	0	0	-1	-1	0
KCLE	0	0	1	102	0	2	0	0	-1	1	0	-1	1	0	1	1	1
KCLT	0	0	1	6	179	2	2	1	1	1	0	0	1	-1	-1	0	2
KCVG	0	0	1	1	0	54	1	0	-1	1	0	0	1	0	0	1	0
KDCA	0	1	0	0	0	-1	48	0	-1	1	-1	0	0	0	0	0	-1
KDEN	0	0	1	2	2	1	3	64	1	2	-1	-1	0	1	-1	-1	4
KDFW	0	1	0	1	0	0	0	2	82	1	1	0	0	0	0	-2	2
KDTW	0	0	1	0	0	1	1	-1	-2	51	0	-1	1	0	0	0	1
KEWR	0	4	5	6	4	2	2	-1	0	8	117	1	5	2	4	-1	4
KFLL	0	0	2	0	3	-1	3	2	-1	1	1	43	0	1	2	0	2
KIAD	0	1	1	5	2	1	1	1	1	3	0	-1	121	0	2	-1	5
KIAH	0	1	1	11	2	3	5	3	2	3	5	-1	0	77	0	1	2
KJFK	0	9	2	10	4	12	4	0	-2	1	0	0	1	0	130	1	8
KLAS	0	0	2	5	0	-1	-1	8	5	3	1	0	1	1	5	102	13
KLAX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29
KLGA	0	19	-1	14	13	-1	39	1	1	31	-4	2	4	0	-1	4	1
KMCO	0	0	1	1	1	0	0	1	-4	0	-2	0	0	0	-1	2	1
KMDW	0	0	1	4	0	0	0	3	0	0	0	0	0	0	0	0	0
KMEM	1	0	2	-2	3	-1	1	0	0	-2	0	0	0	0	-3	3	0
KMIA	0	-1	1	2	0	0	1	1	0	0	0	-1	0	0	1	1	0
KMSP	0	0	1	5	2	2	2	12	2	9	2	0	3	1	1	0	2
KORD	0	3	3	11	3	13	6	8	10	15	3	0	4	3	0	0	6
KPDX	0	0	1	3	1	2	0	-1	-2	1	1	-2	2	0	-2	0	4
KPHL	0	4	6	3	5	4	3	1	2	5	1	2	3	1	1	0	5
KPHX	-1	-2	5	5	0	-2	-1	14	0	0	2	0	-1	-2	-3	13	4
KPIT	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	-1	0
KSAN	0	0	0	2	2	0	-1	-2	0	2	-2	-1	0	0	0	0	0
KSEA	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	2
KSFO	-1	0	2	1	0	1	-3	11	3	-1	-3	-2	2	-1	2	9	21
KSLC	0	0	3	4	0	-1	0	2	1	-1	-3	-2	-2	-1	-2	2	2
KSTL	0	-1	-1	1	0	2	-3	-1	-6	0	-2	-2	0	0	0	-1	1
KTPA	0	0	2	-1	0	1	-1	2	-1	1	0	0	0	0	1	0	1

Airport	KLGA	KMCO	KMDW	KMEM	KMIA	KMSP	KORD	KPDX	KPHL	KPHX	KPIT	KSAN	KSEA	KSFO	KSLC	KSTL	KTPA
KATL	23	12	74	66	22	52	7	0	15	4	47	13	5	0	11	55	18
KBOS	1	0	0	1	0	1	2	0	3	0	8	2	0	0	-2	0	1
KBWI	0	-1	-1	-5	0	-1	0	0	-1	0	0	0	0	1	1	0	0
KCLE	0	0	1	0	0	1	0	0	0	1	0	0	-1	0	0	0	0
KCLT	0	0	0	2	0	2	0	0	1	0	10	-1	1	0	0	0	1
KCVG	0	0	0	0	0	1	1	0	0	0	0	1	1	0	1	-1	0
KDCA	0	0	0	0	0	0	-1	2	1	0	1	1	-1	0	-1	0	0
KDEN	4	-1	0	1	0	-4	3	4	2	2	6	3	3	0	4	0	0
KDFW	0	0	1	0	0	3	1	0	0	1	1	2	2	0	3	0	1
KDTW	0	0	1	-5	-1	2	1	1	-1	0	1	2	1	0	0	1	-1
KEWR	0	2	3	0	1	1	5	2	0	0	6	2	0	-1	2	5	2
KFLL	3	3	-1	0	-1	0	0	-1	2	1	5	1	0	0	1	1	3
KIAD	0	-1	0	1	1	4	1	2	0	1	4	4	5	-1	2	2	2
KIAH	3	0	0	5	0	5	2	0	0	3	0	5	7	-2	5	3	0
KJFK	0	3	0	1	1	-1	2	3	0	1	1	4	12	1	3	1	4
KLAS	0	1	6	1	2	7	1	6	1	6	3	22	6	0	13	3	3
KLAX	0	0	0	0	0	0	0	0	0	1	0	2	0	0	1	0	0
KLGA	151	-1	9	1	1	-2	7	-1	3	2	6	3	2	0	1	2	1
KMCO	1	1	1	2	0	0	2	0	1	0	2	1	2	1	0	1	1
KMDW	0	1	49	0	0	2	0	4	0	1	0	3	1	0	0	3	0
KMEM	2	-2	-1	65	0	-4	1	-1	0	2	4	2	3	-3	1	0	2
KMIA	0	-1	2	0	16	0	0	-1	1	0	2	1	0	-1	0	-1	3
KMSP	0	1	6	2	0	407	2	2	1	2	4	7	3	1	3	7	1
KORD	3	1	-1	7	2	11	276	9	3	3	9	15	11	1	3	11	4
KPDX	1	0	0	10	-1	-3	0	4	-1	1	4	5	13	2	-1	0	-1
KPHL	1	4	5	-1	1	3	5	3	146	2	14	6	1	0	1	4	8
KPHX	2	-3	9	-2	1	-7	7	26	2	124	11	7	8	-6	19	0	-6
KPIT	0	0	0	0	-1	1	-1	0	0	0	1	0	0	0	0	0	0
KSAN	0	0	-1	1	0	0	-2	1	1	2	0	2	2	0	1	2	-1
KSEA	0	0	0	1	0	1	0	6	0	1	0	3	99	0	2	0	0
KSFO	-1	-1	-1	1	0	7	2	13	0	3	-1	8	20	58	15	5	-3
KSLC	1	-2	1	-2	-1	-3	2	9	-2	0	4	4	4	2	274	3	0
KSTL	1	-1	-2	7	-1	-1	0	-3	-1	2	-1	1	0	0	2	22	-2
KTPA	0	-1	1	1	0	-1	0	-1	1	0	1	2	1	1	2	3	89

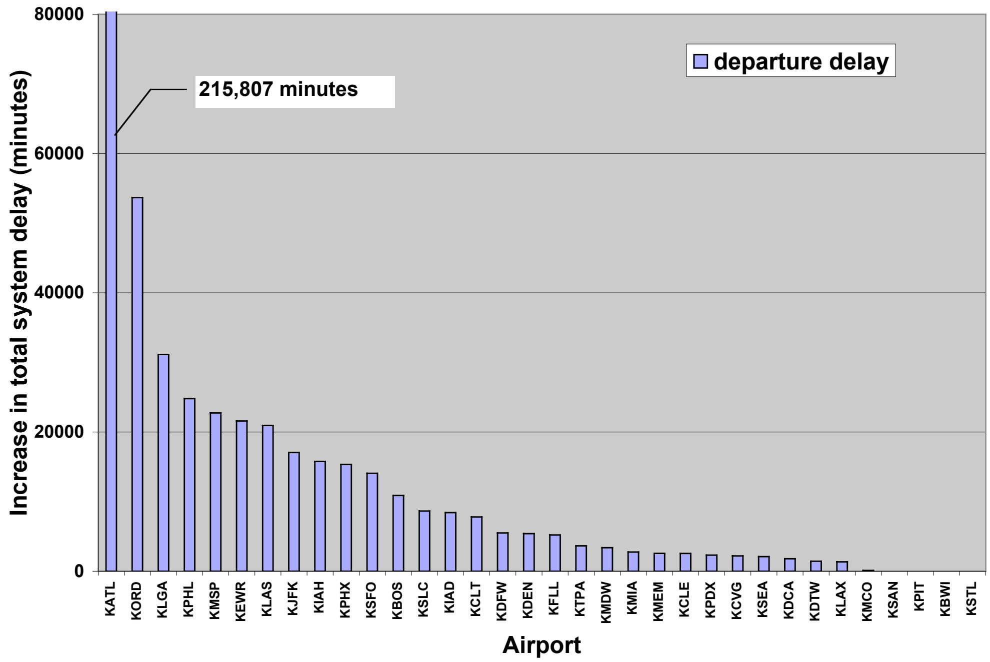

Figure 9. System-wide impact of ADR and AAR reduction on departure delays.

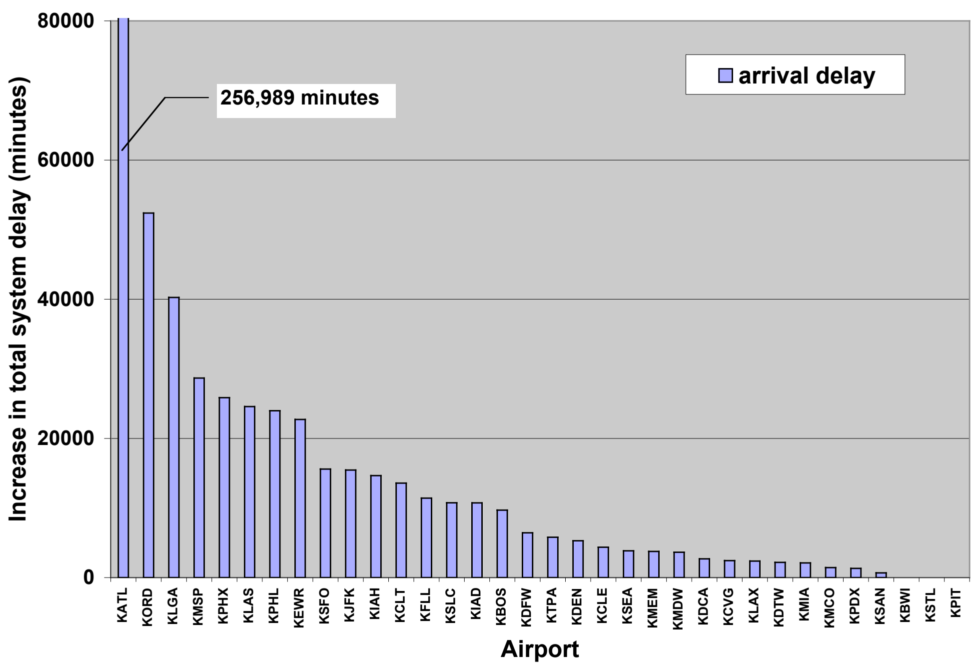

Figure 10. System-wide impact of ADR and AAR reduction on arrival delays.

Atlanta might be considerably less because of the following reasons. Fifty-percent capacity for three hours with a peak demand capacity ratio of 3.3 (see Fig. 6), which means three times the demand, is extreme. When delays are this severe, flights are cancelled in the real system. Flights were not cancelled during the ACES simulations.

The results presented in this paper were generated with a single day of air traffic data. The trends seen in the results are expected to hold for days with similar characteristics as those of the day used for computing the results. If the demand patterns change, numerical values will change but the method described in the paper can be used to generate the new sensitivity matrices. The impact of capacity reduction was studied by altering capacities one airport at a time. On the typical day multiple airports are impacted. The impact of combinations of ADR and AAR capacity reductions at multiple airports has not been studied.

V. Summary

This paper described a method for sensitivity study in which the airport departure rate (ADR) and airport arrival rate (AAR) were reduced at each of the 34 major airports in the United States, one at a time, and the impact on the departure and arrival delays at these airports was assessed. To compute these delay values, the Airspace Concept Evaluation System (ACES) was used. One-hundred-and-three ACES simulations were conducted to complete the study. In the first set of 34 runs, only the ADR values were altered. The AAR values were kept at their baseline level. In the second set of 34 runs, the AAR values were changed. The ADR values were kept at their baseline level. Both the ADR and AAR values were reduced for the final set of 34 simulations. The results obtained show that ADR reduction at an airport directly increases the departure delay at that airport. This departure delay then appears as arrival delay at the other airports. It was observed that the departure delays at other airports increase indirectly due to flight-connectivity effects. Reduction of AAR was seen to increase the arrival delay at the affected airport. Passing back of this arrival delay causes the departure delay to increase at the airports sending flights to this affected airport. Flight-connectivity was responsible for causing departure delays at the affected airport. Data tables in the paper provide numerical values that quantify the degree of impact of capacity reduction at one major airport on another.

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