12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSM
17 - 19 September 2012, Indianapolis, Indiana

AIAA 2012-5698

Delay Sensitivity to Call For Release Scheduling Time

Kee Palopo*
NASA Ames Research Center, Moffett Field, CA, 94035, USA
and
Gano B. Chatterji†
University of California Santa Cruz, Moffett Field, CA, 94035, USA
and
Noam Almog‡
Aerospace Computing Inc., Moffett Field, CA, 94035, USA

A goal of any precision departure concept, such as NASA Precision Departure Release Capability, is to improve throughput, efficiency and capacity by integrating departure, arrival and surface operations. This kind of concept is believed to have the potential of increasing flight efficiency and throughput by not missing assigned overhead-stream or arrival-stream slots. In the current Call For Release scheduling, a slot can be missed because of airport-departure delay, which is the sum of gate-departure delay, ramp delay, and taxi-out delay. This delay can be reduced by improved precision departure scheduling. The main thrust of the paper is to determine the delay-cost impact of Call For Release scheduling before gate-push-back and at gate-push-back. Seven different variations of scheduling algorithms were used in the simulation. Results reported in the paper considers 37,346 flights in the National Airspace System for one day in January 2011. Approximately 1,500 airports were included in the simulation. Results show that there is no significant benefit of scheduling before gate-push-back as opposed to at gate-push-back under assumed gate-departure and taxi-out time uncertainties, assuming a Call For Release is strategically done for all departures from all airports. However, if there were no gate-departure and taxi-out time uncertainty, which is unlikely in reality, the maximum benefit of scheduling an hour before gate-push-back is limited to 6.8% reduction in weighted delay (2*airborne delay + ground delay) compared to delay resulting from scheduling at gate-push-back.

I. Introduction

A Precision departure capability seeks to improve the delivery of departing aircraft to join constrained overhead flows such that they take-off on time and arrive at the assigned slot at an en route metering point and at the destination airport. An early or late departure from the origin airport means that the originally assigned slot will potentially be missed if no compensatory maneuvers are made. Aircraft will need to reduce speed or take a longer path to compensate for early departure, and will need to speedup to make up time for late departure. Slot recovery, however, is limited by the aircraft's ability to speedup and slow down. Furthermore, controllers and pilots are reluctant to accelerate beyond filed flight plan speeds and in excess of that prescribed by the standard departure procedures. In current operations, speeding up is not a common solution. In instances when it is not possible for the aircraft to arrive at a planned slot, a new slot needs to be assigned by the scheduler, which can cause additional departure delays. The cost of aircraft not departing on time is determined in terms of delays, more fuel being consumed, and potentially additional controller workload due to vectoring required to work an early departure into the overhead stream slot.

References 1 and 2 describe the approval request process, also known as Call For Release process, in which the tower requests the traffic management coordinator at the Air Route Traffic Control Center (or Center) for departure release of a flight. The traffic management coordinator identifies a slot in the overhead stream, operating with a miles-in-trail restriction, for insertion of the requested flight and issues a departure time. Reference 1 proposes a Departure Release Communications capability to reduce the time it takes to coordinate departure release and Ref. 2 suggests

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*Aerospace Engineer, Systems Modeling and Optimization Branch, M/S 210-15.

†Scientist and Task Manager, U. C. Santa Cruz, M/S 210-8, Associate Fellow.

‡Programmer Analyst, Aerospace Computing Inc., M/S 210-8.

the use of a Departure Release Calculator to improve the accuracy of departure release time. Three recent studies are described in Refs. 3, 4, and 5. Reference 3 describes the Precision Departure Release Capability operational concept, system design, and system evaluation recently completed at the NASA/FAA North Texas Station facility that precedes another test that will generate data for benefit analysis of the concept. Reference 4 describes the shortfalls of the current day utilization and performance of the tactical departure scheduling process in the National Airspace System and how the Precision Departure Release Capability technology can potentially address the shortfalls. Reference 5 describes the impact of early and late departures from the departure runway when an aircraft has a slot assigned at Houston with only the at-gate-push-back scheduling. In that study, 808 arrivals from 174 airports were considered. Results show that the probability of getting the initially assigned slot, after perturbation and rescheduling, decreases with increasing standard deviation of the departure delay distributions. Further, slots were either captured or missed. When slots were missed, the study did not show by how much they were missed. By knowing the delay distribution of flights that miss their slots, a mitigation strategy can be created to recover some of the delays.

An objective of the research described in this paper is to further characterize the relationship between departure time uncertainty and the cost incurred in terms of increased delay and captured/missed slots when a Call For Release scheduling are performed before gate-push-back and at gate-push-back. Results of the study establish departure scheduling strategies. In this analysis, missed-slot data are presented for the before and at gate-push-back scheduling.

The rest of the paper is organized as follows. Section II provides descriptions of the Gate Departure Delay and Taxi-out Delay Distribution Modeling Using ASPM Data, Airspace Concept Evaluation System, and the scheduler. The last two are the two tools used in the study. The method for studying the effect of departure time uncertainty on increased departure delay and capturing/missing slots is detailed in Section III. This section discusses how ACES is used for simulating flights without sector and airport arrival rate constraints, and its output data are used by the scheduler to determine initial departure and arrival times based on airport arrival rate constraints. The additional steps of perturbing departure times assuming departure delay distributions at the airports of origin and subsequent rescheduling for meeting the airport constraints using the scheduler are also described in this section. The results of this study are presented in Section IV. Finally, the main findings are summarized in Section V.

II. Simulation Data, Tools, and Departure Scheduler

This section describes the input data modelling and the two tools used for this study. Modelling of gate departure delay and taxi-out delay distribution using the real-world Federal Aviation Administrations (FAA) Aviation System Performance Metrics (ASPM) data is described in Section II.A. Tools used include the Airspace Concept Evaluation System (ACES), an air traffic simulator, and a traffic scheduling system. A brief description of ACES is provided in Section II.B. The scheduler is described in Section II.C.

A. Gate Departure Delay and Taxi-out Delay Distribution Modeling Using ASPM Data

This section describes modelling of gate departure delay and taxi-out delay distributions using the ASPM database, which is accessible on the web for authorized users. The FAA uses these data for monitoring airport efficiency, aspects of system performance, and retrospective trend analysis studies. It provides detailed data on flights to and from the 77 major U. S. airports (ASPM 77 airports) and flights operated by 29 major carriers (ASPM 29 carriers). Flights operated by ASPM carriers to international and domestic non-ASPM airports are also included. The ASPM database also contains information on airport weather, runway configuration, and arrival and departure rates. Data in ASPM provide insight into air traffic and air carrier activity.

To model gate departure delay and taxi-out delay distributions, data were derived for each of the 77 major U. S. airports in the ASPM database for each hour of every day in 2011 using the standard "Analysis By Airport By Hour Report (compared to flight plan)." This report includes counts of scheduled departures/arrivals and departures/arrivals used for metric computation, percentages of on-time gate departures, airport departures and gate arrivals, average gate departure delay, average taxi-out time, average taxi-out delay, average airport departure delay, average taxi-in time, and average gate arrival delay. Times are reported in minutes. Numbers of scheduled arrivals and departures are based on carrier published schedules. Numbers of arrivals and departures for metric computation are based on itinerant flights to/from the ASPM 77 airports or operated by one of the ASPM 29 carriers. General aviation and military flights are excluded.

Percent on-time metrics are captured as follows. Percent on-time gate departures is computed as the ratio of the number of flights that departed within 15-minutes past the flight plan gate-out time to the number of departures. Percent on-time airport departures is given as the ratio of the number of flights that departed within 15-minutes past the flight plan wheels-off time to the number of departures. Percent on-time gate arrivals is determined as the ratio of the number of flights that arrive at the gate less than 15-minutes late compared to the flight plan gate-out time plus the scheduled block time to the total number of arrivals.

Delays are computed as follows. Taxi-out/taxi-in delay is the difference between taxi-out/taxi-in time and unimpeded taxi-out/taxi-in time. Airport departure delay is computed as the difference between the actual wheels-off time and the sum of flight plan gate-out time and unimpeded taxi-out time. Average gate arrival delay is determined by adding minutes of gate arrival delay of one-minute or more, and dividing it by number of arrivals. Gate arrival delay is defined as the difference between the actual gate-in time and the flight plan gate-in time. All average delays are hourly averages.

Histograms of hourly average gate departure delay and hourly average taxi-out delay constructed for Hartsfield-Jackson Atlanta International airport are shown in Fig. 1 (a) and (b).

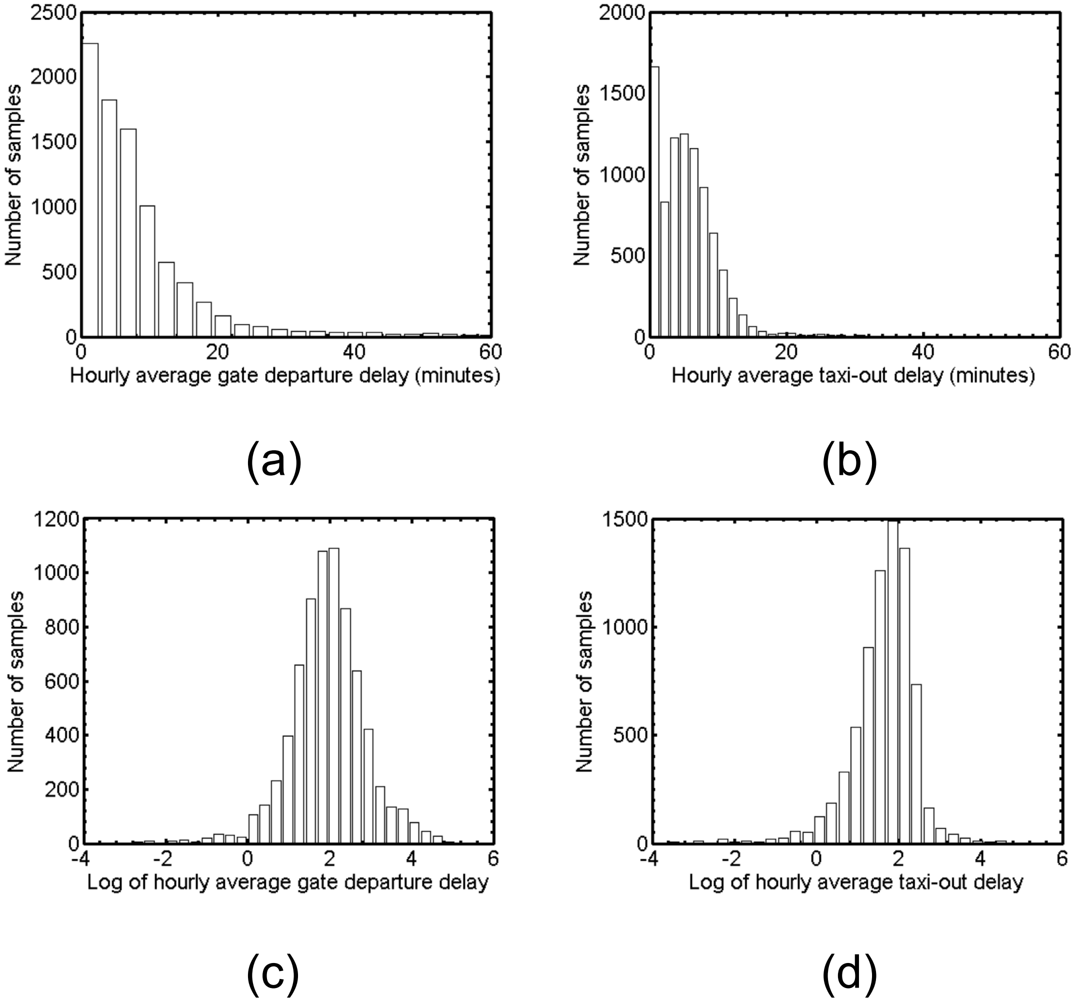


Figure 1. (a and b) Atlanta hourly average gate-departure and taxi-out delay histograms and (c and d) their log-normal transforms.

The maximum hourly average gate departure and taxi-out delays were found to be 4.6 hours and 2.4 hours, respectively, but are outliers. There are 8,727 samples (approximately 24 hours 365 days) in the histogram, with data missing for some hours on some days. Observe that data are shown up to 60 minutes. The outliers are not shown. These histograms exhibit the characteristics of exponential distributions.

Exponential distributions are commonly modelled with log-normal distributions. To construct the log-normal distribution, zero delay values were first separated from positive delay values. Natural logarithm was then computed with the positive values and its distribution was examined. Figure 1 (c) and (d) show the resulting histograms of the hourly average gate departure and taxi-out delays. Both of these distributions appear to be approximately Gaussian after the log transform. These distributions can now be approximated by the mean and standard deviation values. To account for the zero-delay values in the model, a probability of zero-delay is computed as the ratio of the number of zero-delay samples to the total number of samples. For Atlanta, the zero hourly average gate departure delay and taxi-out delay samples were found to be 1,410 and 1,249. The probabilities of zero hourly average gate departure and taxi-out delays are thus 0.16 and 0.14 with 8,727 total samples. Data for the 77 airports is given in the Table 3 in the Appendix.

The first step in simulating gate departure and taxi-out delays of a flight from one of the 77 ASPM airports consists of generating a uniformly distributed pseudo-random number between zero and one. If this value is less than or equal to the zero-delay probability value in column two for gate departure delay in Table 3 and in column five for taxi-out delay in the same table, zero delay is assigned. When the value is greater than the zero-delay probability, the second step consists of generating a normally distributed pseudo-random number with mean and standard deviation values specified in Table 3. If the numerical value of the pseudo-random number is x, delay δ is obtained as shown in Eq. 1.

$$\delta = e^{x} \tag{1}$$

These two steps approximate the exponential distributions shown in Fig. 1 (a) and (b).

B. Airspace Concept Evaluation System

ACES is a gate-to-gate simulation of air traffic at local, regional, and national levels developed at the NASA Ames Research Center.[6] ACES simulates flight trajectories using aircraft models derived from the Base of Aircraft Data (BADA)[7] and traffic data consisting of departure times and flight-plans obtained from recorded Aircraft Situation Display to Industry (ASDI) files. Traffic flow management and air traffic control models in ACES use airport and sector capacity thresholds. Flights are delayed on the ground and in flight to ensure that the specified capacity constraints are not violated. ACES can also be run without traffic flow management. This function enables open-loop simulation of traffic to establish a baseline. Typical ACES outputs include system performance metrics of arrival, departure, en-route and total delays. Validation studies in Refs. 8 and 9 have shown that ACES generates delays and metrics comparable to those observed in the real-world.

In this study, ACES is used for simulating traffic without airport and airspace capacity constraints. The resulting output data is then used for generating inputs for the scheduler, which is discussed in the next section, and for verifying that the departure schedule generated by the scheduler satisfied the capacity constraints.

C. Scheduler

Table 1 shows seven variations of the scheduler used in this experiment for evaluating the Call For Release (CFR) scheduling procedure before gate-push-back and at gate-push-back. Variation 7 represents an ideal scheduling with respect to arrival airport constraints. All variations of the scheduler use the first-come first-served principle to create a departure/arrival schedule for all flights. Delay is generated to satisfy constraints at the arrival airports.

Table 1. Seven Scheduler Variations by Arrival Queue, Departure Time, Uncertainty, and Scheduling Order

Scheduler Variation	Arrival Queue	Departure Time	Uncertainty	Scheduling Order
1	Fixed	Fixed	No	By Departure
2	Fixed	Fixed	Yes	By Departure
3	Flexible	Fixed	No	By Departure
4	Flexible	Fixed	Yes	By Departure
5	Flexible	Flexible	No	By Departure
6	Flexible	Flexible	Yes	By Departure
7	Fixed	Fixed	No	By Arrival

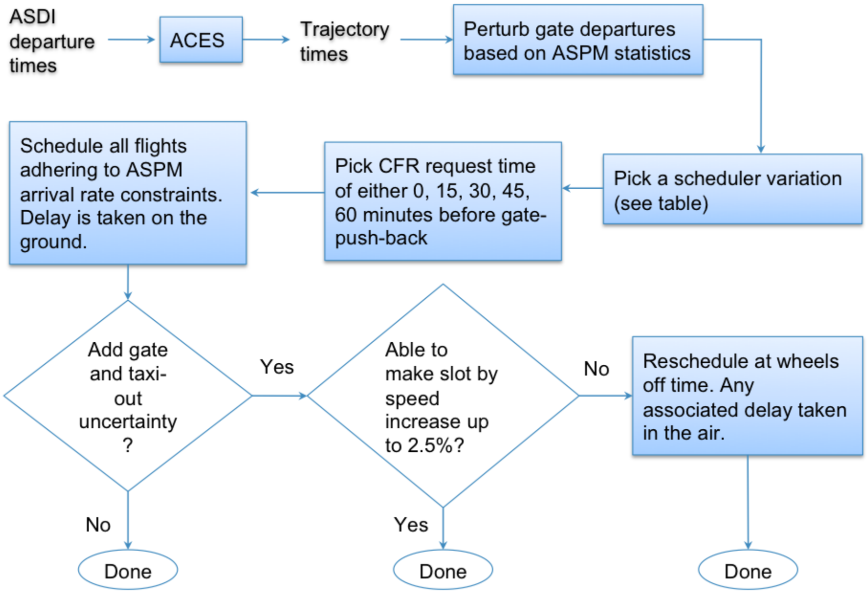
The main inputs to the scheduler are a list of flights including flight-plan departure time, flight time, and arrival time, as well as arrival capacity rates for all airports in the simulation. Flight time and arrival time at the destination airport are generated by an ACES simulation of unconstrained traffic. Arrival Constraints are derived from ASPM data of the day being modelled in the experiment.

The scheduler sorts all flights according to their flight-plan departure or arrival times, depending on the scheduler variation selected in Table 1, and then begins scheduling by allocating airport resources to the flights. As flights occupy these resources for the time periods corresponding to arrival time, the available capacity is reduced to the point that none is available. The schedulers used here are an extension of the methods described in Refs. 10 and 11. For portions of the experiment, uncertainty is added to departure times, for which the scheduler permits limited speed increase of up to 2.5% to maintain arrival slots.

The Approach in Section III further describes the experiment and includes more details about the scheduler.

III. Approach

The procedure for evaluating the impact of departure time uncertainty on additional delays and captured/missed slots is summarized in the block diagram in Fig. 2.



Repeat process for each schedule variation (x7), for each CFR request time (x5) for a total of 35 different scheduling scenarios.

Figure 2. Experiment procedure showing how simulation is done.

The effect the scheduler variations in Table 1 on delay propagation from arrival airport capacity constraints and missed arrival slots was examined. Each of these schedulers was run with CFR scheduling at 0, 15, 30, 45, and 60 minutes before gate-push-back for a total of 35 different scenarios. The 0-minutes before gate-push-back case represents at gate-push-back scheduling for each scheduler, the rest of the scenarios represent scheduling before gate-push-back. Each of the 35 scenarios was run 100,000 times in a Monte Carlo simulation, with each run having a different set of gate and taxi time perturbations. However, this set was the same across each of the 35 scenarios within the run to more accurately compare one scheduler to another. The uncertainty in gate departure associated with CFR request time before gate-push-back differed for each scenario depending on the time amount. Taxi uncertainty was modeled as well. All schedules produced by the schedulers adhered to capacity constraints at the arrival airports.

A. Input for the Scheduler

1. Gate Departure Times and Arrival Times

In the first stage, flight arrival times and stochastically perturbed gate departure times are generated. For the rest of this paper, these times are called ”proposed” gate departure times. To start, a list of real-world ASDI scheduled gate departure times are input into ACES, generating flight durations and arrival times for each flight on the flight list. Using the methods described above for generating realistic gate departure delay based on ASPM data, a randomized gate departure time is generated for each flight on the flight list. In this experiment, all delays are positive, which is unlikely in reality, so a flight’s proposed gate departure time is always equal or greater than its input ASDI gate departure time; i.e., no flights leave earlier than scheduled. Only positive delays were used in order to simplify the problem in this study. Once a proposed gate departure time is generated, the transit time calculated in ACES is added to this proposed gate departure time, creating a ”proposed” arrival time.

2. *Airport Arrival Rates and Unimpeded Taxi Times*

Airport arrival rates and unimpeded taxi times are input into the scheduler based on the real-world ASPM airport data. Non-ASPM airports use an arrival rate of 30 aircraft per hour. The airport arrival rates are used to calculate the minimum time separation between aircraft arrivals, which are used when generating arrival slots. Unimpeded taxi rates were derived from the ASPM data and were used in calculating wheels off time for scheduling. Non-ASPM airports assumed an unimpeded taxi time of 5 minutes.

B. Scheduling

In this stage, slots at the arrival airport are scheduled such that airport arrival capacity constraints are maintained. Seven methods of CFR scheduling are used to compare results from different scenarios. Each method is performed with 0, 15, 30, 45, and 60 minutes before the proposed gate departure times calculated in Section III.A.1. Delay propagates from airport arrival constraints corresponding to a flight's proposed arrival time. This study considers only a maximum time of 60 minutes as uncertainty increases as time before gate-push-back increases. Considering that the commonly recommended domestic check-in time is 60 minutes, this value seems reasonable. In addition, uncertainty beyond this value is expected to saturate.

1. *Scheduling by Gate Departure with Fixed Arrival Queue*

In this method of scheduling, flights are scheduled in the order of their proposed gate departure times generated in Section III.A.1. Flights are scheduled at the proposed gate departure times minus the CFR request time. At this point a slot is assigned for the flight at the arrival airport based on its proposed arrival time, also calculated in Section III.A.1, including the unimpeded taxi time for its departure airport. If the proposed arrival time is too close (smaller than minimum time separation) to that of a previously scheduled flight with respect to arrival rate constraint separation, the next available slot is assigned. The time difference between the originally proposed arrival time, and the final arrival slot assigned, is taken as ground delay. Delay is therefore always positive. Once a flight has been scheduled, subsequent flights being scheduled do not affect it.

2. *Scheduling by Gate Departure with Flexible Arrival Queue*

This method of scheduling has two variations, described in sub-sections 3 and 4 below. It behaves exactly as the previous method, with the following exception: when a flight is scheduled at the arrival airport, it can add delay to flights that have already been scheduled in order to achieve optimal utilization of the airport arrival capacity. Flights can be delayed upstream to maximize usage of available arrival capacity. The scheduler achieves this by starting at the flight's proposed arrival time, and finding the first available gap in the scheduled arrival queue that meets the separation required by arrival capacity constraints. It then inserts the flight into the gap. If the gap is too small, it shifts the upstream flights' slots later as little as possible to maintain arrival constraint separation. Again, the time difference between the proposed arrival time and the final assigned arrival slot is taken as ground delay. The amount the other flights are shifted is taken as added delay to their schedule and is always positive. The other flights take this delay either on the ground or in the air depending on which variation of the scheduler is run and whether the flight has taken off yet.

3. *Fixed Departure Time*

With the fixed departure time variation of this scheduler, all delay added to a flight's schedule by the scheduler after the flight's original scheduling is taken as airborne delay. In this way a flight's scheduled departure time is fixed at the time of scheduling. The disadvantage of this approach is that airborne delay has a higher weighted cost than ground delay.

4. *Flexible Departure Time*

This variation of flexible arrival queue scheduling favors ground delay over airborne delay. If the scheduler is modifying a previously scheduled flight's arrival slot before its departure time, the added delay is taken on the ground, otherwise it is taken in the air. This prioritizes ground delay over airborne delay, but gives flights no guarantee as to when they will be departing.

5. *Scheduling by Arrival Time*

The final scheduling method is an idealized approach used to identify the lowest cost scheduling solution. This method is identical to the first method except it is done by order of the proposed arrival time calculated in Section III.A.1. This type of scheduling implies perfect knowledge of all flight durations and proposed departure times prior to scheduling, without uncertainty. This type of scheduling produces minimal delay with respect to arrival rate constraints, since it ensures maximum utilization of arrival capacity, and since all delay is taken on the ground, which is weighted less than airborne delay.

C. Departure Time Uncertainty and Rescheduling

Each of these preceding four types of scheduling, with the exception of the idealized scheduling by arrival time, is simulated with and without departure uncertainty. With stochastic uncertainty added to departure times, some flights miss their arrival slots entirely and must be rescheduled.

1. *Uncertainty*

Uncertainty in departure times has been added in two ways. First, gate departure time uncertainty is added as positive, random Gaussian numbers with standard deviation increasing 2 minutes for every 15 minutes of CFR request time before gate-push-back. So if a flight is being scheduled 45 minutes in advance of its proposed gate departure time, its actual departure time would differ from its proposed departure time, by a positive random Gaussian with a standard deviation of 6 minutes. Second, regardless of which CFR request time before gate-push-back is used, an additional taxi time perturbation is added based on the ASPM statistics of the flight's departure airport, using the methods described in the earlier section. Both methods only output positive perturbations to the flight's final wheels off time; this was done to simplify the problem in this study.

2. *Rescheduling*

In the scenarios using uncertainty, actual departure times are later than those used for their scheduling; consequently some flights miss their slots and need to be rescheduled. After adding in uncertainty associated with CFR request time before gate-push-back, and taxi time uncertainty, flights are allowed up to 2.5% speed increase to attempt to compensate and still make their original arrival slots. If this speed up is insufficient to recover the slot, the scheduler determines the flight will miss its original slot and reschedules the flight using its final wheels off time. In this case, the flight is removed from the arrival queue at the last point in time it could have departed and still hit its original slot by speeding up. This is done so that its slot is available for later flights being scheduled. The flight is then rescheduled at wheels off time, using the nominal speed and the same scheduling method it originally used, with any associated arrival constraint delay being taken in the air.

IV. Results

The approach described in Fig. 2 is applied to arrival traffic to all airports in the National Airspace System (NAS). The traffic for this scenario consists of departures between January 2, 2011, 9:00 p.m. Central Standard Time (CST) and January 3, 2011 midnight CST, a period spanning 27 hours from NAS airports. The arrival rate constraint of sixty to a hundred arrivals per hour is specified as a function of the time of this day based on the FAA ASPM reported ADR and AARs. In the simulation, 1,357 arrival airports dispense delays due to their respective arrival rate constraints to 1,552 departure airports. Out of a total of 46,249 flights in the entire dataset, 37,346 flights, excluding purely international flights, are included in the analysis. International flights that depart from the NAS or arrive into the NAS are included. The arrival time for the departures were calculated incorporating a relatively small speedup adjustment of up to 2.5% for slot capture. Delay statistics for ground and airborne were obtained for the 100,000 Monte-Carlo runs.

Results of the simulations are for seven scenarios corresponding to the scheduling variations shown in Table 1: 1) fixed or flexible arrival queue, 2) fixed or flexible departure time, 3) with or without uncertainties, and 4) an idealized scenario for reference. First, the weighted cost of delay is presented in Section IV.A. Next, descriptive statistics from the Monte Carlo runs are presented in Section IV.B. The delay distribution of flights missing their slots is presented in Section IV.C. Finally, the top 20 airports dispensing delays are presented in Section IV.D.

The approach assumes a Call For Release is done for all departures from all airports. The main reason for applying a common Call For Release policy for all departures is that if this policy is beneficial for departures from some airports it should benefit departures from other airports also.

A. Weighted Cost of Delay

Figures 3, 4, and 5 show the total cost of seven scenarios when CFRs are requested 0, 15, 30, 45, and 60 minutes before gate-push-back. Total cost is shown on the vertical axis and CFR request time before gate-push-back is shown on the horizontal axis. The cost is represented as a weighted sum of the ground and airborne delays. As airborne delay is more expensive than ground delay, the weight for airborne delay is twice as much as the weight for ground delay, using the 2009 FAA Economic Information for Investment Analysis Data Package estimates.

Figure 3 shows four scenarios under the ideal condition of no uncertainty. These costs – marked by grey circles, black triangles, orange dots, and a single green star – represent what could be achieved if there were no uncertainty. Out of the four scenarios in this figure, the fixed departure time scenario, without uncertainty and with fixed arrival queue, shown as grey circles has the highest costs at 1,770 hours. This figure shows that flexible arrival queue can reduce cost from a flat 1,770 to a flat 828 hours. It is flat cost regardless of CFR request time because fixed departure time – with or without uncertainty – does not reschedule. In this case, any further delays would be taken in the air. As in flexible arrival queue scenarios, costs also decrease in the flexible departure time scenarios (orange dots), from 828 hours to 758 hours at 60 minutes before gate-push-back. Unlike the previous flexible arrival queue scenario, the flexible departure time scenario, by allowing rescheduling, shows the benefits of scheduling before gate-push-back, when there is no uncertainty. Out of all the scenarios tested, this is the only one that shows benefits of scheduling before gate-push-back.

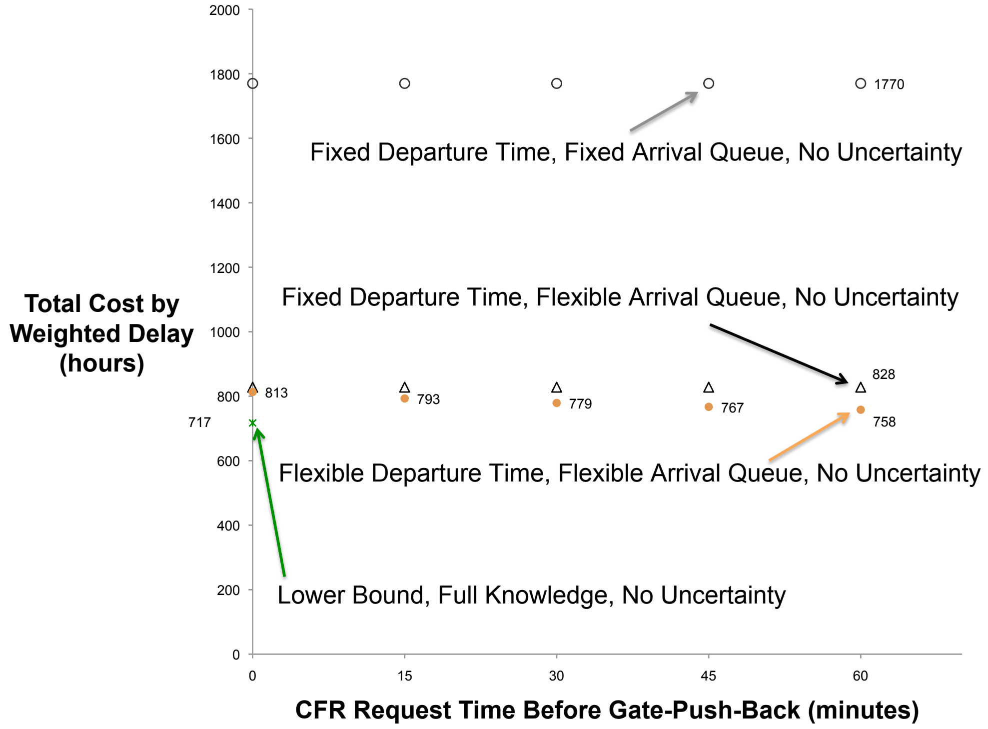


Figure 3. Benefits of flexible arrival queue and flexible departure time. Without uncertainty.

For comparison, the green star in Fig. 3 represents the ideal lower-bound cost (717 hours) for the scenario that involves scheduling in advance with full knowledge and no uncertainty. In this case, as in any previous flat cost cases, the times before gate-push-back are meaningless. Every flight on the list is going to land on time as first scheduled before it takes off; so each can be ideally scheduled. The closer a cost to this lower-bound the better a scheduling strategy is.

Figure 4 shows three scenarios. The top two sets of data (purple crosses and cyan stars) show the scenarios with uncertainty. Observe that the weighted cost increases with increasing time before gate-push-back. There are two reasons for this: 1) longer CFR request time before gate-push-back has higher uncertainty and 2) CFR is strategically (as opposed to tactically/opportunistically) done for every flight therefore no flight has an advantage over another.

In a future study, CFR could be applied in select cases to more closely model the current operations. For example, CFR can be applied to portions of flights according to airports, airlines, regions, or a combination of these. It is expected that CFR request time before gate-push-back could show some benefits for some flights while penalizing other flights in these situations. The bottom set of data (orange dots) assumes flexible departure time, flexible arrival queue and no gate-departure time and taxi-out time uncertainties. Observe that in this scenario, the weighted cost decreases with increasing time before gate-push-back. The set of data shows a 6.8% cost reduction from 813 hours when scheduling at gate-push-back to 758 hours when scheduling 60-minute before gate-push-back.

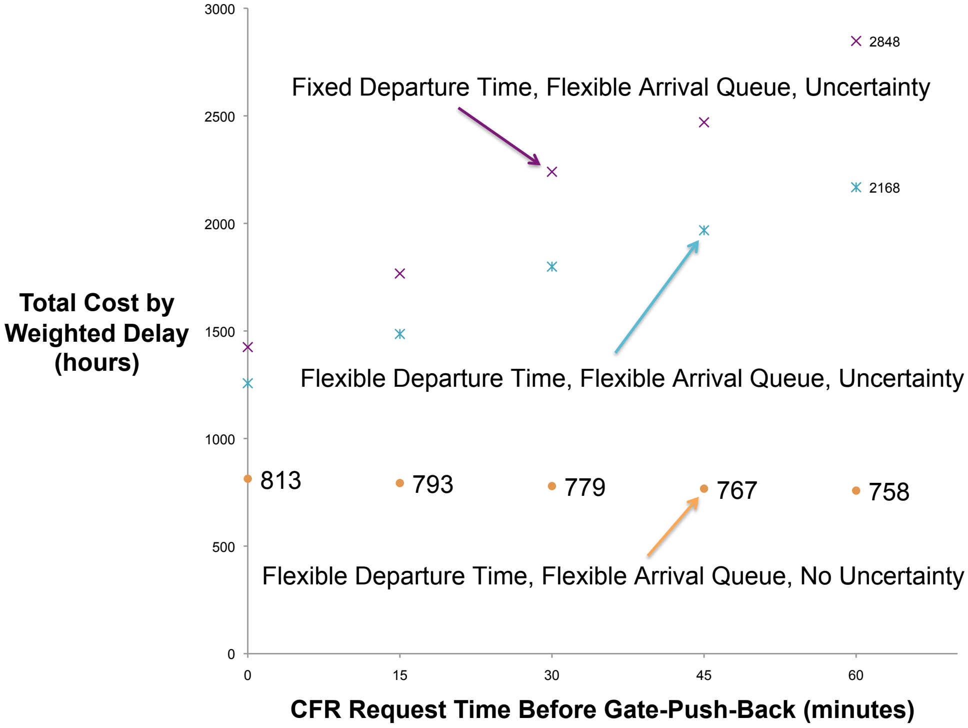


Figure 4. Benefits of flexible departure time. With and without uncertainty.

Figure 5 shows three select scenarios from previous figures in one chart to highlight the benefits of flexible departure time and flexible arrival queue scheduling under uncertainty. The top set of data (orange triangles) shows the scenario for fixed departure time, fixed arrival queue, with uncertainty. At 60-minute CFR request before gate-push-back, the cost with fixed departure time and fixed arrival queue is 6,117 hours. The middle set of data (purple crosses) shows the scenario for fixed departure time, flexible arrival queue, with uncertainty. By using flexible arrival queue, the cost reduces to 2,848 hours. The bottom set of data (cyan stars) shows the scenario for flexible departure time, flexible arrival queue, with uncertainty. When a flexible departure time is used, the cost further reduces to 2,168 hours.

In current DFW operations, CFR scheduling is performed close to or at the spot (i.e., Apron Entry/Exit Point), which is after departure from gate. It is not practical to issue multiple ground delays to a flight after departure from gate. On the other hand, in before-gate-push-back cases, a release time could be issued up to closer to the last minute; i.e., till soon before gate-push-back time by using a flexible departure time with flexible arrival queue. Providing ATC more information about flights readiness, can potentially reduce the airborne delay cost. In this study, a simplified modeling is performed to allow issuing of release time up to wheels-off time.

Figure 6 shows airborne delay reduction in the simulation. The vertical axis shows the additional ground and airborne delays in hours. The horizontal axis shows the CFR request time before gate-push-back in minutes. The bottom blue columns show the additional ground delay amounts. The top red columns show the additional airborne delay amounts. As shown in Fig. 6 (a) and (b), although the total delay remain approximately the same, flexible departure time transfer delays from air to ground as shown by the shorter red columns. It reduces the cost from 994 in (a) to 132 in (b) at 60-minute CFR request time before gate-push-back.

Figure 7 shows how a flexible arrival queue can reduce delay. The top part of the figure shows an arrival time line

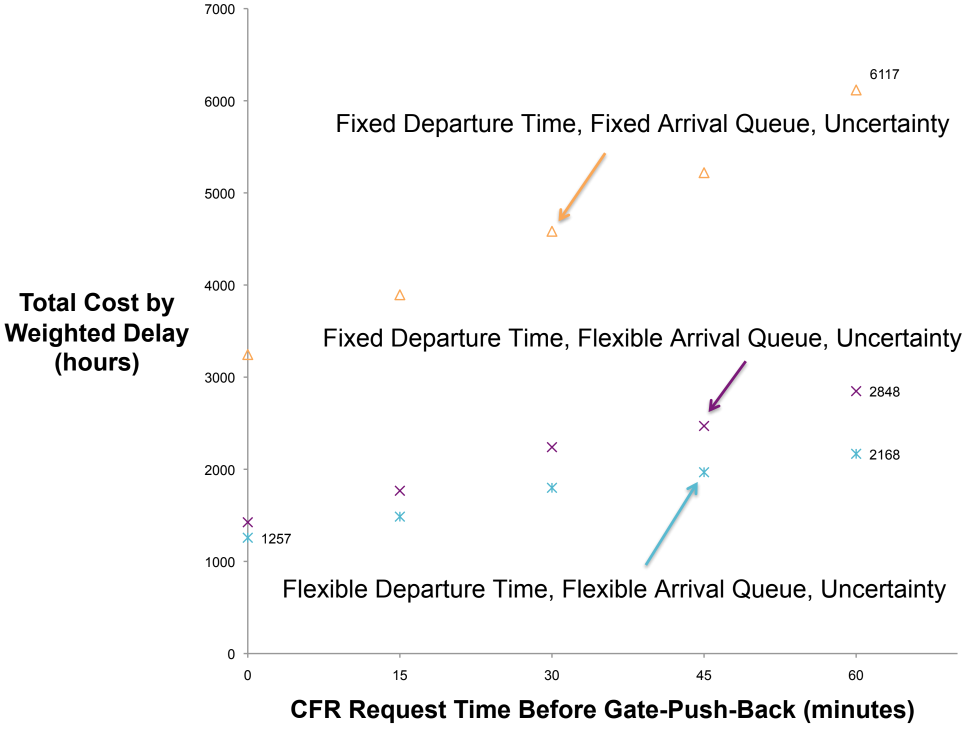
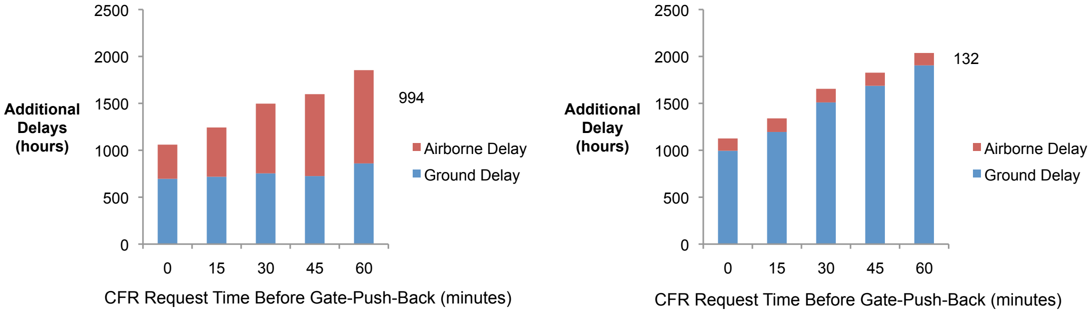


Figure 5. Benefits of flexible arrival queue and flexible departure time. With uncertainty.



(a) Fixed Departure Time (b) Flexible Departure Time

Figure 6. Airborne delay transferred to ground delay if release time is issued up to gate-push-back time.

for, as an example, two flights UAL and JBU. The next two time lines show scheduling with fixed arrival and flexible arrival queue, respectively. UAL is a long-haul flight from San Francisco bound for JFK and JBU is a short-haul flight from Boston to JFK. The UAL flight departs earlier than the JBU flight – indicated by the supper-scripts 1 and 2, respectively – but the latter has an earlier arrival schedule as indicated in the time line (i.e., the beginning of the blue and green bars). The length of the bars indicate minimum time separation, which can generally vary throughout the day. The two flights are scheduled so to arrive at JFK in an Open time slot (grey bar indicates a Closed time slot). In this example, since UAL arrives later than JBL, there are two choices of how to space the two flights. One is to delay JBU on the ground to place it after UAL's arrival while another is to delay UAL in the air such that it would arrive after JBU, observing the minimum time spacing requirement in each case. With fixed arrival queue, JBU would incur additional delay on the ground, yielding a longer total delay indicated by the longer red bar, as compared with the one with flexible arrival queue.

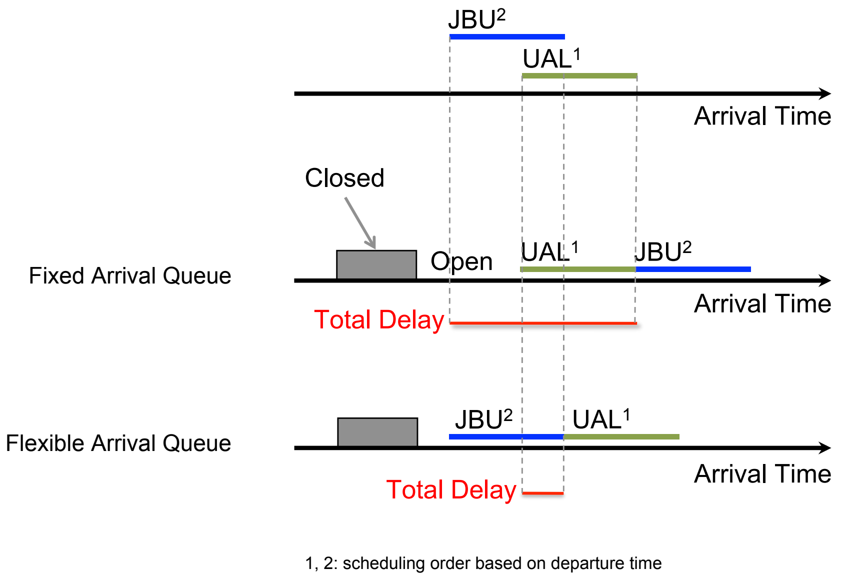


Figure 7. How First Come, First Served scheduler yields benefits with flexible arrival queue at arrival slots.

B. Monte Carlo Statistics

Table 2 summarizes the statistics (minimums, averages, and maximums) of the Monte Carlo runs for three cases, one in each column. The first two – shown in column two and three, respectively – show the difference between CFR requests 60 minutes before gate-push-back and CFR requests at gate-push-back. These cases were scheduled using flexible departure time, flexible arrival queue, and uncertainty. The third is the ideal lower-bound reference without gate-departure time and taxi-out time uncertainties. Its scheduling is done based on first-come first-served arrivals as opposed to first-come first-served departures. This was referred to as scheduler variation 7 in Table 1. Observe that this reference scenario resulted in all ground delays; hence least weighted delay, and all flights captured their slots.

Comparing scheduling 60-minutes before gate-push-back with scheduling at gate-push-back, observe that there is no real advantage to scheduling before gate-push-back. The average weighted delay of 3.62 minutes per flight is higher than 2.2 minutes for scheduling at gate-push-back, and 94% of the flights miss their slots. While the weighted delay is higher, the airborne delay is a bit lower.

C. Delay Distribution of Flights that Missed Their Slots

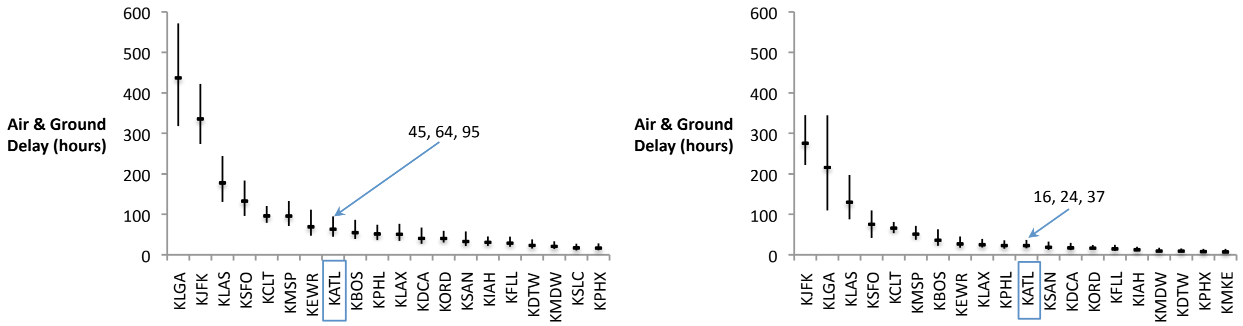
In addition to the slot miss metric, Table 2 shows the amount of time by which the slot is missed. Compared to the slot miss metric, which is a binary metric, the slot-miss time metric is a continuous metric. For scheduling before gate-push-back, flights missed their arrival slot by 10.4 minutes on an average. This delay is far greater than the three-minute (+2/-1 or 2-minute late/1-minute early) wheels-off time compliance window used in the current operation which means that these flights cannot reacquire their assigned slots in the arrival stream. A smaller average slot-miss time of 2.8 minutes for scheduling at gate-push-back suggests that more flights can reacquire their assigned slots.

Table 2. Monte Carlo Statistics of Select Scenarios to Show Variations

1	2	3	4
	Flexible Departure Time, Flexible Arrival Queue, Uncertainty		Full Knowledge, Without Uncertainty
Variable	60 min before pushback	At pushback	
Average total weighted cost of delay (min)	3.62	2.20	1.10
Average airborne delay (min)	0.23	0.25	0
Max airborne delay (min)	22.7	20.0	0
Max of standard deviation of airborne delay (min)	0.82	0.85	0
Average ground delay (min)	3.2	1.7	1.1
Max ground delay (min)	393	323	82
Max of standard deviation of ground delay (min)	15.3	12.1	5.1
% flights missing their slots	94	56	0
Average slot-miss time (min)	10.4	2.8	0
Max of standard deviation slot-miss time (min)	11.6	7.6	0

D. Top 20 Arrival Airports Imposing Delays to Departing Flights

Figure 8 (a) and (b) show the top 20 airports that impose delays. Scheduling was done with flexible departure time, flexible arrival queue, and gate-departure time and taxi-out time uncertainties. The vertical axes show the sum of ground and airborne delays in hours. Minimum and maximum delays are indicated at the lower and upper ends of the bars. The average value is indicated by a dash between these two values. For example, the lower, average and maximum values for Atlanta in Fig. 8 (a) are 45, 64 and 95 minutes. The horizontal axes show the top 20 airports ordered by total delay. As discussed before, the figures show that delays are lower with scheduling at gate-push-back. Observe that the order of airports is different with scheduling 60-minutes before gate-push-back compared to at gate-push-back.



(a) CFR Requested 60-min Before Gate-Push-Back

(b) CFR Requested At Gate-Push-Back

Figure 8. (a) Top 20 arrival airports imposing delays to departing flights at departure airports, with CFR requested 60-min before gate-push-back, (b) Top 20 arrival airports imposing delays to departing flights at departure airports, with CFR requested at gate-push-back.

V. Conclusions

This paper examined the benefit of Call For Release scheduling before gate-push-back and at gate-push-back. The results discussed in the paper are based on a single day of traffic data. Airport arrival rate constraints were specified as a function of time at the 1500 airports considered in the study. A first-come first-served scheduler was then used to schedule departures from airports by delaying them to ensure that the specified airrival capacities were not exceeded. Gate-departure time and taxi-out time uncertainties were considered for scheduling. It was also assumed that flights could speedup by up to 2.5% above their nominal cruise speed. Monte-Carlo simulations were done to generate the results.

Results for the single-day simulation show that there is no significant benefit of scheduling before gate-push-back as opposed to at gate-push-back, assuming a Call For Release is requested for all departures from all airports. Although there is no system-wide benefits measured in terms of delay, there might be some coordination benefit, which could lead to more precise departures from the gate and precise taxi-out time. However, if there were no gate-departure and taxi-out time uncertainty, the maximum benefit of scheduling an hour before gate-push-back is limited to 6.8%

reduction in weighted delay (2*airborne delay + ground delay) compared to delay resulting from scheduling at gate-push-back.

This study did not examine benefits when a Call For Release is requested for portions of departures; e.g., from some airports and not from others. A future study should consider Call For Release scheduling for portions of departures, more days with different demand capacity, speed slow down, early departures, scheduling up to soon-before gate-push-back, and opportunistic cases.

Acknowledgments

The authors thank Charlene Cayabyab for configuring and running the simulations, and for output data reduction. The authors also thank Huu Viet Huynh for his support in running the Monte Carlo simulation.

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Table 3. Appendix: Hourly average gate departure and taxi-out delay model data

1	2	3	4	5	6	7
	Hourly Average Gate Departure Delay			Hourly Average Taxi-out Delay		
Airport Code	Zero-Delay Probability	Mean Log-Normal	Standard Deviation Log-Normal	Zero-Delay Probability	Mean Log-Normal	Standard Deviation Log-Normal
ABQ	0.34	1.43	1.23	0.289	0.539	0.945
ANC	0.131	1.434	1.085	0.154	-0.126	1.527
ATL	0.162	1.959	0.918	0.143	1.634	0.803
AUS	0.299	1.677	1.181	0.25	0.174	1.102
BDL	0.313	1.734	1.214	0.272	0.354	1.267
BHM	0.417	1.843	1.306	0.411	0.428	1.089
BNA	0.29	1.689	1.137	0.259	0.469	0.966
BOS	0.198	1.885	0.968	0.179	1.216	0.842
BUF	0.307	1.936	1.257	0.335	0.259	1.28
BUR	0.36	1.53	1.289	0.23	0.333	0.934
BWI	0.215	1.856	1.08	0.202	0.747	0.87
CLE	0.239	1.739	1.107	0.243	0.603	1.099
CLT	0.176	1.92	0.906	0.145	1.425	0.772
CVG	0.297	1.854	1.129	0.313	0.135	1.264
DAL	0.229	1.991	1.032	0.227	0.038	1.036
DAY	0.475	1.739	1.328	0.461	0.522	1.222
DCA	0.224	1.668	1.02	0.191	1.064	0.907
DEN	0.174	1.915	0.983	0.135	0.817	0.928
DFW	0.179	2.026	0.797	0.176	0.918	0.666
DTW	0.224	1.965	0.938	0.227	0.592	1.114
EWR	0.153	2.167	0.977	0.123	1.637	0.901
FLL	0.228	1.803	1.01	0.199	0.962	0.914
GYY	0.938	3.042	1.005	0.986	-0.41	0.186
HNL	0.113	1.077	1.057	0.095	0.276	0.843
HOU	0.258	1.938	1.06	0.253	0.146	0.939
HPN	0.307	2.614	0.966	0.362	0.262	1.3
IAD	0.189	2.229	0.936	0.191	0.646	1.083
IAH	0.206	1.884	0.824	0.18	1.13	0.847
IND	0.204	1.846	1.163	0.249	0.057	1.216
ISP	0.617	1.82	1.419	0.466	-0.006	1.148
JAX	0.34	1.537	1.309	0.257	0.391	1.037
JFK	0.11	2.134	0.945	0.093	1.348	1.183
LAS	0.157	1.764	0.855	0.13	1.008	0.706
LAX	0.074	1.842	0.737	0.058	1.102	0.606
LGA	0.203	1.957	1.02	0.181	1.963	0.982
LGB	0.498	1.668	1.301	0.339	0.488	1.129
MCI	0.254	1.656	1.119	0.25	0.327	1.048
MCO	0.222	1.673	1.05	0.168	1.004	0.732
MDW	0.232	2.082	0.952	0.224	0.679	0.883
MEM	0.279	2.148	1.109	0.269	0.326	1.276
MHT	0.383	2.026	1.327	0.407	0.038	1.286
MIA	0.16	2.329	0.802	0.153	0.909	0.699
MKE	0.229	1.88	1.162	0.228	0.36	1.123
MSP	0.266	1.78	0.973	0.237	0.788	0.988
MSY	0.324	1.467	1.282	0.288	0.332	0.982
OAK	0.141	1.778	1.077	0.13	0.005	1.061
OGG	0.539	1.042	1.177	0.316	0.035	0.964
OMA	0.352	1.71	1.205	0.342	0.216	1.207
ONT	0.288	1.756	1.436	0.203	0.083	1.184
ORD	0.109	2.061	0.923	0.098	1.277	0.797
OXR	0.957	3.004	1.06	0.945	1.2	0.459
PBI	0.343	2.19	1.148	0.269	0.372	1
PDX	0.21	1.418	1.114	0.172	0.464	0.863
PHL	0.166	2.039	1.005	0.153	1.223	1.147
PHX	0.158	1.617	0.899	0.135	0.877	0.826
PIT	0.242	1.885	1.142	0.281	0.389	1.215
PSP	0.544	2.039	1.24	0.36	0.669	1.074
PVD	0.349	1.877	1.263	0.392	0.442	1.206
RDU	0.253	1.913	1.124	0.243	0.774	0.926
RFD	0.783	2.394	1.381	0.953	-0.482	0.595
RSW	0.373	1.515	1.288	0.275	0.357	1.074
SAN	0.193	1.512	1.107	0.164	0.752	0.792
SAT	0.29	1.597	1.167	0.224	0.579	0.909
SDF	0.25	1.958	1.246	0.323	-0.02	1.302
SEA	0.195	1.285	0.972	0.163	0.595	0.802
SFO	0.137	1.855	0.924	0.12	1.181	0.664
SJC	0.208	1.452	1.2	0.151	0.223	0.915
SJU	0.36	1.61	1.231	0.292	0.234	1.043
SLC	0.233	1.492	1.047	0.212	1.038	0.954
SMF	0.203	1.384	1.194	0.146	0.351	0.926
SNA	0.174	1.484	1.144	0.135	0.436	1.142
STL	0.22	1.808	1.036	0.239	0.187	0.955
SWF	0.71	2.641	1.285	0.815	0.171	1.6
TEB	0.269	3.299	0.8	0.853	-0.521	0.333
TPA	0.288	1.414	1.329	0.264	0.45	0.874
TUS	0.476	1.373	1.317	0.271	0.563	1.044
VNY	0.676	3.271	0.905	0.933	-0.426	0.296