Estimating Departure Queues to Study Runway Efficiency

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Abstract

The ability to analyze the current efficiency of surface operations is limited by the lack of availability of surface surveillance data. To study surface and departure issues, and identify opportunities for automation to improve traffic management, this paper first presents a method for reconstructing the departure queues that existed at each runway from available information. Observations of the departure queues are of particular interest because they provide insight into the management of departures prior to takeoff. The method correlates pushback data and radar data to estimate the departure runway, the takeoff time, and the time at which the aircraft joins the departure queue, for every departure. By calculating the interval of time for which each aircraft is waiting at the runway, the departure queue at each runway can be reconstructed at every point in time. The paper uses this method to study five days of data from Dallas/Fort Worth airport. Substantial departure queues and delays are observed, consistent with expectations for a hub airport. Moreover, knowledge of the departure queues provides insight into the efficiency with which the departure runways were

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used. The departure queues on the primary departure runways are shown to be well balanced at most times. However, during periods of time when departure demand was present at the runway, the inter-departure gaps exhibit significant variability. These delays between consecutive departures may indicate an opportunity for automation to increase throughput.

Introduction

The ability to analyze the current efficiency of surface operations, including the management of departures prior to takeoff, is limited by the lack of availability of surface surveillance data. To develop surface automation tools that would increase capacity, efficiency, flexibility, and predictability, the dynamics of aircraft surface movements (e.g., the location and causes of delays) must be modeled; surface surveillance is necessary to develop these models. To enable the study of surface and departure issues, and identify opportunities for automation to improve traffic management, this paper presents a method for synthesizing surface surveillance data. Observations of the departure queues (i.e., the line of aircraft waiting at the runway to take off) are of particular interest because they would provide insight into how the departure runways are being used and, therefore, may suggest automation tools that might improve the management of departures prior to takeoff. This paper presents a novel method for reconstructing the departure queues that existed at each runway, as a function of time, using currently available information.

A few surface automation tools have been introduced (e.g., the Surface Movement Advisor (SMA) [1] provides air carriers with track information for aircraft within the terminal-area, and the Datalink Delivery of Expected Taxi Clearances (DDTC) tool reduces radio frequency congestion as well as controller and pilot workload). However, surface traffic management has received far less attention than both terminal-area and enroute traffic management, leaving substantial opportunities for automation tools to improve surface operations. In fact, a variety of ideas for new surface automation have been suggested (e.g., [2]) but have received little study, since the detailed information about the current movements of aircraft on the surface, needed to identify the existing inefficiencies and determine which automation ideas should be pursued, is not available. Many of these future automation tools will require real-time surface surveillance. The Airport Surface Detection Equipment (ASDE) that currently operates at many large airports does not identify the aircrafts’ flight numbers, since it is a primary (i.e., skin paint) surface surveillance radar and, therefore, is of limited use for traffic management automation. New surface surveillance systems, currently being tested, will provide real-time information about the location and identification of aircraft. However, until data from these new surveillance systems becomes available at many airports, other methods for studying surface issues are required.

This paper introduces a method for reconstructing the departure queues that existed at a runway after the aircraft have taken off. Note that this method does not replace the need for surface surveillance, since it cannot operate in real-time. Previously, little was known quantitatively about aircraft movements between pushback and takeoff. Although qualitative observations and limited data have been collected by hand (e.g., [3, 4]), data for longer periods of time or at many airports has not been available. This technique will permit more complete study of how departure runways are used (e.g., departure balancing and inter-departure times when demand exists at the runway). Note that this technique does not provide visibility into the nature of surface movements between the aircraft pushing back and reaching the departure queue at the runway.

The remainder of the paper is organized as follows. Following a brief background describing surface surveillance systems and previous work modeling airport surface dynamics, the next section presents the novel method for reconstructing the departure queues. The subsequent section applies the method to data from Dallas/Fort Worth airport (DFW) and examines the queues that existed for evidence of inefficiencies. The paper finishes with conclusions and planned future work.

Background

The Airport Surface Detection Equipment (ASDE) has provided surface surveillance at many major airports for a number of years, and is especially useful during periods of poor surface visibility. However, the ASDE display, a map of the airport surface showing the locations of aircraft and other vehicles, does not identify each target (i.e., provide a data tag with the aircraft's flight number). The lack of target identity limits the usefulness of ASDE for surface automation. The FAA is currently developing several new surface systems. The Airport Movement Area Safety System (AMASS) uses the ASDE sensor to provide hazard (i.e., possible ground conflict) alerting to Tower controllers. Multilateration-based surveillance systems, called Airport Surface Target Identification Systems (ATIDS), have been successfully tested at several airports. Multilateration is a technique that compares the times at which an aircraft’s transponder signal reaches receivers at various locations on the airport surface to triangulate the location of the aircraft. ATIDS can also receive ADS-B reports. Since the aircraft’s transponder is used, identity information is provided. However, multilateration requires aircraft transponders to be turned on while on the surface. For historical reasons (i.e., to avoid saturating the terminal-area radar with too many targets), procedures currently require aircraft to turn their transponders off while on the surface, although the technological need for this requirement no longer exists. The FAA’s ASDE-X program will combine a multilateration system with a primary radar. At airports that do not currently have an ASDE-3 radar, a less expensive x-band radar will be used.

A variety of literature has studied airport surface operations. Idris and others [5-9] have studied the flow constraints affecting the departure process, and their causalities, to provide insight into how departures should be managed. Idris [5] has modeled the movement of aircraft on the airport surface as a controlled queueing system, and observed that aircraft queues are manifestations of flow constraints. For example, Idris identified the Tower air traffic controllers as a flow constraint, because aircraft are delayed when flight strips queue due to controller workload (i.e., the controller being occupied with another task) rather than move between controllers. Idris demonstrated that while runways, taxiways, ramps, gates, and air traffic control all contribute to departure delays, the largest queues and delays occur at the runways. Runway flow constraints are the result of the required minimum separation between departures, as well as downstream restrictions that propagate back to require additional inter-departure separation at the runway.

This paper begins to examine the efficiency with which runways are currently used, in order to identify opportunities for departure management automation. In particular, this paper studies the queues of aircraft at the runway. Note that departure queues and delays do not necessarily imply an inefficient use of the runways. When the departure demand temporarily exceeds the theoretical maximum capacity of the runway, aircraft will queue, and temporal bunching of demand is expected in any stochastic queueing system. However, when demand is present at the runway (i.e., a queue exists) and the airport’s departure rate is less than the maximum feasible rate, there may be an opportunity to improve the departure management. One possible inefficiency occurs when the queue at one runway is long while another runway is idle due to a lack of demand at that runway. A second possible inefficiency occurs when the sequence of departures requires large inter-departure gaps that could be avoided by resequencing the aircraft to mitigate downstream constraints.

An Algorithm for Reconstructing Departure Queues

Algorithm Overview

The algorithm begins by using flight numbers to correlate two separate sets of data. For every departure, the pushback and reported takeoff time from the Airline Service Quality

Performance (ASQP) data are matched with the departure runway and measured takeoff time derived from the radar data. The algorithm then uses the departure sequence from the radar data to construct the sequence in which aircraft joined the departure queue. To estimate the time at which the aircraft joins the queue, the algorithm makes assumptions about the time required for the aircraft to taxi from the gate to the runway. Note that this quantity – the individual movement time for each flight – is not observable from the available data. By calculating the interval of time for which each aircraft is waiting in the departure queue, the departure queue at each runway can be reconstructed at every point in time.

Data Sources

The Department of Transportation (DOT) collects ASQP data to assess the on-time performance of the major airlines; only the top ten airlines submit data to the DOT. ASQP data contains a record for every flight the participating airline operates, including the flight number, origin, destination, date, scheduled departure and arrival times, and the actual OUT, OFF, ON, and IN (OOOI) times. The OUT time is the time at which the aircraft pushes back from its gate; the OFF time is the time at which the aircraft takes off; the ON time is time at which the aircraft lands, and the IN time is the time at which the aircraft reaches its gate. For aircraft with ACARS datalinks, these times are recorded automatically (e.g., the OFF time is recorded automatically using a weight-on-wheels sensor). For other aircraft, these times are recorded manually, with less precision and accuracy. Substantial pre-processing is required to convert the ASQP data from the format received from the DOT into a usable format. A newer database, the Consolidated Operations and Delay Analysis System (CODAS) uses the Enhanced Traffic Management System (ETMS) to estimate OOOI times for flights not reported in ASQP. CODAS may be used in place of ASQP in the future.

The second data source is the Airport Surveillance Radar (ASR), processed by the TRACON’s Automated Radar Terminal System (ARTS) computer system. This data provides radar tracks for every flight, updated approximately every 4.7 seconds. Each record includes the aircraft’s flight number (or call sign), altitude, horizontal position, and the time at which the measurement was taken. The aircraft’s heading and velocity can be estimated from consecutive radar measurements.

ASQP data is insufficient, by itself, to study departure operations, since it does not include all flights. For example, a large gap between two departures in the ASQP data may have occurred because the runway was temporarily inactive or may have been occupied by a departure not included in the data. Furthermore, at airports with multiple departure runways, the runway from which each flight departed cannot be determined from ASQP data. Radar data includes all of the flights, and allows the inter-departure times as well as the runway from which each flight departed to be estimated. However, the departure demand at each runway cannot be calculated from radar data alone. Consequently, a gap between consecutive departures may result either from a lack of demand at the runway or the following departure being delayed. To determine the cause of these inter-departure delays, and how an automation tool may improve system efficiency, their occurrence must first be identified. The present method combines these two data sets to provide the necessary full picture of runway usage. Note that the input data is not available in real-time. For example, the departure runway cannot be determined from radar data until after the aircraft has taken off. Also, the ASQP data is currently not available until several weeks after the month containing the day of interest ends. Consequently, this method cannot operate in real-time.

Estimating the Departure Runway

The runway from which an aircraft most likely took off may be determined, using radar data, by considering the position of the aircraft relative to the ends of the runways and the aircraft’s heading relative to the runway headings. At some airports with rigid departure splits (i.e., mappings from the departure fixes to the departure runways), the departure runway may be determined by identifying through which departure fix the aircraft exited the TRACON. Closely spaced parallel runways, which exist at DFW and many other airports, complicate departure runway estimation. For example, determining with confidence whether an aircraft took off from 35L or 35C at DFW, from TRACON radar data alone, is problematic. The farther the initial radar track for an aircraft is from the runway, and the closer the runways are to each other, the more uncertain the runway determination. Figure 1 shows the runway geometry for DFW; runways 35L and 35C are separated by only 1000 feet. Knowledge of airport procedures can be used to improve estimation accuracy. For example, although runway 35C is sometimes used for departures, most departures are from 35L. Although such a heuristic cannot be used alone, this a priori knowledge may be used with the radar data to improve the estimation of the departure runway. Andrews [10] has developed a Bayesian runway estimation algorithm, a variation of which was used in this paper.

Aircraft that, at the beginning of the record, are already too far from the airport to determine their departure runway are removed from the data. Small aircraft, especially turboprop aircraft, tend to turn rapidly as soon as they are off the ground. Consequently, these aircraft may already be substantially away from the runway centerline and heading when the radar first detects the aircraft, making the determination of the departure runway more uncertain. At DFW, these flights mainly take off from the diagonal runways (13L and 31L), which are not studied in this paper.

Andrews [10] discusses issues that affect the accuracy of estimating departure runways from radar data. An error in the estimation of an aircraft’s departure runway causes the aircraft to be omitted from the correct queue and incorrectly included in a different queue. A large number of these errors would cause correspondingly large errors in the reconstructed queues. Although the truth data required to determine the accuracy of the runway estimates used in this paper is not available, the runway estimates are consistent with expectations from substantial experience at DFW. Therefore, the errors that may exist are not expected to substantially affect the trends that are observed in runway use at DFW.

Takeoff Times

Many aircraft automatically record the ASQP OFF time (e.g., through a weight-on-wheels switch) and report it via the Aircraft Communication Addressing and Reporting System (ACARS) datalink. However, for some older aircraft, the takeoff time reported to ASQP is manually recorded by either the flight crew or the air carrier’s ramp tower/station personnel. In these cases, errors of up to several minutes are possible.

To reduce these errors, the takeoff time may be estimated from the radar data instead. The time stamp of the first radar track does not equal the takeoff time, due to the radar not being able to see all the way to the ground and the small (up to 4.7 seconds) random delay in the radar detecting the aircraft associated with the frequency of the radar rotation. In the Dallas/Fort Worth data used in the following section, the radar first detected most aircraft at approximately 1000 ft above ground level (AGL). Some aircraft were detected as low as 600 ft AGL, while a few were first detected above 2000 ft AGL. The takeoff time can be estimated from the aircraft’s position relative to the runway and the time of the initial radar measurement, using a model of the aircraft’s performance. The current implementation uses a simple performance/trajectory model for all aircraft types. Although more accurate models are possible, such refinement may only change the takeoff time and, therefore, the time spent in the queue, by a few seconds.

<u>Estimating When Aircraft Join the Queue</u>

The taxi time, which is typically defined as the total time between pushback and takeoff, can be divided into the *movement time* (i.e., the time between pushback and reaching the departure queue at the runway), the delay waiting in the departure queue, and the takeoff roll time. To identify the delays incurred at the runway, the movement and takeoff roll times must be subtracted from the difference between the OUT and OFF times. The individual movement times for each flight are not observable from the available data. Therefore, to estimate when an aircraft joins the departure queue, a constant movement time of 15 minutes is assumed in the analysis of the DFW data. This assumption introduces some error into the estimates of when each aircraft is waiting in the queue, due to the variation in the actual movement times.

Two adjustments were made to the constant movement time assumption. If the difference between the takeoff time and pushback time is less than the constant movement time, the movement time is reduced such that the aircraft takes off immediately upon reaching the runway (i.e., spends no time in the queue). If the take off time is more than the constant movement time after the pushback time, but the queue is empty, the movement time is increased such that the aircraft does not spend any time waiting in the queue. This assumption may be false if the aircraft waits at the runway prior to departure, which could occur if the aircraft reaches the runway before its EDCT, for example. Since the queue is empty prior to the aircraft reaching the runway, the consequence of this error is that the queue will be estimated to be empty when one aircraft is actually waiting in the queue.

Initial validation exercises (i.e., a comparison of the model results with the known queuing behavior at DFW) suggest that this model is sufficient for reconstructing the approximate departure queues. The consequence of a movement time error is that the estimated queue length will be off by one aircraft for time between when the aircraft actually joined the queue and was estimated to have joined the queue. During busy periods, movement time errors will be on the order of a minute, since they are bound by the previous and subsequent departures joining the queue. Although these errors are not expected to change the overall shape of a plot of queue length versus time over time horizons of an hour or more, the impact of this error will depend on how the queue length estimate is used.

Although possible, the current implementation did not use different movement times depending on the runway to which the aircraft was taxiing. If information about the gate or terminal from which each aircraft pushed back were available, a matrix of average movement times from each terminal (or gate) to each runway could be used. The movement time may be decomposed into an unimpeded movement time and delays, both of which contribute to variability. The distance from gate to runway, the speed at which the aircraft taxis, and the time required for the aircraft to push back and start its engines affect the unimpeded movement time. Delays occur when aircraft wait for other surface traffic (arrivals or departures) or to cross active runways. At some airports (e.g., DFW), aircraft enter the FAA controlled movement area from an airline controlled ramp across a “spot” (DFW has 34 spots on the east side of the airport and 3 on the west). Therefore, aircraft may be delayed by activities on the ramp, prior to being under the control of the ATC Tower. Procedures call for aircraft to hold at a spot until the FAA Tower clears the aircraft to proceed. Therefore, controller workload may also delay an aircraft’s progress toward the runway.

Figure 2 plots the times at which aircraft pushed back, joined the queue (i.e., reached the runway), and took off from DFW runway 36R for an hour on February 29, 2000.[†] Each aircraft is represented by a set of symbols marking the times when the three events occur, connected by line segments. The number of aircraft in the departure queue at any point in time is represented by the number of line segments connecting the join and off times that cross the time of interest. For example, at 14:45 there are 6 aircraft in the queue.

Resequencing

The takeoff order may be different from the pushback order, due to resequencing either during movement to the runway or in the queue at the runway. The order in which aircraft reach the departure queue may differ from the order in which they push back due to differences in the movement times. For example, the gates from which the aircraft pushback may be different distances from the runway, causing longer or shorter travel times to the runway. Also, controllers may intentionally reorder departures taxiing to the runway at available control points (e.g., taxiway intersections). At some airports, such as DFW, the taxiway widens at the runway and is capable of holding the aircraft waiting to depart in multiple columns. By assigning in which column each aircraft waits, and selectively choosing the next departure from the various columns, the controllers can change the departure sequence relative to the

[†] Neuman and Erzberger [11] used figures similar to Figure 2 to represent the relative times of various events for multiple aircraft while studying arrival traffic management.

order in which aircraft reached the departure queue. Therefore, at airports where the aircraft waiting at the runway are organized into multiple columns, the departure queue estimation algorithm cannot distinguish by which of these two mechanisms resequencing occurred. This lack of observability confounds the problem of estimating the time at which aircraft join the departure queue.

The DFW data contained occurrences of aircraft taking off in a different order than they pushed back. The results for DFW assumed all resequencing occurred within the queue, and used the constant movement time to estimate when aircraft joined the queue. An alternative approach would have been to assume no resequencing occurred within the queue, and to adjust the movement times so that aircraft joined the queue in the order in which they took off. Some airports exhibit one mechanism for resequencing more frequently than the other; both mechanisms are observed at DFW.

Missing Pushback Times

The radar data is assumed to include all of the departures from the airport, some of which are not included in the ASQP data. For the 5 days of data for DFW studied in the following section, the ASQP data includes approximately 66% of the departures (according to the radar data), and does not include any departures that are not also in the radar data. For flights for which ASQP data exists, the OUT and OFF times are used to estimate the time at which the aircraft joins the queue at the runway. In the absence of ASQP data for a flight, the times at which the aircraft join the queue and takeoff must be estimated. The takeoff time is calculated from the radar data directly; the time at which the aircraft joins the queue is estimated from information about the neighboring departures.

First, the departures which took off from the same runway before and after the departure whose pushback time is not known are identified. If pushback times are missing for multiple consecutive departures, the two closest departures for which pushback times are known and which bound the departures with unknown pushback times are found. For example, let aircraft **A**, **B**, and **C** be consecutive departures from a runway. Assume ASQP data exists for aircraft **A** and **C**, such that the times at which these aircraft join the queue can be calculated in the manner described above, but that the pushback time of aircraft **B** is not known. The aircraft are assumed to take off in the order in which they join the queue (i.e., no resequencing occurs in the queue). Therefore, aircraft **B** is assumed to have joined the queue between when aircraft **A** and **C** joined the queue, and the time at which aircraft **B** joined the queue is estimated by interpolation. The interpolation depends on how close the takeoff times of **A** and **C** are to **B**’s takeoff time. If aircraft **B** is in the middle of a departure push (i.e., the queue length is greater than zero), aircraft **B** is assumed to join the queue at the mid-point of the interval between when **A** and **C** joined. Examination of the 5 days of data for DFW revealed that the maximum error that could have resulted from this approach was 7.5 minutes, and the expected root-mean-square (RMS) error (modeling the actual time at which the aircraft joins the queue as a uniformly distributed random number) was 40.5 seconds.

If aircraft **B** takes off within a certain time after **A** (3 minutes is used in the DFW analysis), but **C** takes off much later than aircraft **B** (more than 3 minutes was used in the DFW analysis), then **B** is assumed to be the last aircraft in the queue and is estimated to join the queue 1 minute after aircraft **A**. This assumption could cause the queue length estimate to be one aircraft too large for as long as aircraft **A** is in the queue, if aircraft **B** did not join the queue until approximately when aircraft **A** took off (which is feasible since aircraft **B** is the last aircraft in the queue). However, considering how the queue length estimate is used in this paper, an error of one aircraft will not change the results. Similarly, if aircraft **A** took off sufficiently earlier than aircraft **B** (i.e., the queue length equals zero before **B** reaches the runway), then aircraft **B** is the first aircraft in the queue and is assumed to join the queue at it's takeoff time. The assumption being made here is that the aircraft at the start of a new queue should not incur any delay at the runway.

A similar interpolation scheme is used to handle the case where ASQP data does not exist for several consecutive aircraft. A few other scenarios are possible. If ASQP data does not exist for the very first or last departure in the radar data, that flight is discarded (i.e., the period of time over which the departure queue is reconstructed is slightly shortened). Finally, large queues occur only during departure pushes by the larger airlines at DFW; American, American Eagle, and Delta all submit ASQP data. Therefore, in the DFW data studied in the following section, there are no instances of queues consisting entirely of aircraft without pushback information. By calculating the interval of time for which each aircraft is waiting in the departure queue, the algorithm can reconstruct the departure queue that existed at each runway at each point in time.

DFW Departure Queues

The algorithm was used to study five days of data (February 29 – March 4, 2000) from Dallas/Fort Worth (DFW) airport. Substantial departure queues (exceeding 20 aircraft at times) and associated delays (some exceeding 30 minutes) were observed, consistent with expectations for a hub airport. For example, Figures 3 and 4 show the queues that existed at runway 18L/36R on February 29. Notice that the airport operated in both *south flow* (i.e., aircraft departing to the south) and *north flow* on that day. FAA logs confirm that the airport began the day in south flow, switched to north flow at 12:19 (local time), returned to south flow at 15:32 until 18:23, and operated in north flow for the remainder of the day. The peaks in the departure queues result from banks of departures pushing back from their gates in a short period of time and queueing at the runway, since the takeoff rate is less than the rate at which aircraft reach the runway. The departure pushes are separated by periods of time with few departures, during which arrival rushes land. The queue that occurs on runway 18L between 15:38 and 16:42 (local time) in Figure 3 demonstrates that a departure queue may exist continually for an hour or more. Figure 5 shows the queue history for runway 36R in greater detail over a shorter period of time on February 29, revealing each event of an aircraft joining or leaving the queue. From 14:15 to 14:45, approximately 11 aircraft takeoff per 15 minutes; the departure rate slows to 7 departures per 15 minutes for the 15 minute interval ending at 15:00.

Figure 6 plots a histogram of the length of time aircraft waited in the queue (i.e., the delay) at runway 18L on February 29, which exhibited typical departure operations. Each bar represents a 1 minute bin; for example, 96 of the 213 departures waited in the queue for less than 1 minute, while 11 aircraft waited between 10 and 11 minutes. The corresponding time history of the queue for this runway on this day is shown in Figure 3. Although the plot is sensitive to errors in determining the movement times from pushback to joining the queue, it illustrates that a significant percentage of the departures at a hub airport like DFW spend substantial time waiting at the runway. In this case, 70 aircraft waited for more than 5 minutes, including 34 aircraft that waited for more than 10 minutes.

Knowledge of the departure queues provides insight into the efficiency with which the departure runways were used. The majority of the larger jet departures take off from runways 18L and 17R when DFW is operating in a south flow configuration, and from runways 36R and 35L when the airport is operating in a north flow configuration. Smaller aircraft, including turboprops, typically take off from the diagonal runways: 13L in south flow and 31L in north flow. Figure 7 shows the departure queues for the two primary runways for large jet departures (36R and 35L) during a period of north flow on March 4. The symmetry demonstrates that the runways were well balanced (i.e., the number of aircraft in each queue was nearly equal at all times) during this period.

Equal length queues implies that the aircraft in each queue incur comparable delays, assuming the departure rates on each runway are similar. Imbalanced departure queues could be a source of departure inefficiency. For example, available capacity is wasted when one departure runway is idle while aircraft are waiting to takeoff on another runway. Furthermore, the delays for different departure runways being unequal may be unfair to certain air carriers and make predicting takeoff times more difficult. Figure 8 shows an imbalance in the departure queues for runways 18L and 17R, during a period of south flow on March 2. Figure 9 shows the times at which aircraft entered the queues and took off for the same period of time. FAA logs indicate hail, use of Severe Weather Avoidance Procedures (SWAPs) and several instances of stopping arrivals and/or departures. Logs also indicate that, after stopping departures at 17:59, the airport switched to north flow at 18:02 until 19:29. Radar data indicates only 6 aircraft departed to the north (between 18:20 and 18:305); ASQP data indicates that these aircraft pushed back after the aircraft that queued at runways 17R and 18L. As a result of the unbalanced runway queues, 10 aircraft were still waiting to depart from runway 17R when the queue for runway 18L was empty; the last of these 10 aircraft did not take off for another 20 minutes. Automation may have been able to help the controllers plan surface movements and use the runways more efficiently.

Under current procedures at DFW, runway assignments are based on the assigned TRACON/Center departure gate/fix, which is a function of the flight plan. An east-bound aircraft will not depart from a runway on the west side of the airport, and a west-bound aircraft will not use a runway on the east side. Consequently, a departure push with a greater percentage of east-bound aircraft may result in the west-side runways being under-utilized. Additional research is required to determine whether runway imbalance is a significant source of inefficiency at DFW, and under what conditions (e.g., during bad weather). The present method could also be used to quantify the occurrence of runway imbalances at other airports.

Atlanta (ATL) and Memphis (MEM) airports, for example, are believed to exhibit unbalanced departure runways due to their rigid departure splits.

Past analyses of inter-departure times have not known when departure demand existed at the runway. Consequently, discerning whether a large inter-departure gap resulted from air traffic control delaying a departure or from a lack of demand at the runway was impossible. The method presented in this paper permits inter-departure gaps to be studied at times when there is known demand at the runway. Figure 10 shows a histogram for the time intervals between consecutive departures from runway 36R on March 3. The horizontal axis identifies 30 second bins, and the vertical axis plots the number of departures that followed the preceding departure by an amount of time that falls within that bin. For example, 116 aircraft followed the previous departure by between 60 and 90 seconds. Figure 11 plots a subset of the data from Figure 10. Figure 11 plots the inter-departure times when demand was present at the runway (i.e., for pairs of aircraft in which the following aircraft was waiting in the queue when the lead aircraft took off).

Notice that many of the longer inter-departure times in Figure 10 are the result of a lack of demand at the runway. However, when demand was present at the runway (Figure 11), 62 aircraft followed the previous departure by more than 2 minutes, including 13 aircraft pairs with inter-departure times of more than 3 minutes – longer than required by only wake vortex considerations. Long inter-departure gaps when a queue is present do not necessarily imply an inefficiency (e.g., the runway may be temporarily closed due to weather at the airport or runway sweeping operations) or a delay over which the ATC Tower has any control (e.g., if an aircraft does not have its final numbers from its dispatcher). However, the presence of occasional delays between consecutive departures on these days may indicate that resequencing, or other automation aiding, could increase throughput. Additional research is required to identify the cause of the inter-departure delays. Also note that incorrect estimates of the departure runways would appear as either a large inter-departure gap that did not actually exist or an unrealistically small gap.

Although the actual surface operations were not observed on the days for which data was studied, observations of surface operations at DFW on other days qualitatively support these results. Therefore, although additional application of the method is required to conclusively identify opportunities for surface automation to improve departure operations, these results demonstrate the ability of the method to reconstruct the departure queues that existed at the runways and its utility for studying the efficiency of departure operations.

Conclusions

The ability to analyze the current efficiency of surface operations is limited by the lack of availability of surface surveillance data. To enable the study of surface and departure issues, and to identify opportunities for automation to improve traffic management, this paper presented a method for reconstructing the departure queues that existed at each runway from currently available information (i.e., ASQP and TRACON radar data). Observations of the departure queues are of particular interest because they provide insight into the management of departures prior to takeoff. The method correlates pushback data and radar data to estimate, for every departure, the departure runway, the takeoff time, and the time at which the aircraft joins the departure queue. By calculating the interval of time for which each aircraft is waiting at the runway, the departure queue at each runway can be reconstructed at every point in time. Note that this algorithm cannot synthesize surface surveillance in real-time, since the required inputs are not available in real-time.

Using this algorithm, the paper studied five days of data (February 29 – March 4, 2000) from Dallas/Fort Worth (DFW) airport. Substantial departure queues (exceeding 20 aircraft, at times) and delays (some exceeding 30 minutes) were observed, consistent with expectations for a hub airport. Moreover, knowledge of the departure queues provided insight into the efficiency with which the departure runways were used. For these days at DFW, the departure queues on the primary departure runways were shown to be well balanced at most times. Additional days of data are required to determine conclusively whether or not DFW experiences inefficient runway imbalances under certain conditions. A second area of future work is to validate these results against observations of airport operations and, when it becomes available, surface surveillance data. In addition, the algorithm will be used to study other airports, to determine whether runway balance inefficiencies exist at airports other than DFW.

The DFW data also revealed that some of the inter-departure gaps (i.e., the difference in takeoff times for consecutive departures from a runway) were significantly larger than the expected gaps, at times when departure demand was present at the runway (i.e., the departure queue was not empty). Delays between consecutive departures may indicate an opportunity for automation to increase throughput by advising an efficient departure sequence or other surface management. In addition to studying more days of data and other airports, further research is required to identify the cause of the inter-departure delays.

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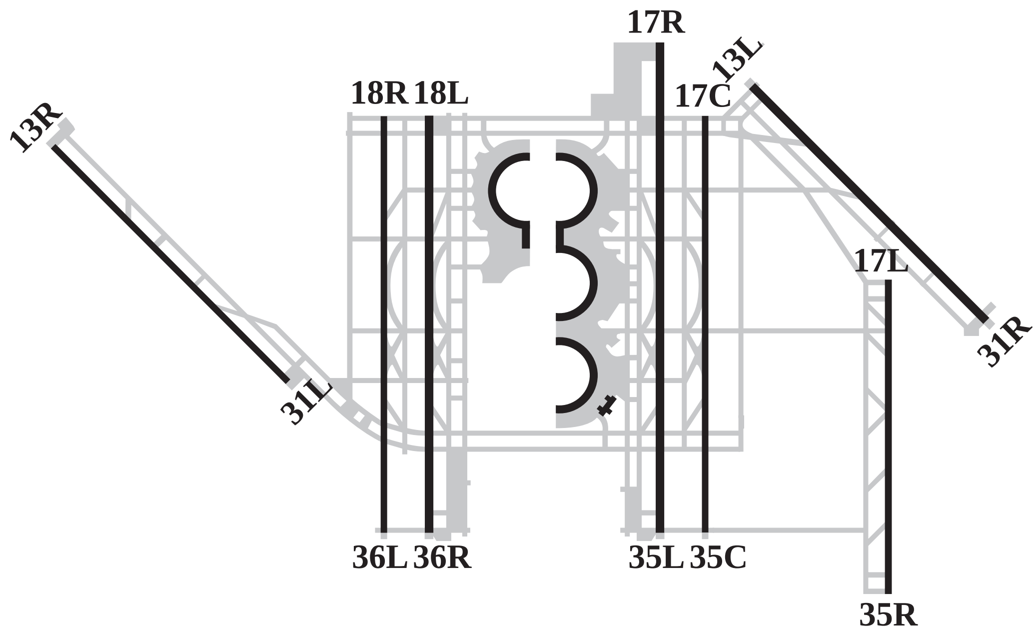

Figure 1. Dallas/Fort Worth (DFW) Runway Diagram.

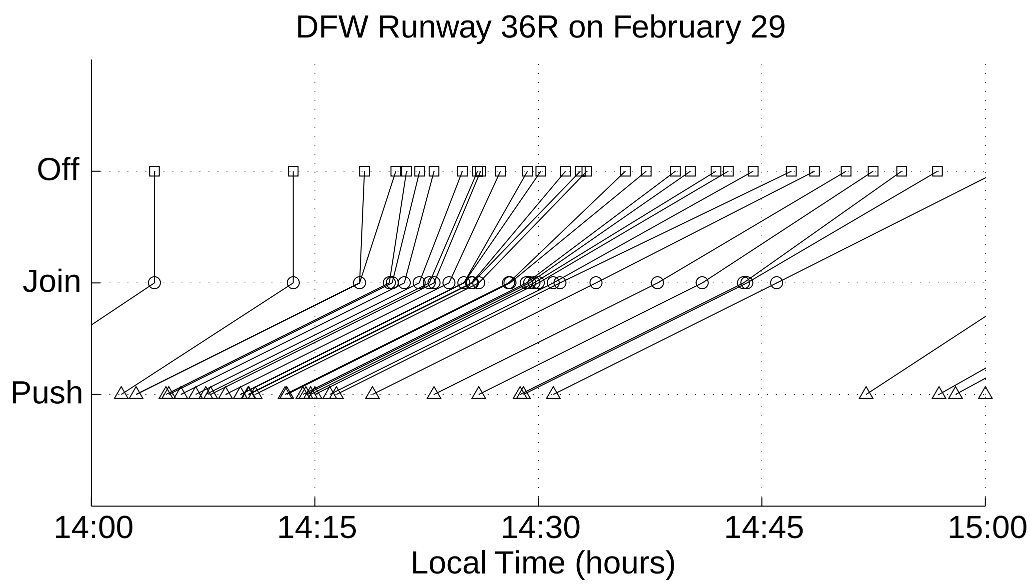

Figure 2. Times at which aircraft push back, join the queue, and takeoff for runway 36R on February 29, 2000.

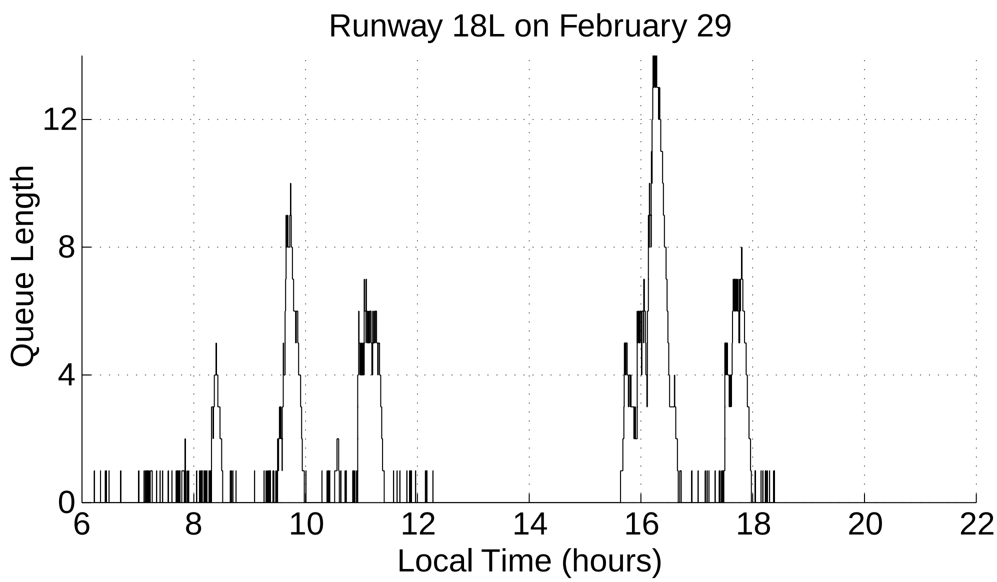

Figure 3. Queue for runway 18L on February 29, 2000.

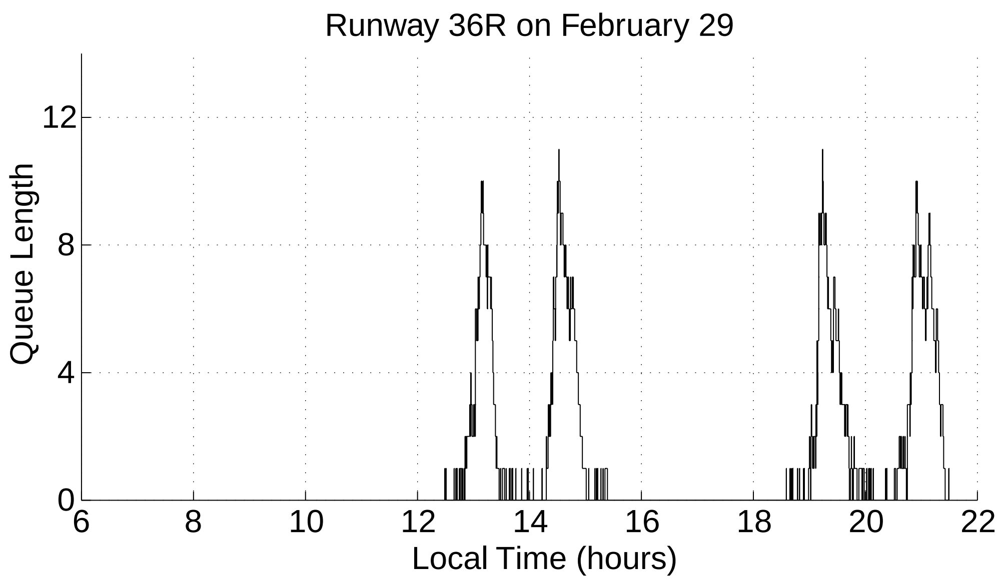

Figure 4. Queue for runway 36R on February 29, 2000.

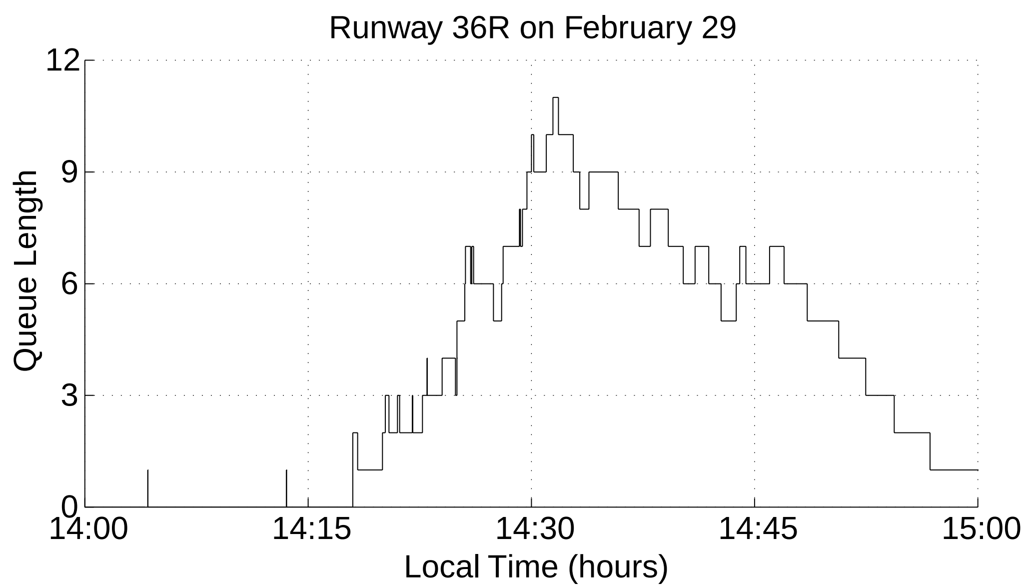

Figure 5. Queue for runway 36R on February 29, 2000.

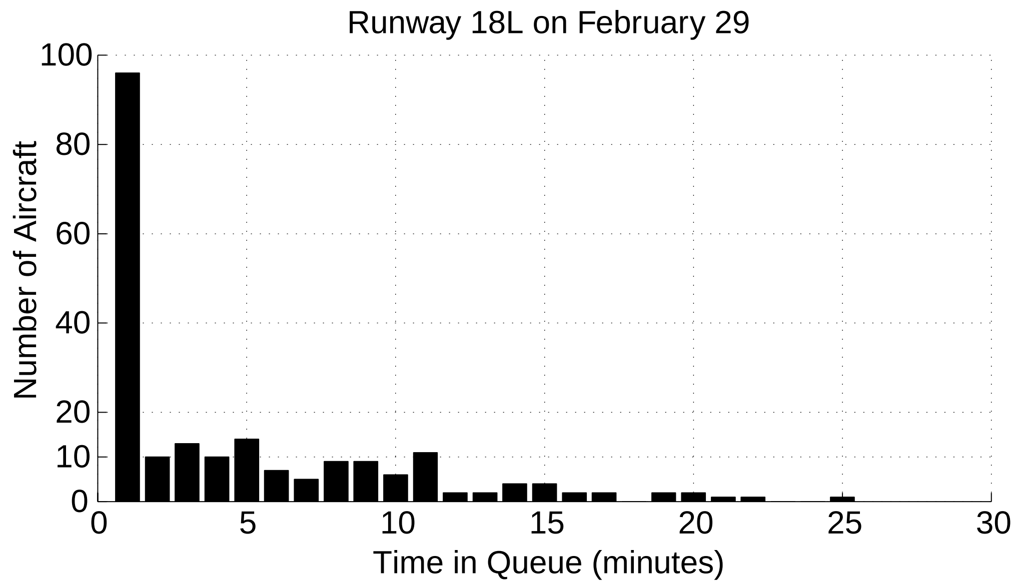

Figure 6. Delay at DFW runway 18L on February 29, 2000.

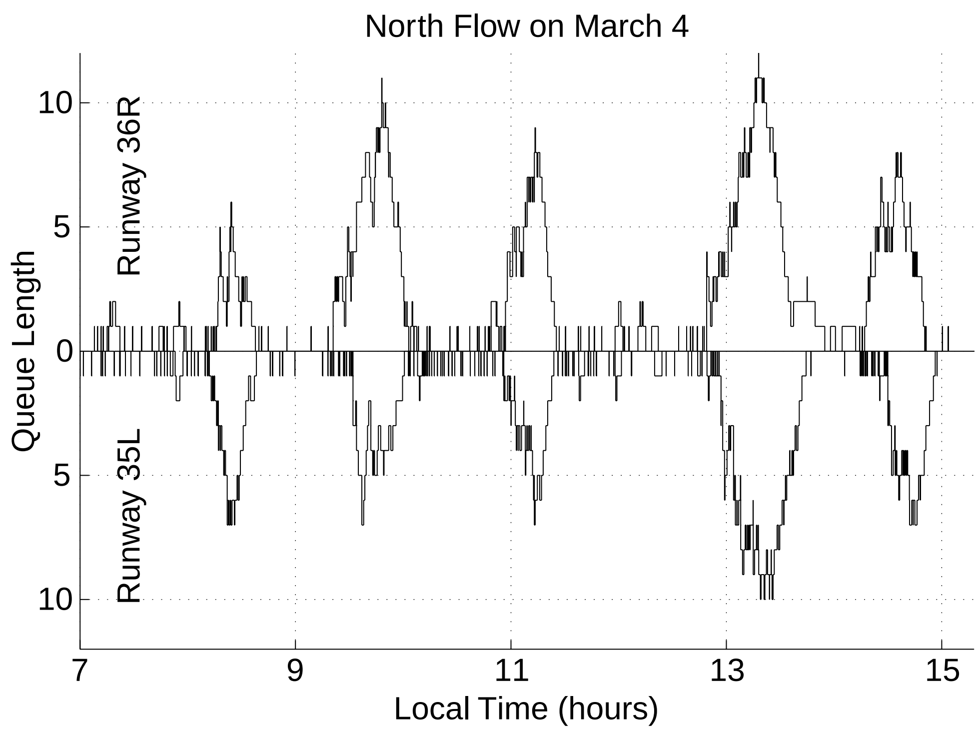

Figure 7. Queues for runways 35L and 36R on March 4.

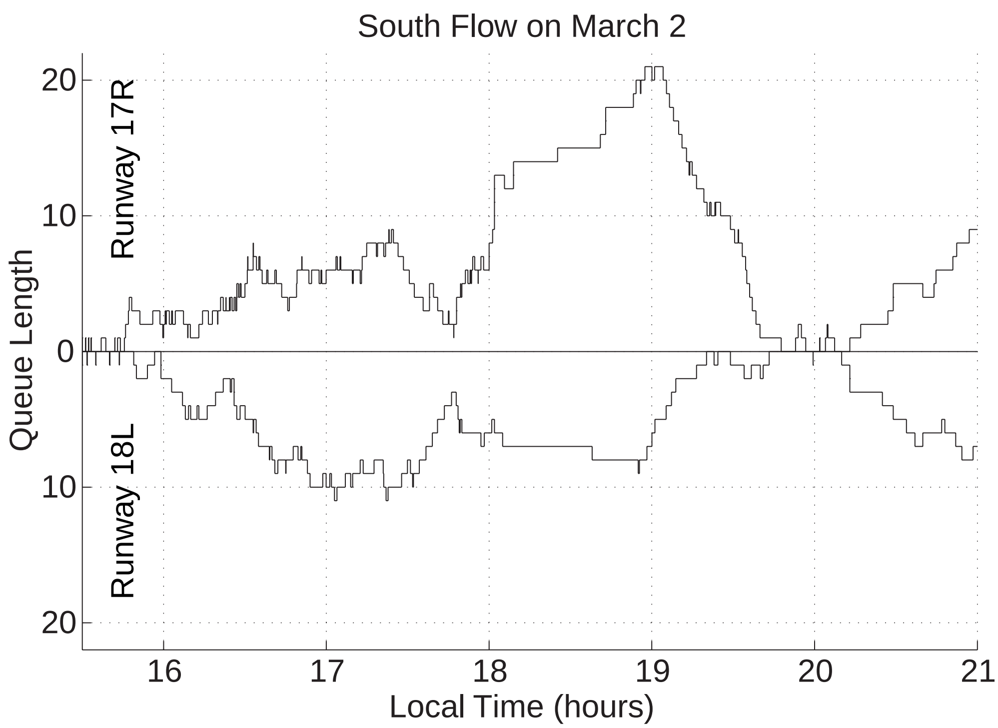

Figure 8. Queues for runways 17R and 18L on March 2.

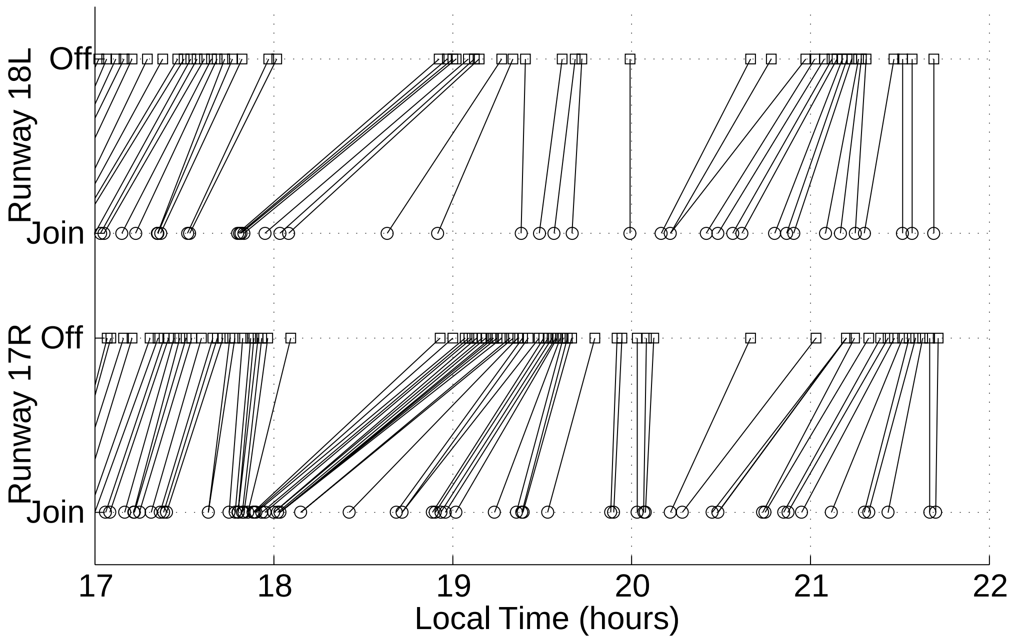

Figure 9. Times at which aircraft joined and exited the queues for runways 17R and 18L on March 2.

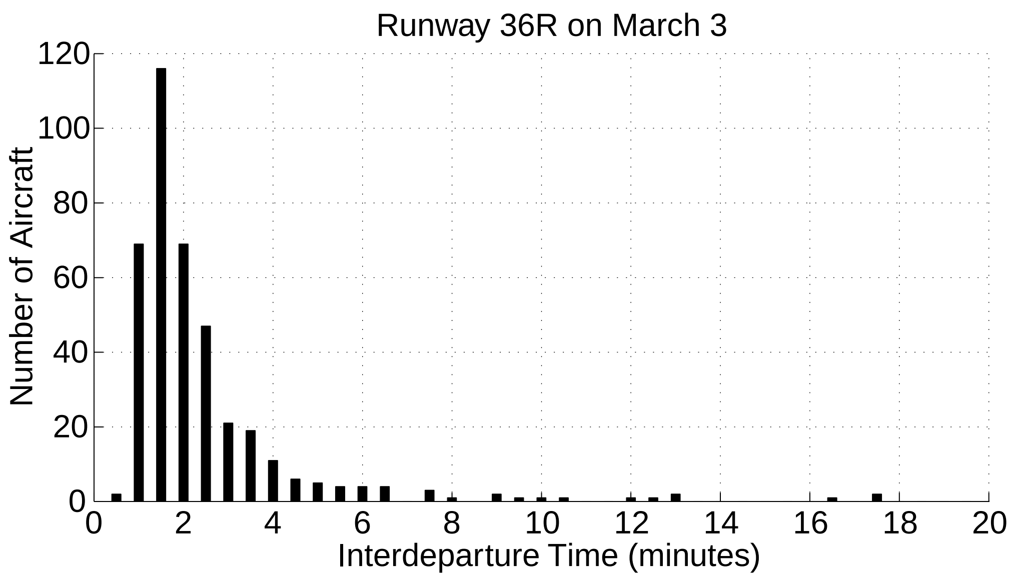

Figure 10. Inter-departure times on runway 36R on March 3.

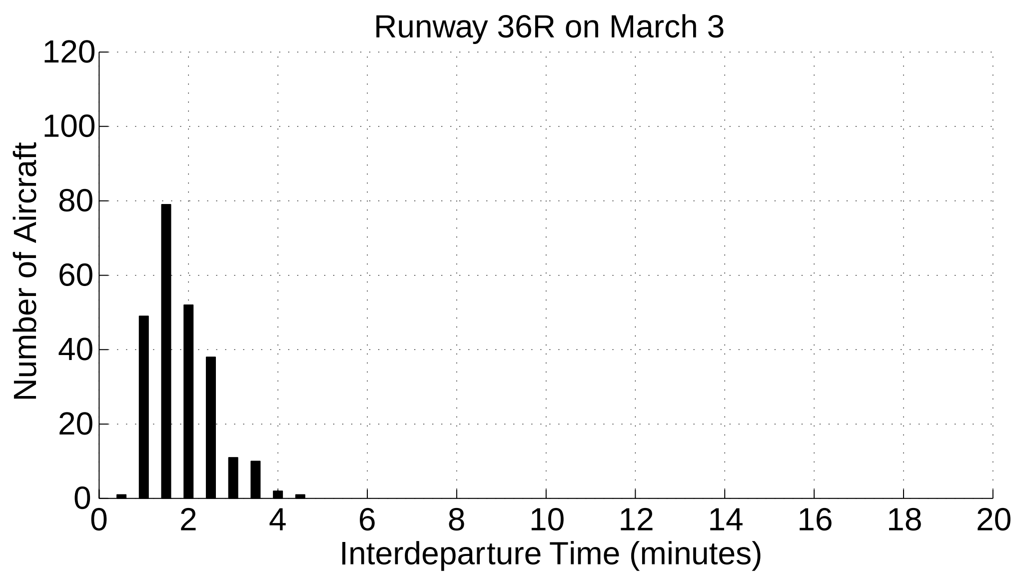

Figure 11. Inter-departure times on runway 36R when demand was present at the runway, March 3.

Figure 1. Dallas/Fort Worth (DFW) Runway Diagram.

Figure 2. Times at which aircraft push back, join the queue, and takeoff for runway 36R on February 29, 2000.

Figure 3. Queue for runway 18L on February 29, 2000.

Figure 4. Queue for runway 36R on February 29, 2000.

Figure 5. Queue for runway 36R on February 29, 2000.

Figure 6. Delay at DFW runway 18L on February 29, 2000.

Figure 7. Queues for runways 35L and 36R on March 4.

Figure 8. Queues for runways 17R and 18L on March 2.

Figure 9. Times at which aircraft joined and exited the queues for runways 17R and 18L on March 2.

Figure 10. Inter-departure times on runway 36R on March 3.

Figure 11. Inter-departure times on runway 36R when demand was present at the runway, March 3.