Proceedings of the American Control Conference
Anchorage, AK May 8-10, 2002

Prediction and Control of Departure Runway Balancing at Dallas/Fort Worth Airport

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Abstract

At many airports, aircraft take off from multiple departure runways. During periods of high departure demand, whether or not the departure runways are balanced directly affects the capacity and efficiency of the airport. This paper begins by investigating the cause of runway imbalances. Homogeneity in the direction of flight during a departure push and the procedures for runway assignments are demonstrated to be the primary source of departure runway imbalances. Second, the paper studies how well departure runways are currently balanced. A method for reconstructing the departure queues that existed at each runway is presented along with results from applying the method. Dallas/Fort Worth (DFW) airport is used as a case study throughout the paper. Controllers currently do not have accurate information about the future departure demand, nor the ability to predict how the surface situation will evolve, necessary to plan efficient traffic management strategies. Finally, the paper introduces automation concepts that will reduce the occurrence and impact of imbalanced departure runways, by providing this information along with traffic management advisories.

1. Introduction

Departure taxi delay is the largest of all aviation movement delays and results in the largest direct operating cost. The average taxi-out delay in minutes-per-flight is approximately twice the airborne delay. Although aircraft burn fuel roughly five times faster when airborne, crew and equipment costs make the spend-rate of taxiing aircraft about two-thirds that of airborne aircraft. Consequently, the cost of taxi-out delay exceeds that of airborne delay by about one-third. On average, taxi-out delay is three times larger than taxi-in delay [1].

This paper begins to study the queues of aircraft that form at runways, and the delays aircraft incur while waiting in these queues. When the departure demand temporarily exceeds the capacity of the runway, aircraft will queue. Temporal bunching of demand, and the resulting queueing, is expected in any stochastic service system. However, the nature of the departure demand, operational procedures, and controller actions can result in a long queue existing at one runway while another departure runway is idle due to a lack of demand at that runway. Whether or not the departure runways are balanced (i.e., equal departure delays are experienced at each runway) directly affects the capacity and efficiency of the airport. Although the eventual goal is to reduce departure delays, this paper studies departure runway balancing, rather than delays, because tower controllers appear to make decisions with the objective of maintaining balanced runways, possibly because runway balance is more easily observed than the total delays that occur.

The paper begins by investigating the cause of runway imbalances. Homogeneity in the direction of flight during a departure push and the procedures for assigning departure runways are shown to cause departure runway imbalances. In addition, controllers currently do not have the necessary information about the future departure demand, nor the ability to predict how the surface situation will evolve as a result of this demand, to plan efficient traffic management strategies for maintaining balanced runways. Second, the paper studies how well departure runways are currently balanced. The extent to which runway imbalances occur, and the effect on departure capacity that results, has not been studied quantitatively, primarily due to the unavailability of surface surveillance data. The second section of this paper presents a method for reconstructing the departure queues that existed at each runway, as a function of time, using currently available information. The paper presents results from applying the method at DFW, which is used as a case study throughout the paper. Finally, the paper introduces a variety of automation concepts that could reduce the occurrence and impact of imbalanced departure runways.

2. Cause of Runway Imbalances

There are 4 departure *gates* (north, south, east, and west) through which jet departures from DFW leave TRACON airspace and enter Fort Worth Center airspace. Each departure gate contains 4 departure *fixes*. Every jet exits the TRACON over one of the 16 fixes. In south flow (wherein departures take off to the south and arrivals land from the north), DFW uses two runways, 17R and 18L, for jet departures. Arrivals land on 18R, 17C, 17L, and 13R; turbo-prop departures take off from 13L. When departure demand is high, departure runway assignments are proceduralized to maintain controller workload at an acceptable level and assure safety. Current procedures assign departures to a runway according to a one-to-one mapping from departure fixes to departure runways. The different mappings of fixes to runways will be referred to as the *departure scenarios*. The purpose of these runway assignment rules is to assure that the airborne trajectories of aircraft that takeoff from different runways do not cross.

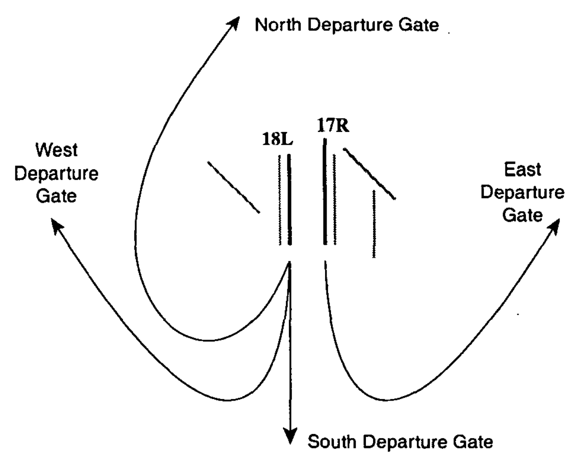

Figure 1. *South Flow East Push* departure scenario.

The *South Flow Uniform* departure scenario is preferred when the demand is spread uniformly between the east and west. Runway 18L is used for departures to the west gate and to the two western fixes in each of the north and south gates; departures to the 8 eastern fixes take off from 17R. When this scenario is active, a departure push with a greater percentage of east-bound aircraft may result in the west-side runway being under-utilized. The *South Flow East Push* departure scenario (Figure 1) is used when the majority of the departures are headed east. Departures to the east gate use runway 17R while south, west, and north-bound aircraft depart from runway 18L. Similar departure scenarios exist to accommodate west-bound departure pushes and north flow operations. The tower Traffic Management Coordinator (TMC) is responsible for selecting a departure scenario to minimize departure delays by balancing the runways. The Ground controller also contributes to runway balancing by making runway assignment exceptions.

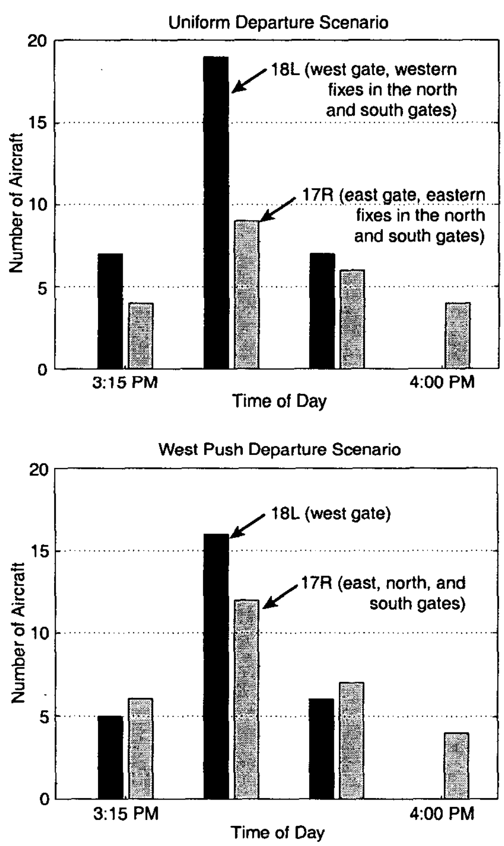

Figure 2. Demand on each runway assuming the *Uniform* and *West Push* departure scenarios.

These departure scenarios are examined for their impact on runway balancing, using several days of actual traffic data from DFW. The following graphs are drawn using data from the Post Operations Evaluation Tool (POET). POET archives data from a variety of sources including the Aggregate Demand List (ADL). The best estimate of the actual pushback times are the "filed OUT time" field in POET. The following figures plot traffic that was observed on December 2, 2001, and are representative of the studied data. Figure 2 plots the demand that would exist on each of the two departure runways during a departure push, assuming aircraft are assigned to runways according to the *South Flow Uniform* and *West Push* departure scenarios. The bars plot the number of aircraft that pushed back during that 15 minute interval and would be assigned to that runway assuming that departure scenario. For example, under the *Uniform* departure scenario (top half of Figure 2), between 3:15 PM and 3:30 PM, 7 aircraft pushed back that would be assigned to runway 18L and 4 aircraft pushed back that would be assigned to runway 17R. Notice that runway 18L is overloaded under the *Uniform* scenario, while the demand for the two runways is more equal under the *West Push* scenario.

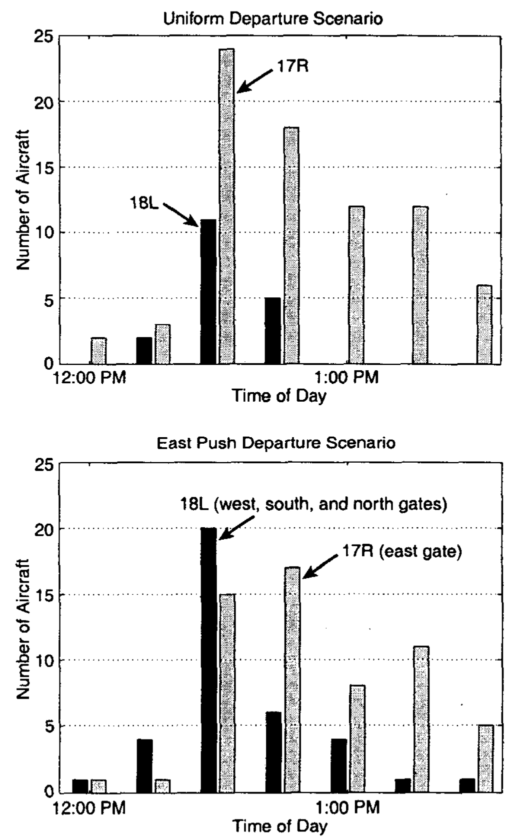

Figure 3. Demand on each runway assuming the *Uniform* and *East Push* departure scenarios.

Figure 3 shows demand that would exist for each runway assuming the *Uniform* and *East Push* departure scenarios, during a departure push in which more than 50% of the aircraft depart through the east gate. Although the *East Push* scenario achieves closer to equal demand, runway 17R remains overloaded relative to runway 18L. In this case, selection of the departure scenario does not provide sufficient controllability to balance the demand on the runways. The following section will discuss the use of exceptions to the departure scenario (e.g., some east-bound aircraft being assigned to runway 18L) for balancing demand.

These graphs illustrate how the nature of the departure demand at DFW, together with the operational procedures, create the potential for runway imbalances. Since the actual runway that each aircraft used is not available, these figures illustrate how the runways would have been loaded under the various departure scenarios. The actual departure queues and delays that existed at each runway are also not known. Although an imbalance in the demand for the two runways may result in a proportional imbalance in the departure delays at DFW, this would not be true, for example, if one of the runways were being used for mixed operations. The following section outlines a method for determining the actual queues and delays that existed.

3. Current Runway Balancing Performance

Airport surface surveillance that includes aircraft identity is not available. Therefore, to study runway-specific departure queues and delays, a method for reconstructing the queues from available information is presented and then used to study five days of data from DFW.

3.1 An Algorithm for Reconstructing Departure Queues

The algorithm 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. By calculating the interval of time for which each aircraft is waiting at the runway, the departure queue and delay at each runway can be reconstructed at every point in time.

The ADL includes both OUT and OFF time estimates for every flight which has filed a flight plan. The taxi time, which is 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) and the delay waiting in the departure queue. The individual movement time for each flight is not observable from the available data. Therefore, to estimate when an aircraft joins the departure queue, a simple model is used. A constant movement time of 15 minutes is initially assumed and then two adjustments are made as necessary. 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.

The ADL information is insufficient by itself to study departure operations since it does not identify which runway each aircraft used. The second data source used in this analysis 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, including the aircraft's flight number, altitude, horizontal position, and the time at which the measurement was taken, updated approximately every 4.7 seconds. The runway from which an aircraft most likely took off may be determined from 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. Closely spaced parallel runways, which exist at DFW and many other airports, complicate departure runway estimation, because the ASR does not detect the aircraft until it is several hundred feet above the ground, during which time it may have begun a turn from the runway heading. For example, determining with confidence whether an aircraft took off from 17R or 17C at DFW, from TRACON radar data alone, is problematic. Knowledge of airport's departure procedures can be used to improve estimation accuracy. For example, at DFW, most of the aircraft that depart from either runway 35L or runway 35C, depart from 35L. Although such a heuristic cannot be used alone, since 35C is used for some departures, a Bayesian runway estimation algorithm, which was used in this paper, uses this a priori knowledge in combination with the radar data to improve the estimation of the departure runway [2].

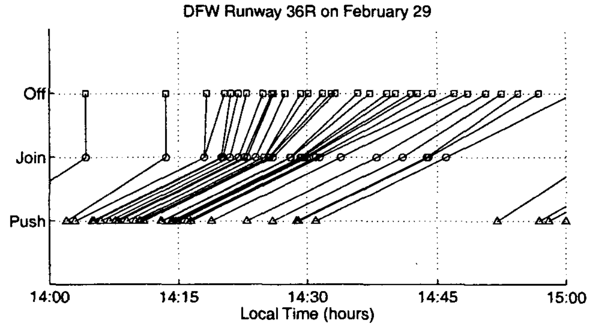

Figure 4. Times at which aircraft push back, join the queue, and takeoff.

Figure 4 plots the times at which aircraft pushed back, joined the queue, and took off from DFW runway 36R for an hour on February 29, 2000. Each aircraft is represented by a set of symbols 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.

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. Since detailed movement of each aircraft was not observable from the available data, the departure queue estimation algorithm cannot distinguish by which of these two mechanisms resequencing occurred. The DFW data contained occurrences of aircraft taking off in a different order than they pushed back. The results presented in the following section assume that all resequencing occurred within the queue. Given which runway each aircraft used and the times when they joined the queues and took off, the departure queue at each runway is reconstructed at every point in time.

3.2 Estimated DFW Departure Queues

The algorithm was used to study five days of data (February 29 – March 4, 2000) from DFW. Substantial departure queues (exceeding 20 aircraft at times) and associated delays (some exceeding 30 minutes) were observed, consistent with expectations for a hub airport. Figure 5 shows, as an example, the queue that existed at runway 36R on February 29. Each event of an aircraft joining or leaving the queue can be seen. From 14:15 to 14:45, 10 and 11 aircraft took off per 15 minutes, respectively; the departure rate slowed to 6 departures per 15 minutes for the interval ending at 15:00.

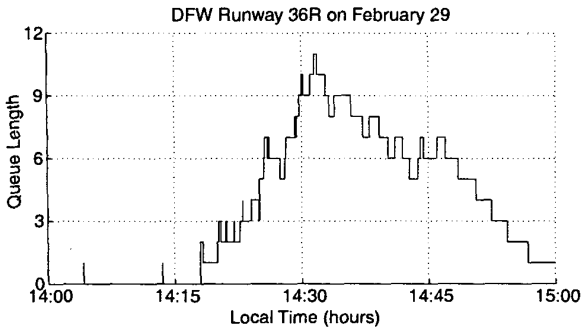

Figure 5. Queue for runway 36R on February 29, 2000.

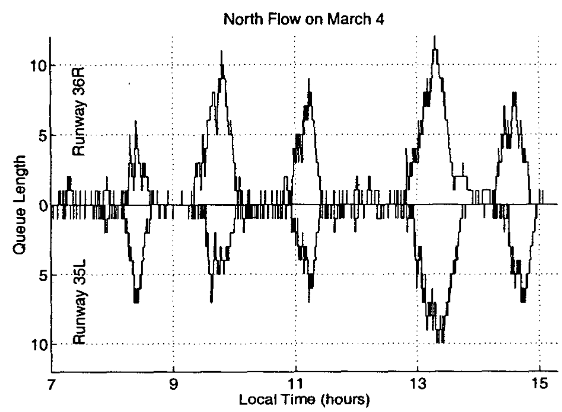

Figure 6. Queues for runways 35L and 36R on March 4.

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 6 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 delay for an aircraft joining the queue at any point in time could be similarly plotted. 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. If the departure rates are different, the delay at each runway could be plotted to show whether or not the runways are balanced. 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 typically land and passengers and cargo make connections. The queues that occurs between 12:50 and 14:00 (local time) in Figure 6 demonstrate that a departure queue may exist continually for an hour or more. Figure 7 shows an imbalance in the departure queues for runways 18L and 17R on March 2. 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.

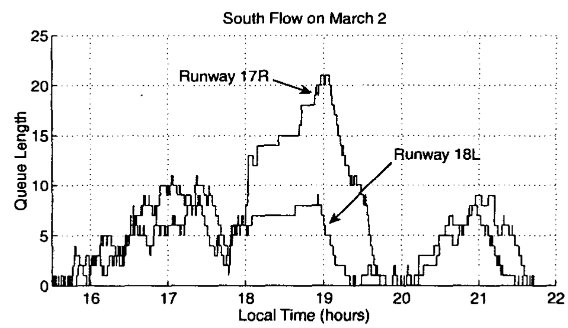

Figure 7. Queues for runways 17R and 18L on March 2.

For the 5 days that were studied, the departure queues on the primary jet departure runways were balanced at most, but not all, times. 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. Although additional application of the method is required to determine how often imbalanced runways occur at DFW or other airports, the observed occurrences motivate investigating automation to improve the management of runway balancing. Controllers currently lack reliable information about the future departure demand, as well as the ability to predict how the surface situation will evolve as a result of that demand. The absence of this situation awareness contributes to runway imbalances and other inefficiencies. The following section presents several approaches by which automation could help controllers to plan efficient traffic management strategies.

4. Control of Runway Balancing

A variety of efforts (e.g., [3]) have studied airport surface traffic management. NASA Ames Research Center, in cooperation with the FAA, is developing automation for aiding surface traffic management. The Surface Management System (SMS) is a decision support tool that will help controllers and air carriers collaboratively manage the movements of aircraft on the surface of busy airports, improving capacity, efficiency, and flexibility. Detailed information about future departure demand on airport resources is not currently available. SMS will provide operational specialists at ATC facilities and air carriers with accurate predictions of the future departure demand and how the situation on the airport surface (e.g., the queues and delays at each runway) will evolve in response to this demand. SMS will also provide advisories to help manage surface movements and departure operations that affect the departure queues. By removing a few aircraft from a queue at the beginning of a departure rush, runway balancing can reduce the delays incurred by every subsequent departure. SMS will aid runway balancing through three mechanisms: 1) supporting the selection of the schedule for the departure scenario, 2) supporting runway assignments for specific flights that are exceptions to the active departure scenario, and 3) supporting flight plan changes that will adjust runway assignments.

4.1 Departure Scenario Selection

SMS will support the tower TMC's selection of the departure scenario first by providing raw information about the demand for each of the departure fixes/gates as a function of time. This information is not currently available. Although controllers can scan all of the flight strips for the proposed flights to determine the demand for each departure fix, the time at which each flight will want to depart is not known reliably. During normal operations, controllers know approximately when each flight departs from experience. However, during irregular operations, flights will not depart at their typical times. SMS will also predict the delays/queues that will exist at each runway/fix, as a result of the demand, for each of the possible departure scenarios. This SMS-provided information would allow the tower TMC to select an efficient departure scenario and to plan when to change the scenario. In the presence of time-varying demand, the timing of capacity allocation decisions can have a significant effect on airport delays [4]. To help controllers select the schedule of departure scenarios to use, SMS will also calculate and advise an optimal schedule that will minimize delays. In this way, the departure scenario may be adjusted more frequently, and the timing of changes may better match the time-varying demand.

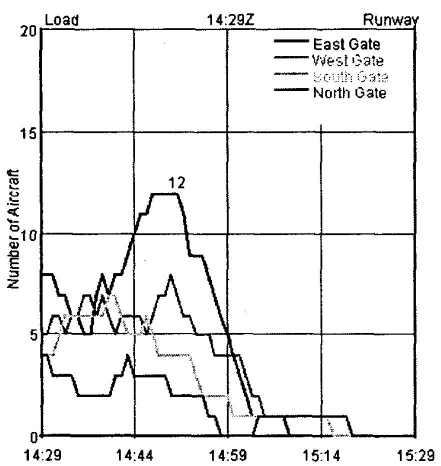

Figure 8. Prototype SMS display showing future departure demand sorted by departure gate.

Although the human factors research necessary to identify an appropriate user interface has not been completed, the following figures show prototype displays that are being considered. Figure 8 shows the departure demand for each of the 4 departure gates over the next hour. The data shown was taken from a traffic scenario used during the second controller-in-the-loop simulation of SMS. Figure 9 shows the average departure delays that will exist at each runway under the *East Push* departure scenario, with and without advised runway assignments. SMS will display graphs like this for several available departure scenarios to aid the tower TMC in selecting the most efficient departure scenario and when to change the scenario.

4.2 Runway Assignment Advisory

Ground controllers make exceptions to the departure scenario when assigning runways both to balance runways and, during less busy periods, to assign aircraft to the runway closest to their parking gate to reduce taxi distance. SMS will support runway assignment decisions, first, by displaying the expected delay for the next departure assigned to each runway. The Ground controller can use this information to determine when to make exceptions to the departure scenario to maintain equal delays at each departure runway.

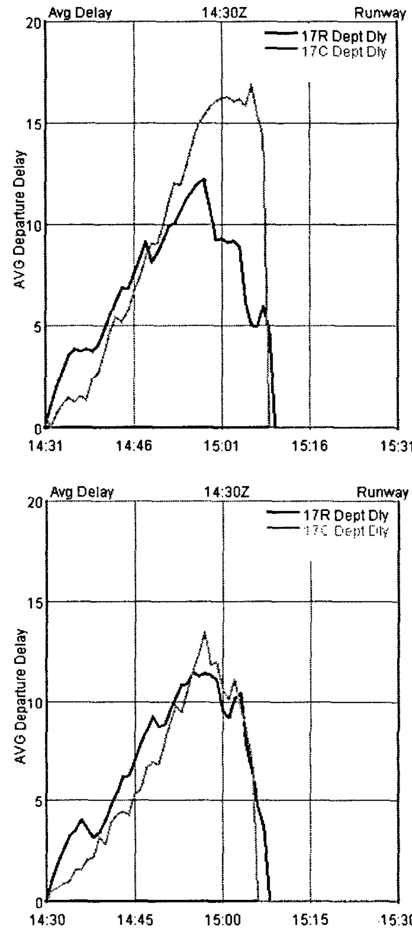

Figure 9. Prototype SMS display showing the predicted departure delays at each runway under the *East Push* departure scenario, without and with SMS advised runway assignment exceptions (top and bottom, respectively).

The flight-specific runway advisory function will search to determine whether a small number of departure runway assignments that are exceptions to the departure scenario could provide a significant reduction in total departure delay. Since these runway assignments would violate the active departure scenario, the search for beneficial alternate runway assignments is constrained by the requirement that the suggested runway assignments cannot cause airborne conflicts. Airborne departure conflicts would represent a safety concern and create high controller workload. For example, in *South Flow East Push* departure scenario at DFW, a departure from Runway 18L could fly to the CLARE departure fix (the southern most fix in the east departure gate) by remaining south of the 17R departures. This flight path would avoid conflicts with the eastbound departures from 17R, as long as two flights bound for CLARE do not depart such that both arrive at the fix at the same time.

SMS considers both the longer taxi distance and additional flight time when calculating the benefit of a runway assignment. SMS suggests changing the departure runway for a particular flight to reduce the overall departure delays. However, SMS currently constrains the search to flights that would not incur a longer delay. The impact of SMS runway advisories can be seen by comparing the two halves of Figure 9. The bottom half of Figure 9 shows the predicted delays at each departure runway assuming SMS runway advisories are used. The delays are better balanced, producing smaller total delay, than in the case where no runway exceptions are made (the top half of Figure 9).

Note that controllers currently do this manually when workload permits. Since the aircraft will be flying to the departure fix in its flight plan, the tower must coordinate with the affected TRACON Departure controllers to assure that airborne separation will be maintainable with acceptable workload. This is easiest done at the beginning of a departure push, before the airspace gets busy. By automating the search for feasible and beneficial runway assignments that are exceptions to the current departure scenario, and by simplifying the necessary coordination, SMS may allow more frequent use of the technique during busy periods, when it will have the most benefit.

4.3 Flight Plan Adjustments

SMS will also consider whether changing a flight plan to use a different departure fix and, therefore, a different departure runway without violating the rules of the active departure scenario, would be beneficial. In this case, the aircraft would rejoin its original route to its destination in Center airspace. The purpose of changing the departure runway for a particular flight could be either to help balance the departure runways or to help that particular high-priority flight takeoff earlier. SMS considers the impact on taxi distance and flight time when calculating the benefit of a flight plan amendment. Currently, the tower will occasionally initiate flight plan changes. At DFW, for example, this is typically done by the Clearance Delivery (CD) controller when issuing the pre-departure clearance. However, it may be done after the aircraft has pushed back and is waiting at a spot, in which case the Ground controller instructs the pilot to contact CD for a new route, and a new flight strip is generated in the tower. SMS could automate the search for candidate flights.

Due to its affect on fuel requirements or business objectives, the flight's dispatcher/airline operations center (AOC) may need to approve a flight plan change. In accordance with the existing Coded Departure Route (CDR) program, which facilitates the communication and coordination of alternate departure routes, the flight's dispatcher will evaluate SMS-recommended CDRs and confirm that the aircraft has the appropriate fuel when initially filing the flight plan. The dispatcher will then inform the pilot which CDRs may be accepted, and SMS will inform the tower which CDRs are available for that flight. SMS will then advise the CD or Ground controller which flights should be rerouted and which of the available CDRs for those flights should be selected. In addition to advising flight plan changes for particular flights, SMS will provide information about the predicted delays for each departure fix to enable the AOC to evaluate which flights to reroute. Based on this information, the AOC may initiate a flight plan change by requesting that a certain CDR be used for a flight.

5. Summary

When multiple runways are used for departures, the relative magnitude of the delays experienced at each runway can directly affect the capacity and efficiency of the airport. This paper began an examination of the issue of departure runway balancing. Three aspects – the cause of runway imbalances, current runway balancing performance, and automation to aid controllers in balancing runways – were examined. The procedures for assigning departure runways and bunching in the direction in which flights want to depart during a departure push were shown to create the potential for runway imbalances. Although this paper used DFW as a case study, this mechanism is common to most hub airports. The extent to which runway imbalances occur has not previously been studied quantitatively, primarily due to the lack of availability of surface surveillance data. The paper presented a method for reconstructing the departure queues that existed at each runway. In the five days studied, the queues at DFW's two primary departure runways were generally well balanced. However, imbalances in which one runway was idle while a queue remained at the other runway were observed. Controllers do not have reliable information about the future departure demand, nor the ability to predict how the surface situation will evolve as a result of that demand, that is necessary to plan efficient surface operations. Finally, the paper described automation, currently being developed by NASA Ames Research Center, that will reduce the occurrence and impact of imbalanced departure runways by improving the controller's situation awareness and providing traffic management advisories.

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