Microscopic Analysis of Airport Surface Sequencing

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In this study we analyzed a limited set of airport surface surveillance data in which flights have been sequenced on the airport surface at intersections between taxiways to attempt to empirically derive operational techniques and factors influencing sequencing decisions. We refer to such analysis as 'Microscopic Analysis' of airport surface sequencing. While controller techniques may vary, initial results suggest that consistent sequencing patterns can be identified. Further, the results indicate that sequencing decisions are dependent on the flight status (in motion vs. stopped) and taxiway location. Our results indicate that almost 90% of flights that are established on a major taxi route are handled in a First-Come-First-Served order, whereas only 50% of flights merging onto the taxiway from the ramp area are handled in this order. These initial results, and the analysis techniques that have been developed through this study, provide the means by which airport surface decision support tools and airport surface models can be improved to accurately represent microscopic decisions on the airport surface that can have significant effects on the flow of the overall air transportation system.

I. Introduction

ALTHOUGH a number of airport surface movement models exist[1,2,3] and have been successfully used for analysis of airport operations, validation of these models has been a challenge due to a lack of advanced airport surface surveillance. With such data, it is now possible to conduct detailed validation of these models. In this study we have conducted a limited set of analyses to empirically derive operational techniques that are used by controllers in sequencing flights on the airport surface at taxiway intersections. These operational techniques provide greater insight regarding airport surface traffic control and can be used to validate and enhance airport simulation modeling capabilities. We have used the Surface Operations Data Analysis and Adaptation (SODAA) tool[4] to collect and analyze these detailed airport surface operations.

To model airport surface operations with detail and accuracy, it is necessary to consider current techniques and strategies used to determine the taxi route of an aircraft and to establish the sequence to be used whenever two or more aircraft place demand on a taxiway or runway resource simultaneously. Until recently such analysis could only be conducted through visual observation of sequencing decisions,[5,6] whereas now it is possible to analyze such details using airport surface surveillance data through the use of the SODAA tool.

The SODAA tool supports NASA's NextGen research[7,8] with a focus on advanced airport surface and terminal operations. SODAA provides the infrastructure and information necessary for NASA researchers and industry analysts to achieve a deep level of knowledge and understanding of airport surface operations. This tool provides data querying and analysis capabilities, as well as advanced data mining features to support analysis of taxi routing, sequencing, and congestion management strategies used by air traffic controllers.

The objective of this paper is to describe a novel method of airport surface operations analysis and to provide initial results demonstrating the viability of the technique. The analysis was conducted using airport surface operations data from the Dallas/Fort Worth International (DFW) airport. The Surface Management System (SMS)[9] installation at the North Texas Research Station (NTX) was used to collect surface operations data, which was then analyzed using SODAA to empirically derive sequencing practices. The first section of this paper describes this new

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methodology used for this work. The second section presents the initial results, and the third section discusses future opportunities and research direction.

II. Methodology

Airport surface operations at DFW airport provide a useful case study environment for sequencing analysis. For the analyses presented here, we focus on the intersection of taxiways K and EL, as shown in Fig. 1. Taxiway K is a primary north/south taxiway located just to the east of the ramp area for DFW terminals A, C, and E. This taxiway is used for both departures and arrivals as they leave the ramp and taxi to their assigned runway for departure or as the flights taxi toward the ramp after landing. The EL taxiway is one of the primary routes used by flights that have arrived on runway 17C and are crossing runway 17R to reach their parking areas. Thus, the K/EL intersection appears to be an interesting case for a sequencing study.

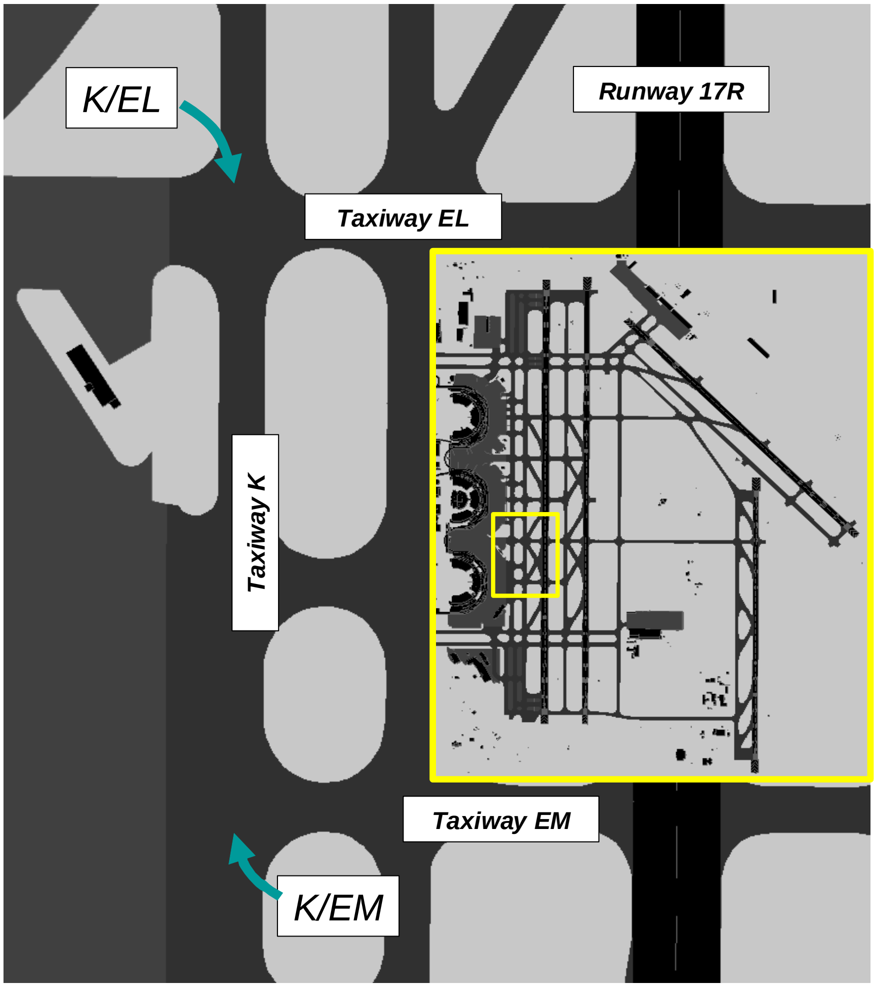

Figure 1. DFW airport east-side taxiway layout.

During periods of peak airport demand, both arrival and departure taxi times tend to increase. This is due to departure queuing, communication frequency congestion, and traffic congestion on the airport surface. Any time two flights are in contention for the same intersection at roughly the same time, the Ground Controller must decide which flight passes through first and which must hold. Once this decision is made, the trailing flight must wait. The total elapsed wait time can be broken into the time required for several events to occur:

1) The leading aircraft must reach the intersection.
2) The lead aircraft must then pass through the intersection.
3) A certain amount of following distance must be established (if following will occur).
4) If not previously provided, the trailing aircraft must obtain clearance to continue.

The first three steps must happen in sequential order, while the last step may be handled concurrently if the controller gives the direction to proceed after the traffic crosses. This sequencing decision regarding which aircraft leads and the resulting delay experienced by the following aircraft has a significant impact on surface operations. For example, as departing aircraft taxi toward a departure runway, the sequencing decision will ultimately determine the departure order. A difference of one position in the departure order will change the taxi time for a particular flight by a minimum of one or two minutes. For arriving flights, the additional time spent waiting for crossing traffic is the primary consideration when modeling taxi time. A special case of sequencing delay incurred more often by

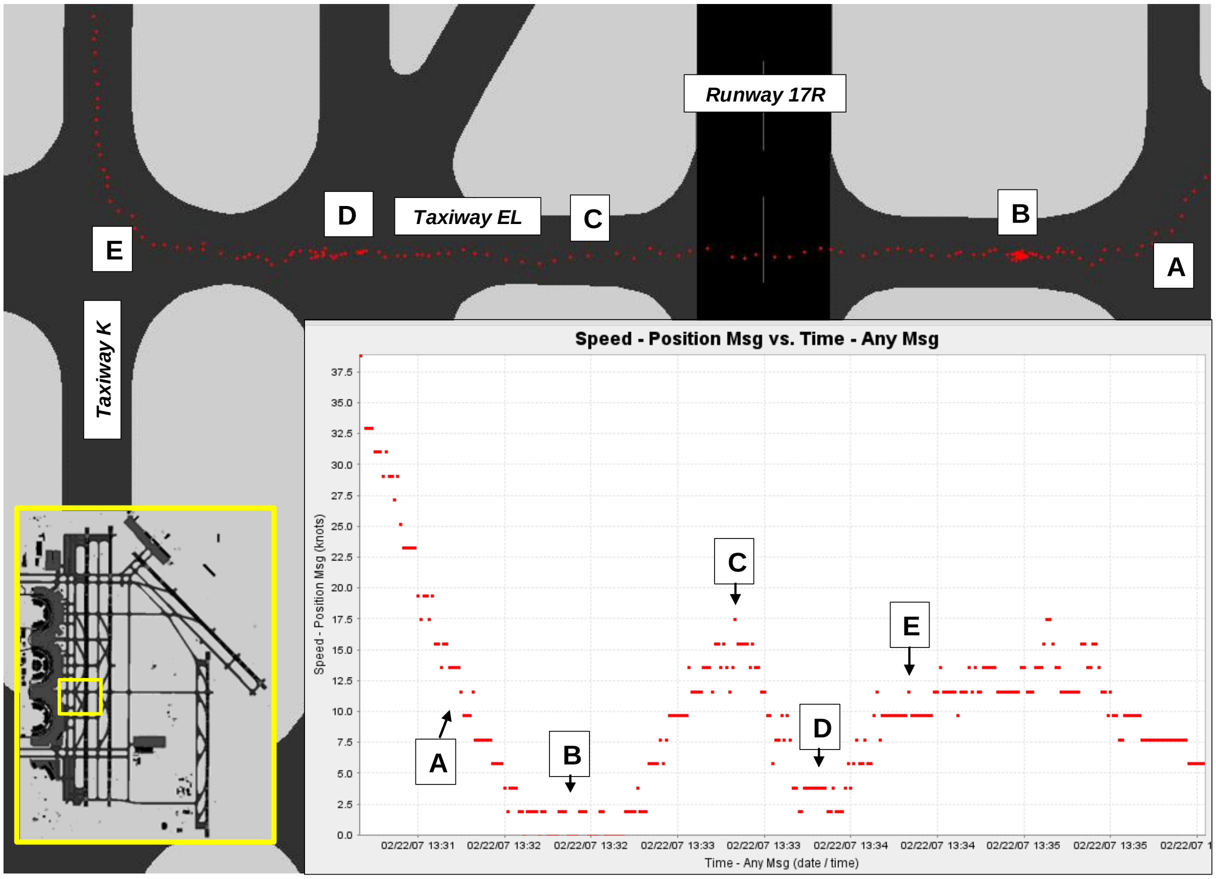

Figure 2. SODAA display showing taxi track and speed on the surface.

arrivals is the crossing of active runways. In this case, the arriving aircraft must wait for departures, and possibly arrivals, to use the runway prior to obtaining clearance from the Local Controller to cross.

Using surface surveillance data, it is possible to determine the location on the taxiway at which flights wait for runway crossings or other sequencing decisions. Figure 2 shows a portion of the taxi path for a single flight that must cross runway 17R and through the intersection between taxiways K and EL on its way to its parking gate. As shown in the figure, the flight stops and waits at both points B and D. However, it is not possible to determine from this information alone what the reasons were for the decision to hold the flight at each of those points. In many cases, a flight is held on the airport surface to implement a sequencing decision. Such sequencing decisions are the focus of this study.

We have a two-fold approach for determining how sequencing decisions are made. The first step is to detect situations where flights are in contention for the same intersection and to identify the intersections of interest—those at which sequencing decisions are actually being made versus those where sequencing is merely First-Come-First-Served (FCFS). The second step is to analyze the relevant intersections and corresponding sequencing events to determine the factors that influence the sequence order.

At any taxiway intersection, SODAA automatically identifies situations in which two aircraft could have crossed the intersection at the same time along crossing or converging paths, as illustrated in Fig. 3. This figure shows a plan view of several DFW terminals, taxiways and runways. The yellow and green lines show the paths of different aircraft that land on different runways, and share a common path during taxi in to the ramp area. In this case, a decision had to be made by a controller to direct one of the aircraft to go first, while the other aircraft would give way to allow the first aircraft to cross. After collecting hundreds or thousands of such sequencing events at each sequencing intersection, SODAA can perform automatic, detailed data mining analysis to find parameters and correlations that provide the strongest indicator of which aircraft would be selected to proceed and which one would be held. For example, at a given intersection, SODAA may find that aircraft on taxiway A are given priority over aircraft on taxiway F over 90% of the time if the aircraft on A can reach the sequencing intersection at or before the time the contending aircraft on taxiway F arrives.

Once determined by SODAA, these sequencing parameters can be directly applied to improve the airport surface modeling capabilities of SMS or other fast-time models used to evaluate the benefits of future airport operational procedures. In order to analyze current airport operations, and to also provide the ability to model procedural changes to implement NextGen concepts, it is necessary to develop a modeling system that can both mimic current operational characteristics and implement future procedures. Airport surface sequencing behavior must be a model parameter. For example, future research may identify a novel runway crossing procedure. In order to evaluate the benefits of this procedure, the airport modeling system must be able to conduct both a baseline case model run without the new procedure and a future case model run with the new procedure.

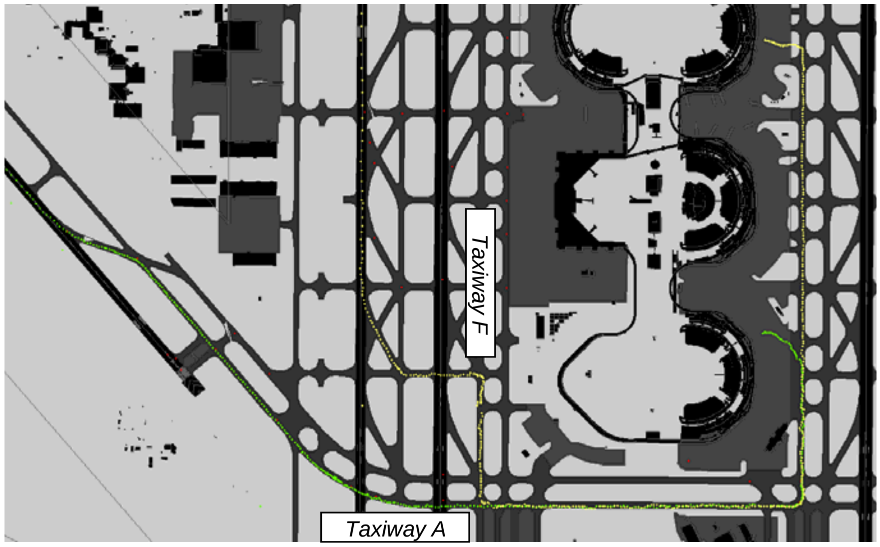

Figure 3. Intersecting aircraft surface tracks at DFW.

SODAA sequencing analysis utilizes recorded target positions on the airport surface to determine locations (e.g., taxiway intersections) that were used by a pair of aircraft. For each situation in which a common intersection was found, SODAA calculates the earliest time that each of the aircraft could have reached the common intersection based on a nominal taxi speed. This earliest crossing time and the actual crossing time for each of the aircraft are used to determine whether the two aircraft could have been at the intersection at the same time. If the following aircraft could have been at the intersection at or before the time that the leading aircraft actually crossed the intersection, then a sequencing event is identified by SODAA.

Once a sequencing event has been identified by SODAA, quantitative characteristics of the event are computed and recorded. Example sequencing statistics include the following:

- the actual separation time between the two aircraft at the common intersection;
- the initial time offset between the two aircraft at the common intersection, which indicates how much earlier one aircraft could have reached the common intersection than the other; and
- the amount of delay experienced by each of the aircraft in their taxi from their starting point to the common intersection.

To accomplish this analysis, we have extended SODAA to populate two new tables in the SODAA database when flight data is processed. The first table will contain one record for each (flight, node) pair for all nodes through which a flight actually passed. This table stores the earliest estimated time for crossing that node and the actual time that node was crossed. The second table contains one record for each combination of flight, node, and time, where "time" corresponds to a surface surveillance update. For each surveillance update, we calculate the distance to each node remaining in the actual taxi route and estimate the earliest time that flight may reach each of those nodes by dividing distance by a relatively fast nominal taxi speed.

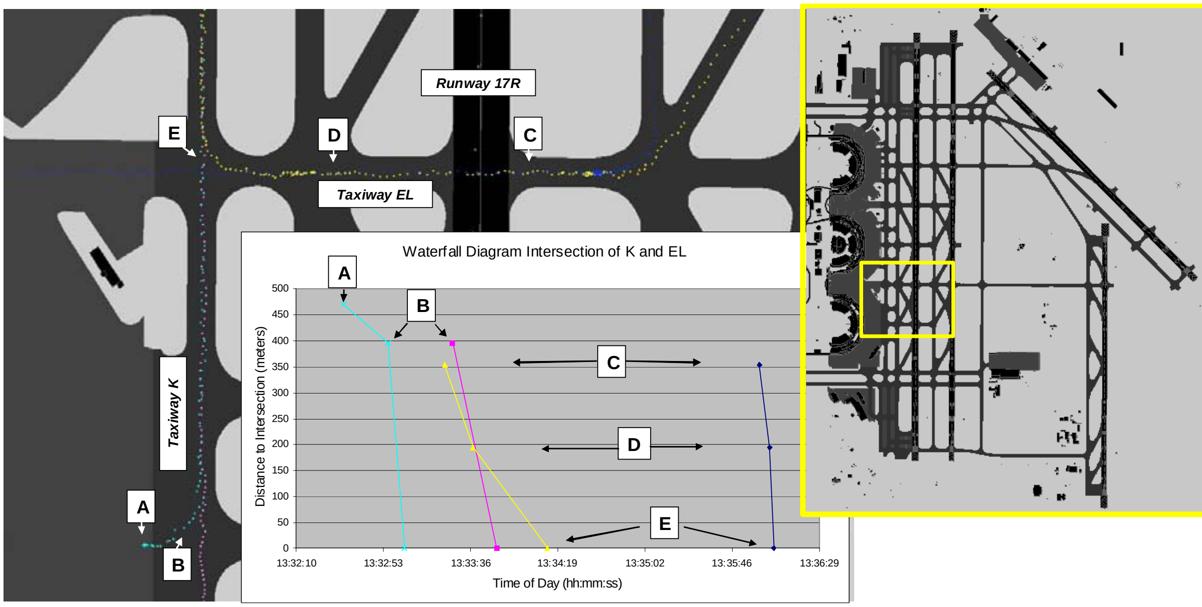

Figure 4. Sample waterfall diagram for intersection K and EL (point E in figure).

After we have the distance and time data populated, we can create "waterfall charts" by plotting, for one node, the distance versus time profile of all flights as they approach that common node. Thus, if a flight stops on the taxiway, its distance to the common node will remain constant as time progresses, and the waterfall diagram will show a flat line. A flight taxiing at a nominal taxi speed will appear in the waterfall diagram as a descending line. This will aid in the exploratory analysis of how the flights behave. Figure 4 shows a sample waterfall diagram. Note that in this sample waterfall diagram, we are only showing the time and distance relative to the intersection at a very limited set of discrete points along the taxi path. In a full waterfall diagram, we would expect to see flat spots in the diagram for flights that are stopped on their taxi path, and we expect to see many instances of crossing lines close to the X axis for intersections where sequencing is not simply based on the order of arrival (i.e., FCFS). If there are many instances of crossing lines far away from the node of interest, we expect that we may have to traverse the network to upstream nodes to determine whether sequencing decisions are made there. If we start the analysis at an intersection where sequencing is known to occur, such as the threshold of a departure runway, we can learn how to graphically identify sequencing events. We may then recursively move through the network to identify sequencing events at upstream intersections.

III. Initial Results

Following the methodology described above, SODAA was used to analyze multiple sets of airport surface sequencing operations at DFW. The first analysis that we conducted evaluates sequencing characteristics at all intersections at DFW over a six-hour period.

Figure 5 compares the initial predicted arrival time of each aircraft in the sequencing event pair at the common intersection. We computed the difference between the two aircraft arrival times to generate the histogram. Positive differences indicate the aircraft that was originally predicted to be able to reach the common intersection first was actually sequenced first. Negative results indicate that the flights crossed the intersection in a non-FCFS order because the flight that crossed the common intersection first was originally predicted to reach the common intersection after the second flight. All intersections that were found to have a sequencing event are included in this set of results. The figure indicates that an FCFS sequence was used in the majority of cases. However, there were some cases in which the sequencing decision resulted in a non-FCFS sequence (at least according to our definition and computation method).

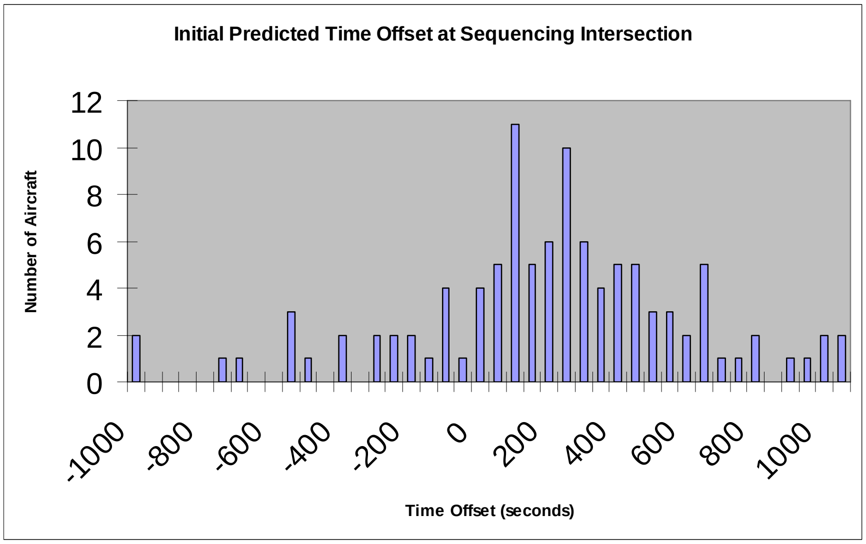

Figure 5. Initial predicted arrival time difference at common intersections.

Figure 6 shows a histogram of the actual separation times observed in surface surveillance data over a 24-hour period at the intersection of taxiways K and EL. The figure shows the distribution of separation times between aircraft that required sequencing on the airport surface. Note that this data only applies to situations in which the two aircraft could have been at the same intersection at the same time. This separation time data provides valuable information about the throughput capacity of an intersection. If all aircraft were able to move freely through the intersection and to continue taxiing without delay, how much time separation would be required between successive aircraft? Physically, this depends on the taxi speed, length of the aircraft, and required buffer distance. As shown in the figure, this information can be derived empirically.

Using the detailed data that has been computed, including the predicted crossing time at this intersection for each flight as a function of time, we have analyzed controller decision-making regarding the sequence of flights through this intersection. To accomplish this analysis, we created a set of geospatial regions in the SODAA tool and used a query to obtain the first entry time of each flight into each of the geospatial regions. The geospatial regions were located on the taxi routes approaching the K/EL intersection, as shown in Fig. 7. As flights taxi through each of the geospatial regions, the SODAA query provides the time of entry. Using a nominal taxi speed and the distance from each of the geospatial regions to the K/EL intersection, we compute the earliest crossing time of the K/EL intersection for each flight at each of the regions.

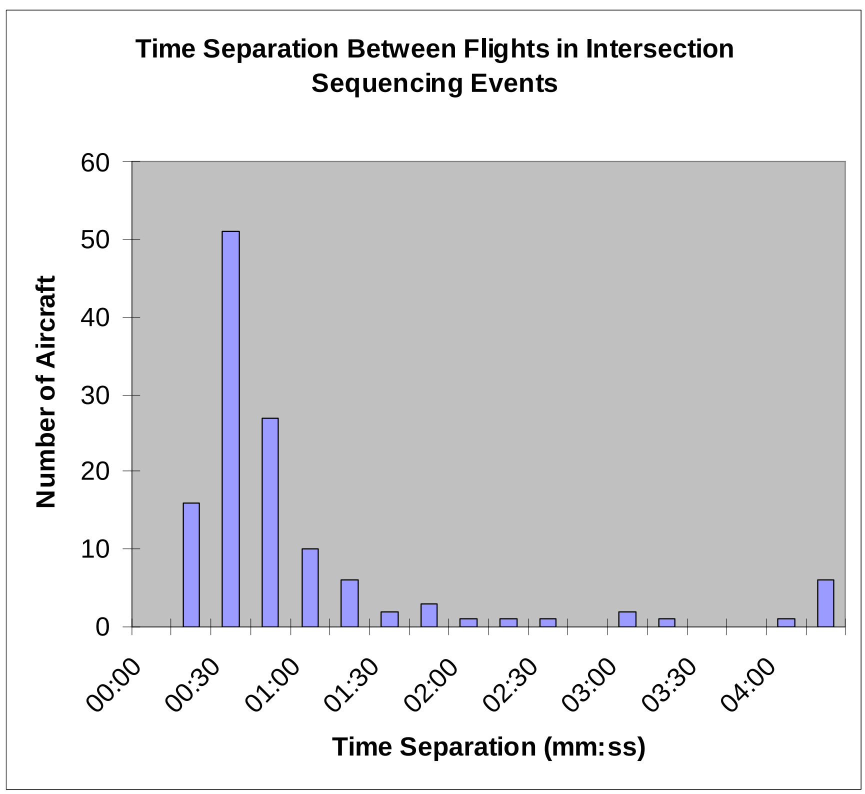

Figure 6. Actual separation times between aircraft at common intersection (K and EL).

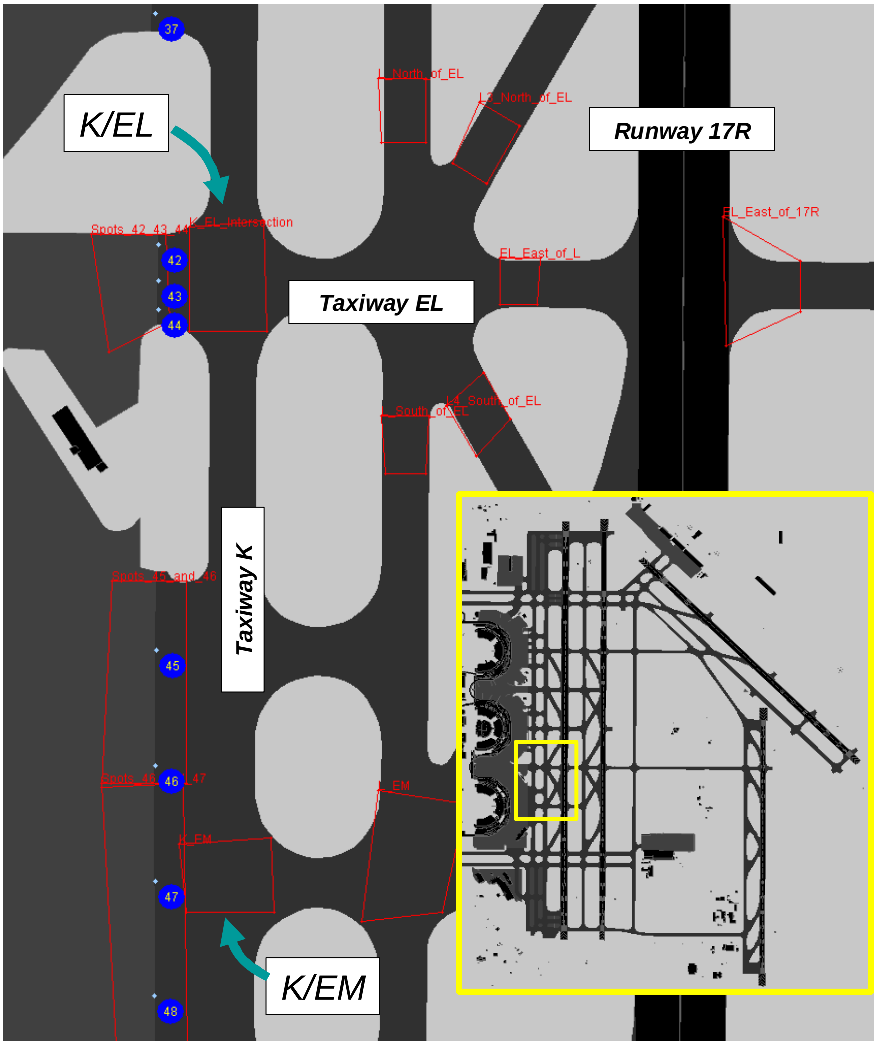

Figure 7. Geospatial regions surround the intersection of taxiway K and taxiway EL.

Although these calculations do not give us a full waterfall diagram for the flight, we can analyze the time of intersection crossing predicted at each of the geospatial regions that the flight crosses to evaluate whether or not the flight is sequenced at the intersection in an FCFS order.

Note that the layout of the geospatial regions has been designed to monitor multiple approaches to the K/EL intersection. Our hypothesis in designing these geospatial regions in this manner is that the direction and route that is used to approach the intersection has a significant impact on the controller decision-making process regarding the flight sequence.

On the left side of Fig. 7, three geospatial regions have been created that encompass a group of 'spots'. A 'spot' or apron entrance/exit point marks a location on the airport surface at which flights transition from the Airport Movement Area (AMA) to the ramp area. The spots that are included in the geospatial regions are 42, 43, and 44 in the first group, 45 and 46 in the second region, and 47 and 48 in the last region. Departure flights stop and hold in these regions waiting for taxi clearance from the tower to proceed onto taxiway K. On taxiway K, we have multiple geospatial regions. A geospatial region at the intersection of K and EM is shown in the figure. The largest portion of traffic through K/EL goes through the K/EM intersection. The traffic through this intersection includes arrival flights heading for their parking gates and departure flights that have left spots further south of the EM taxiway.

The geospatial regions used for this analysis also include intersections on taxiway EL. This taxiway is used by arrival flights to cross runway 17R and to proceed toward their gates. We have created two geospatial regions—one immediately before the flights cross runway 17R, and one after 17R has been crossed and before the intersection with taxiway L.

By identifying the earliest time at K/EL for each flight at each of these geospatial regions, we determine whether or not flights are handled at K/EL in an FCFS order. If a flight's earliest crossing time at K/EL is earlier than the actual crossing time of the flight ahead of it at the intersection, then we consider the flight to have been handled in a non-FCFS order. As the flight enters each geospatial region, we compute the earliest time of arrival at K/EL. Since flights may progress towards K/EL with varying average velocities, the predicted K/EL sequencing order will change from one geospatial region to the next.

Figure 8 shows sequencing analysis results for 414 flights that traversed the K/EL intersection during a 24-hour period. In the figure, a pair of numbers is shown for each of the geospatial regions. The number below the line is the total number of flights that went through the indicated geospatial region on the way to the intersection of taxiways K and EL. The number above the line is the number of flights that were handled at K/EL in non-FCFS order.

For example, 21 flights out of 89 that waited east of 17R on EL were not handled in FCFS order at K/EL. Of those 21, three of them took their non-FCFS sequencing delay before getting to the geospatial region east of the L taxiway. The other 18 took their non-FCFS delay between the geospatial region on EL east of L and the K/EL intersection. This result indicates, as would be expected, that flights taxiing on the K taxiway, which is the primary route for departure and arrivals, are more likely to be sequenced ahead of flights that are merging onto the K taxiway.

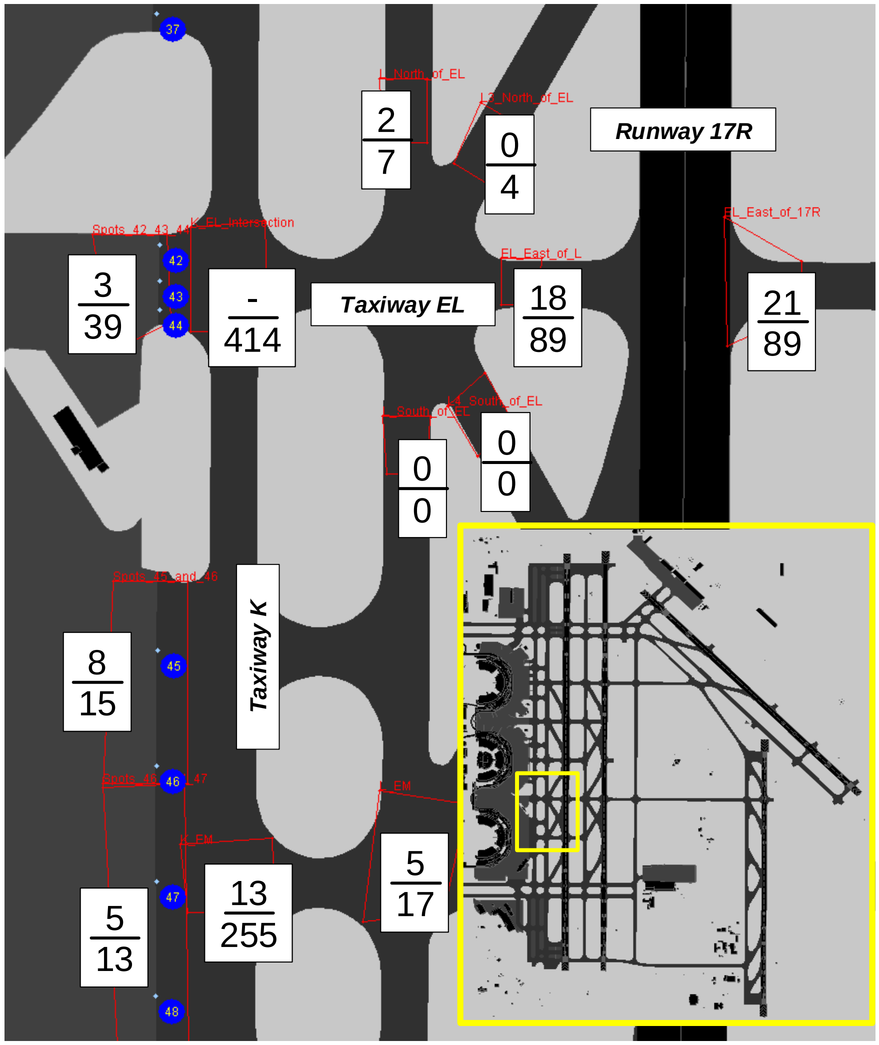

Figure 8. Flights sequenced in non-FCFS order compared to total flights.

Flights that are leaving the spots seem to have a higher percentage of cases in which they are sequenced out of FCFS order. Although we have not analyzed the taxi route pairs for each sequencing decision, based on the number of flights traveling on the K taxiway, we expect that most of the sequencing decisions for flights coming out of the spots are made with respect to flights taxiing north on the K taxiway. It is reasonable to expect that flights on the K taxiway would receive some preference because they are more likely to be up to speed, whereas the flights leaving the spots are more likely to be at a full stop while they wait for a taxi clearance.

It appears from the data that flights taxiing across runway 17R and entering the K taxiway are handled in a non-FCFS order at a higher frequency than those traveling north on the K taxiway. This may be due to the fact that flight crews must be on the Local Controller's frequency while crossing runway 17R, and then (usually) they must switch to the Ground Controller's frequency before receiving the remainder of their taxi clearance. The data indicate that aircraft often stop short of taxiway K after crossing runway 17R, which would be a common result of the need to change frequency and receive further clearance to taxi into the ramp.

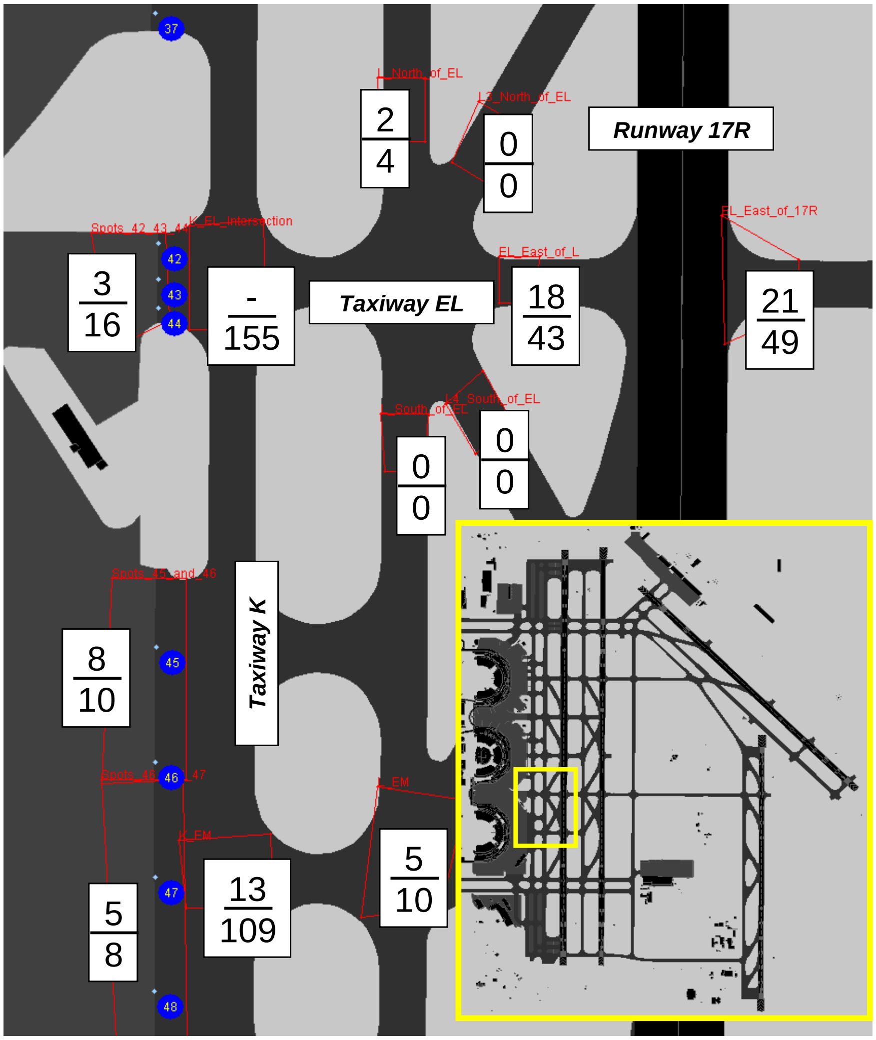

Figure 9. Flights sequenced in non-FCFS order when sequencing is necessary.

Note that the results shown in Fig. 8 include all flights crossing the K/EL intersection during a 24-hour period. During that period of time, however, there would be many flights that crossed through the K/EL intersection that did not require a sequencing decision to be made at all because there were no other flights that were competing for access to the intersection.

By limiting the data to only those pairs of flights that could have arrived at the K/EL intersection within one minute of each other, we can more accurately evaluate the decision-making and sequencing techniques used by the controller when sequencing is necessary. Figure 9 shows the results when we consider only flights that require a sequence decision to be made. Notice that the flights leaving the spots are even more likely to be held for other traffic when there is a sequencing decision to be made.

This version of the results also illustrates another surface operations phenomenon. Note that there are 49 flights that pass through the geospatial region on EL east of runway 17R that are considered to be part of a sequence event at the K/EL intersection. However, after the flights have held and waited to cross runway 17R, only 43 of the original 49 flights are still involved in a sequencing event at the K/EL intersection. This is an example of the upstream effects on a downstream intersection that must be considered when formulating conclusions about controller decision–making at a given intersection.

Finally, in Fig. 10, we present an analysis of the delay allocated to aircraft that are sequenced in a non-FCFS order. Although there are many different reasons that flights may be held on the airport surface—including a parking gate that is not available, a Traffic Flow Management (TFM) restriction, or a mechanical issue—we have designed this analysis to exclusively evaluate the amount of delay assigned to a flight because of the sequencing of that flight behind another. The results shown in the figure indicate that the sequencing delay is generally less than two minutes.

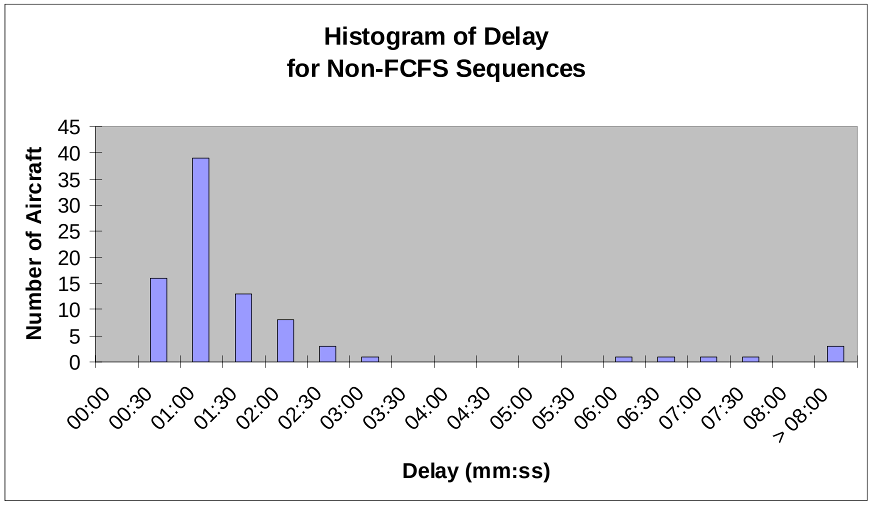

Figure 10. Sequencing delay for flights that are handled in non-FCFS order.

IV. Conclusions

In this study we have conducted a limited set of analyses to empirically derive operational techniques used by controllers in sequencing flights on the airport surface at intersections between taxiways. While controller techniques may vary, initial results suggest that consistent sequencing patterns can be identified. Further, the results indicate that sequencing decisions are dependent on the flight status (in motion vs. stopped) and taxiway location. For example, our results for this particular case study at DFW indicate that almost 90% of flights that are established on a major taxi route (taxiway K) are handled in an FCFS order, while only 50% of flights leaving the spots and merging onto the taxiway are handled in an FCFS order. These initial results, and the analysis techniques that have been developed through this study, provide the means by which airport surface decision support tools and airport surface models can be improved to accurately represent microscopic decisions on the airport surface that can have significant effects on the flow of the overall air transportation system.

V. Future Work

Future work will include analysis to characterize the decision factors involved in sequencing situations. The present study has identified some indicators of controller technique at specific intersections at DFW. In future studies we intend to construct a logistic regression model to predict the likelihood of a flight being the next one to proceed through an intersection. Logistic regression is a generalized linear model that fits a binomial response variable to a linear combination of independent variables. The basic model is described by Eqs. (1–3) below. In our case, π would represent the probability of being the next flight to use the intersection.

$$\pi(x) = \frac{\exp(\beta_0 + \beta_1 x_1 + \ldots \beta_k x_k)}{1 + \exp(\beta_0 + \beta_1 x_1 + \ldots \beta_k x_k)} \tag{1}$$

$$g(x) = \ln\left[\frac{\pi(x)}{1 - \pi(x)}\right] \tag{2}$$

$$g(x) = \beta_0 + \beta_1 x_1 + \ldots \beta_k x_k \tag{3}$$

where:

- $\beta_{0 \ldots k}$ is the vector of fitted model coefficients
- $x_{1 \ldots k}$ are the independent variables included in the model
- $\pi(x)$ is the binomial response variable being fit
- $g(x)$ is the linking function

The independent variables ($x_1 \ldots x_k$) may be designed to represent a combination of categorical or numeric values. Figure 11 shows the shape of the linking function in Eq. (2), which maps the linear model to the non-linear probability. In a fashion somewhat similar to multiple linear regression, we can test the fit of the model with and without each factor to identify those that provide a statistically significant improvement in the fit of the model.

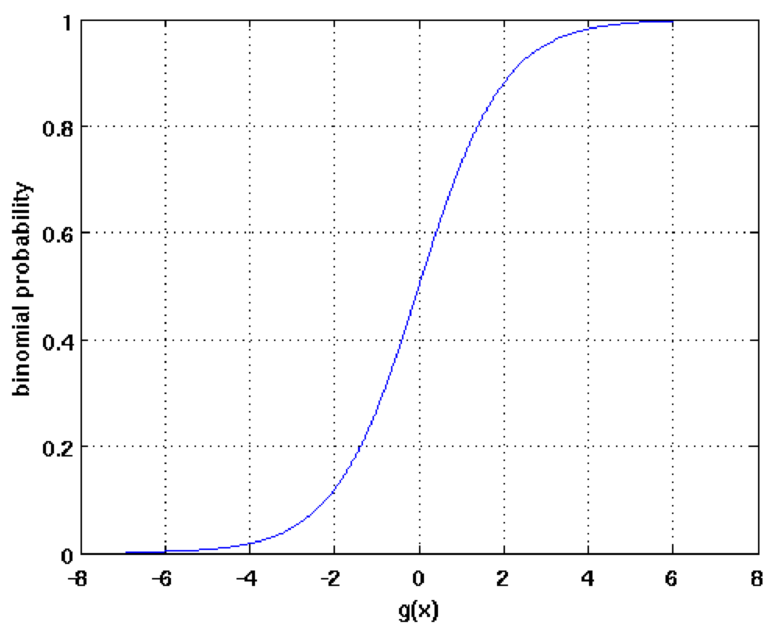

Figure 11. Shape of non-linear linking function.

We plan to build the model data set by sampling at random times from a relatively large time interval of data, where the data for one intersection at one time will consist of all flights that meet all of the following conditions at the sample time:

1) The actual taxi path includes the intersection,
2) The flight is active (meaning we have taxi surveillance data), and
3) The flight has not yet reached the intersection.

The set of state variables to be used is as yet undetermined, but will likely include the following:

1) Distance to the intersection;
2) Current taxiway link;
3) Speed, possibly categorized into {stopped, slow, fast, etc..};
4) Timeliness of flight, possibly categorized into {early, on-time, late, etc...};
5) Aircraft type;
6) Airline;
7) Controlled departure time, if any (departures only); and
8) Departure fix/procedure.

To these state variables, we can add prior knowledge of whether or not the flight actually was next to pass through the intersection, which is the binomial independent variable we are trying to fit.

Once we compute probabilities for being the next in sequence, we must develop a model that applies them to automatic sequencing decisions. For example, we may choose to simply pick the flight with the highest probability or combine the probabilities of potential candidates into an odds ratio and use that to decide. The development of that model will depend heavily on the outcome of the logistic regression and our ability to create a model that will accurately estimate the likelihood of being the next in the sequence. Other aspects of sequencing decisions will be evaluated as well, such as decisions regarding the sequencing of arrivals and departures on a runway, as well as the sequencing of aircraft crossing runways with arrival and departure traffic.

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