Implication of Variability in Airport Surface Operations on 4-D Trajectory Planning

Stephen Atkins[*] and Christopher Brinton[†]
Mosaic ATM, Inc., Leesburg, VA, 20175

Yoon Jung[‡]
NASA Ames Research Center, Moffett Field, CA, 94035

A principal theme of future traffic management is the use of planned four-dimensional trajectories (4DTs) for airborne and surface operations at busy airports. In contrast to autopilots following airborne 4DTs, human pilots will continue to manually control the movement of aircraft on the ground. The resulting variability in compliance with planned surface trajectories will have a significant impact on optimal surface planning systems. This paper first explores, parametrically, the relationship between surface trajectory compliance and elements of surface traffic management operational concepts, such as how frequently aircraft trajectories may be re-planned and how far in advance plans must be frozen. Flexibility similar to current operations must be preserved to maintain capacity in the presence of uncertainty. Second, the paper presents examples of the variability currently observed in the movements of aircraft on the airport surface, as an initial bound on the compliance errors that may be expected. Implications of this variability for future surface traffic management concepts are described. Variability creates a tradeoff between trajectories being feasible and efficient, which motivates re-planning trajectories frequently and providing only partial, immediate clearances to aircraft on the surface. Interoperability with airborne 4DT planning systems will require longer planned windows for coordinated events (e.g., takeoff) where the surface planning system may re-plan frequently, moving scheduled times within those frozen windows.

I. Introduction

THE Next Generation Air Transportation System (NextGen) Concept of Operations[1] states that "4DTs [four-dimensional trajectories] may be used on the airport surface at high-density airports to expedite traffic and schedule active runway crossings." Many existing aircraft autopilots are capable of following the airborne 4DTs envisioned in NextGen, some with high accuracy and confidence. The same ability does not exist for aircraft on the airport surface. Current autopilots, which can automatically deploy aerodynamic speed brakes, provide minimal aircraft control on the airport surface. Aircraft nose-wheel landing gear, for example, are not currently designed to allow an autopilot to steer the aircraft. An auto-taxi capability would require a substantial physical change to the aircraft, likely only being available on newly manufactured aircraft. Even the next generation of aircraft currently being designed by Boeing and Airbus do not include this capability. Other elements of aircraft control on the surface, such as auto-throttles or autopilot control of wheel brakes, might be developed for ground movement, in some cases with minimal hardware changes on the aircraft. However, the technology would still require years to develop and certify. As a result, autopilots will not be the primary controller of aircraft movement on the ground by the 2020 start of the NextGen timeframe. Rather, human pilots will continue to play a major role in controlling the movement of aircraft on the ground. Consequently, four-dimensional surface trajectories (4DSTs) will be followed by manual piloting. Various ground guidance directors might be provided to pilots to help them follow planned trajectories more precisely, analogous to the flight director currently used by pilots when manually flying precision approaches. Still, the resulting variance in aircraft compliance with 4DSTs is anticipated to be larger than the

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[*] Principal Analyst and Vice President, 801 Sycolin Road, S.E., Suite 212, Leesburg, VA 20175, AIAA Senior Member.

[†] Principal Analyst and President, 801 Sycolin Road, S.E., Suite 212, Leesburg, VA 20175, AIAA Member.

[‡] Aerospace Engineer, Mail Stop 210-6, AIAA Member.

compliance errors of autopilots flying airborne 4DTs. This human induced variability in aircraft movements on the airport surface will have a significant impact on optimal surface planning systems.

As a necessary input to research on surface traffic optimization and the integration of airborne and surface traffic management, this paper begins to quantify the uncertainties in airport surface movements that NextGen concepts and automation must accommodate. The results support the design of concepts for the integration of surface management and airborne traffic management and the algorithmic approaches taken to plan surface operations. Although research quantifying the expected errors through pilot simulations using prototype taxi directors is being performed,[2] this paper follows an alternative approach and presents the results of studying the variability currently observed in the movement of aircraft on the airport surface. These results characterize the uncertainty that may be exhibited by unaided aircraft taxiing in the NextGen time frame and provide insight into an upper bound for the uncertainty that will remain after new taxi guidance systems and displays are introduced. The application of these results within the design of NextGen surface concepts and algorithms will identify which aspects of surface movement variations must be studied in more detail and possibly controlled more precisely.

The paper is organized as follows. The next section describes the impact of 4DST compliance error, or more generally variability in aircraft movement, on planning surface operations and integrating surface and airborne trajectory planning. The following section presents results from studying variability in contemporary surface movements. The final section presents conclusions and lists opportunities for future research.

II. Impact of Surface Operations Uncertainty

Uncertainty in pilot compliance with a 4DST will require surface planning systems to either re-plan the trajectories of other aircraft in response to an aircraft's actual trajectory or to initially allocate resources to aircraft for longer periods of time to ensure separation with other aircraft using those same resources. In some cases, there may be insufficient time for the other aircraft to adjust their trajectories in response to the first aircraft's actual trajectory, requiring larger "buffers" to be planned. This section explores the relationship between uncertainty in 4DST compliance, re-planning frequency, planning freeze horizon (i.e., how far into the future the plan cannot be changed), and aircraft controllability (i.e., how much an aircraft's trajectory may be modified at various amounts of time into the future).

A. General Concepts

Uncertainty in a state is determined by the dynamics of the state and the time horizon over which those dynamics are uncontrolled or unobserved. The relevance of this to optimal planning is that a robust plan must handle larger uncertainties if the plan must be frozen (i.e., not subsequently changed) farther in advance. For example, assume a departure must takeoff within a 1 minute time window to comply with a planned airborne trajectory and that the airborne trajectory must be frozen 30 minutes in advance. Assume gate departure time uncertainty is such that the aircraft is equally likely to block out[§] from its parking gate anytime within a 5 minute window around the planned gate departure time. Assume the unconstrained taxi time to the runway is deterministic and known to be 10 minutes. In order to comply with a planned takeoff window, the planned gate departure time must be set so that the latest possible gate departure time is at least 10 minutes (the taxi time) before the end of the takeoff window. Figure 1 illustrates this example. The uncertainty in the actual gate departure time causes four-fifths of the possible gate departure times to result in a delay – the flight will be required to wait after blocking out for the planned takeoff window; the average delay is 1.6 minutes. In contrast, if the airborne trajectory can be re-planned every 5 minutes with no freeze horizon, then the planned takeoff window can be adjusted after the flight blocks out. In this case, the ability to re-plan would eliminate the effect of the gate departure time uncertainty, assuming other constraints allow a new departure time to be feasible.

In constructing 4DSTs, the planned takeoff time for a following departure must consider the uncertainty in the preceding departure's takeoff time. If the leading aircraft takes off earlier than its planned time, the following aircraft may either wait until its originally planned time or take off as soon as separation constraints permit. Current operations depart the following aircraft as separation constraints permit to minimize departure delay and maximize runway throughput. Integration with airborne 4DT planning may require that the second departure takeoff at the originally planned time regardless of the actual takeoff time of the preceding departure. This approach increases

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[§] The term "block out" refers to the time at which the chocks are removed from a parked aircraft's wheels and the aircraft may begin to move. Block out is a more general term than the, possibly, more common term "push back" because not all aircraft park such that they must first move backward away from the parking position.

predictability by always flying/taxiing to cross defined points at specified times, but decreases flexibility to react to the actual situation as it occurs and increases dependence on initial uncertainty.

The amount of flexibility in a 4DT system depends on how frequently or under what conditions the trajectories may be revised, how far in advance the trajectories must be frozen, and the allowable magnitude of the trajectory changes. The combination of the uncertainty characteristics and these planning "dynamics" will determine the efficiency of the 4DT system and create a significant challenge for maximizing runway capacity that does not exist in current operations. Since uncertainties compound over time, the farther in advance a plan must be selected without the opportunity to revise it, the greater the uncertainty that plan must accommodate. Large uncertainties and slow planning dynamics could result in decreased capacity when using 4DTs.

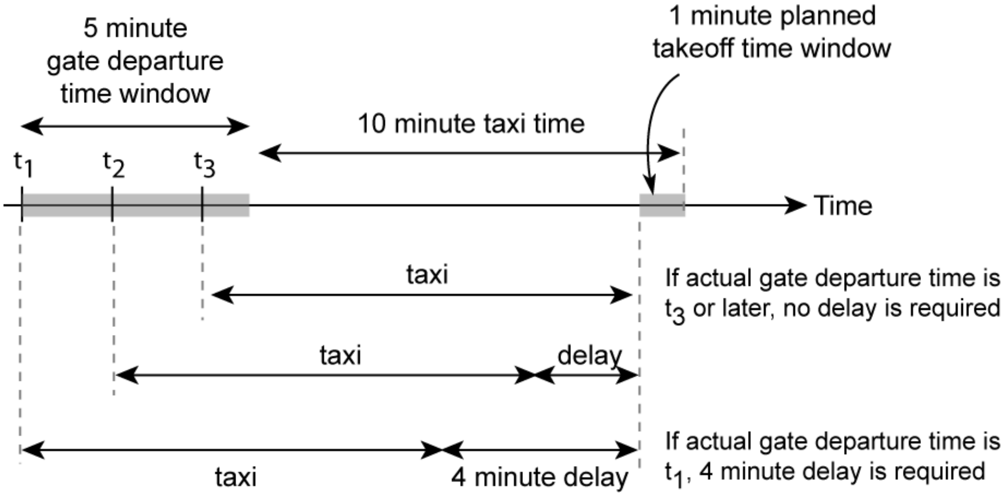

Figure 1. Example of Necessary Taxi Delay to Comply with a Planned Takeoff Window Due to Block Out Time Uncertainty

B. Two-Aircraft Problem

This section uses a two-aircraft problem to explore the relationship between planning event times in the presence of uncertainty and the ability to re-plan. The following section extends these ideas to streams of aircraft to show the effects on throughput. The goal of a planning system is to determine planned times for events that satisfy various requirements including some objective function to measure the goodness of the plan. Figure 2 illustrates the time at which two events, A and B, are planned to occur and may actually occur. In the context of surface traffic planning, an event is an aircraft using a resource that must be managed, such as departures using a runway or aircraft entering a taxiway intersection. Note that some events are not instantaneous; for example, an aircraft crossing a runway will occupy the runway for a period of time. The following concepts directly extend to handle events that occur for a period of time. Given a planned time for an event, the time at which the event actually occurs will vary relative to the planned time, notionally illustrated by probability density functions in Fig. 2. A model of this uncertainty in the actual event time given a planned event time is essential to planning efficient surface operations; the second half of this paper investigates bounding the uncertainties for some surface events. Note that Fig. 2 is not intended to imply that the probability density function describing the uncertainty will be normally distributed. When calculating planned times, the planning system must consider how the actual event time will vary from a planned time. Figure 2 shows a somewhat conservative plan to ensure two events will be separated by a required minimum amount of time. Due to the uncertainty, the planned times are separated by much more than the required minimum.

In general, the uncertainty may have very long tails with small likelihoods. Separating the planned times far enough that the tails will be separated by the required minimum is not practical. Instead, an event occurring at a time far from the planned time must be handled separately by providing a method for handling exceptions. For example, if a flight misses its departure slot due to the discovery of a mechanical problem, a departure slot is wasted and a new slot must be planned for that flight. The expected frequency at which these exceptions may occur will be a design parameter in the planning system. Consequently, the uncertainty is divided into a region where the plan is robust to the uncertainty and regions that would require exception handling. The former is redefined as the "expected" window for the event; any time in that window is an acceptable time for the event from the perspective of the planning system. If the event occurs outside that window, exception handling may be required.

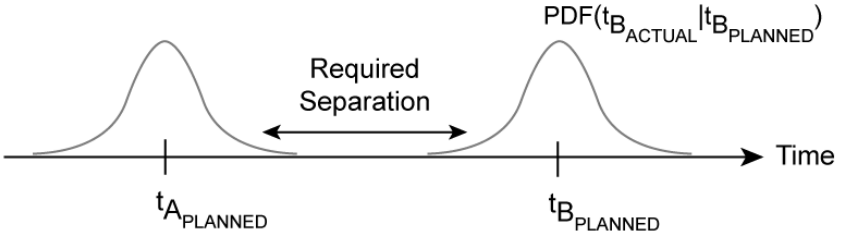

Figure 2. Required Separation Applied Between Two Events Where the Actual Event Times are Uncertain Relative to the Planned Event Times

If the surface planning system must coordinate with an airborne trajectory planning system then a planned window is defined by the uncertainty, the allowable rate of exceptions, and coordination with the other planning system. The planned window may be the same as or larger than the expected window. Figure 3 illustrates the expected and planned windows and the application of the separation requirement to the expected windows. Note that the expected window (darker shading) and the planned window (lighter shading) do not need to be centered on the planned time.

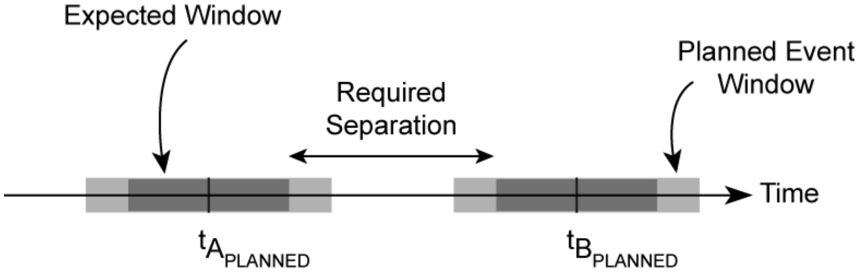

Figure 3. Required Separation Applied Relative to Expected and Planned Event Windows

If the time at which event B occurs is not controllable after event A occurs, then the system runs open-loop after the initial plan is determined. The resource capacity is determined by the required separation and the width of the expected window (which is determined by the uncertainty in the actual event time relative to the planned event time and the tolerance for exceptions), as illustrated in Fig. 3.

As an example, in some situations the takeoff of a departure following a preceding operation on a runway, the planned time for event B may be adjusted after event A occurs (or after receiving additional information that improves the prediction of when event A will occur). The ability to re-plan closes the loop and may improve resource capacity relative to the open-loop situation. The value of being able to re-plan depends on whether re-planning reduces the uncertainty in when event B will occur relative to the planned time and whether the expected window may be moved (either within the planned window or by moving the planned window).

While Fig. 3 represents one extreme case, the opposite extreme case is when the planning system knows that after event A occurs event B will be able to be controlled with no uncertainty. An example of this situation would be a departure (event B) following an arrival (event A) on a runway by the arrival's runway occupancy time (Required Separation). The uncertainty in the arrival's landing time relative to a planned time is due to prediction errors. The a priori uncertainty in the departure's takeoff time is also due to prediction errors in when the departure will reach the runway. However, once the departure has reached the runway and the arrival has landed, the departure time may be controlled accurately.

Figure 4 illustrates the a priori planned times for this case, where the expected window for event A is the set of times t for which $t_{A_{EARLIEST}} \leq t \leq t_{A_{LATEST}}$. In the a priori plan, the only requirement for the expected windows is that $t_{B_{LATEST}} \geq t_{A_{LATEST}} + RS$, where RS is the required separation. This ensures that for every possible time at which event A may occur (i.e., the arrival lands), once that time is known there exists a time within event B's expected window that is at least RS later (i.e., the departure can take off at least the arrival's runway occupancy time after the arrival lands without violating the pre-planned expected window). Interestingly, $t_{B_{PLANNED}} \geq t_{A_{PLANNED}} + RS$ is not a requirement (i.e., the time at which the departure is planned to reach the runway is not required to be after the latest the arrival may land and exit the runway) because these are a priori planned times and the actual event B time may be controlled after event A occurs. Furthermore, $t_{B_{EARLIEST}}$ may be less than $t_{A_{EARLIEST}}$ + RS, because the departure is allowed to reach the runway before the arrival lands and exits the runway, but event B will never actually occur in that portion of its expected window. If $t_{B_{EARLIEST}}$ is greater than $t_{A_{EARLIEST}}$ + RS then excess separation may occur; this would occur if the arrival lands early in its expected window and the departure does not reach the runway until late in its expected window. Also note that $t_{B_{EARLIEST}} \leq t_{A_{LATEST}}$ is possible depending on the relative size of the required separation and shape of the expected windows (i.e., the departure is allowed to reach the runway and be ready before the arrival lands). The ability to re-plan event B in reaction to the actual event A time reduces but does not eliminate the impact of the initial uncertainty on resource capacity. This is significant because the capacity of a resource to which many aircraft are planned depends on the a priori plans.

Figures 3 and 4 showed two extreme cases. An intermediate case exists when event B may be re-planned after event A occurs but uncertainty remains in the when event B will occur relative to the new planned time. In this case, the planning system may consider the a posteriori uncertainty, rather than the uncertainty prior to event A, when determining the a priori plan for event B.

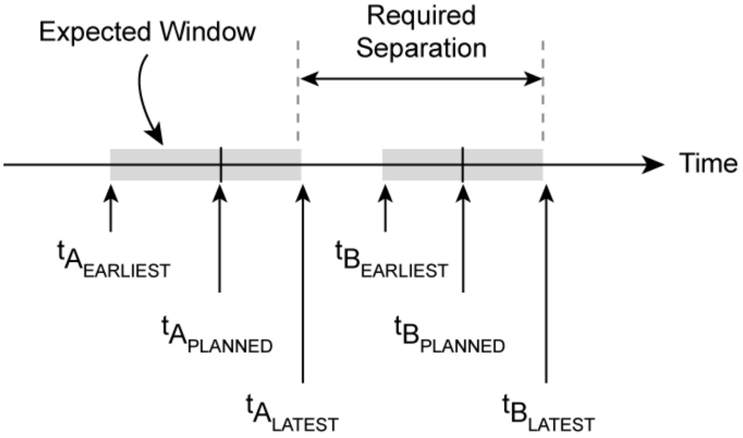

Figure 4. A Priori Plan if Event B May be Controlled after Event A Occurs

C. Many-Aircraft Problem

The effect of a re-planning freeze horizon on resource throughput is more visible by considering multiple aircraft. One typical situation that entails a freeze horizon is exemplified by the Traffic Management Advisor (TMA)[3]. A freeze horizon defines the point at which scheduled arrival times (STAs) are frozen so that controllers may begin controlling aircraft to comply with those times. The uncertainty that affects the planning of STAs is the errors in the estimated times of arrival (ETAs). These errors decrease as the flights approach the freeze horizon, which is characteristic of an "open-loop" system that is predicting an event time[**]. In contrast, a NextGen surface planning system will be a "closed-loop" system in that aircraft will be controlled to the planned times and the uncertainty is due to compliance errors. Uncertainty due to compliance errors is not likely to decrease as the event approaches. Note that the uncertainty about which flights will be exceptions and be unable to comply with their acceptable window will decrease at shorter prediction horizons.

Figure 5 represents a case where there is no freeze horizon, no limit on how much each planned time may be changed, and no limit on how frequently the plan may be modified. Limits on how far a planned event may be moved from the a priori plan, or how frequently the plan could be modified, would reduce the benefit of re-planning. The first row of the figure shows an a priori plan at time T_0 for four events at a resource. Required separation between the events is applied between the expected windows since the actual event times are uncertain. The second, third, and fourth rows in the figure each show the actual time at which the next event occurs and how the plan for subsequent events may be changed. The ability to re-plan achieves significantly higher throughput than the a priori plan at time T_0. The excess separation between events, i.e., greater than the required separation, that remains after

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[**] Note that TMA's ability to "ripple the list" – i.e., momentarily suspend the freeze horizon to reschedule to correct for a buildup of errors – illustrates how real planning systems include complexities beyond the generic concepts explored in this introductory work.

re-planning is expected to be the difference between the expected value for the event time and the earliest time in the event window.

A freeze horizon prevents the planned times for events within the freeze horizon of the current time from being moved. If each event is planned based on a required separation from the prior event then the planned times outside of the freeze horizon cannot be updated based on an observation of an actual event time within the freeze horizon, as depicted in Fig. 6. At time T_1, when event A occurs, the expected windows of events B and C are frozen because they are within the freeze horizon. The expected window of the event D is not changed because it must remain spaced relative to event C.

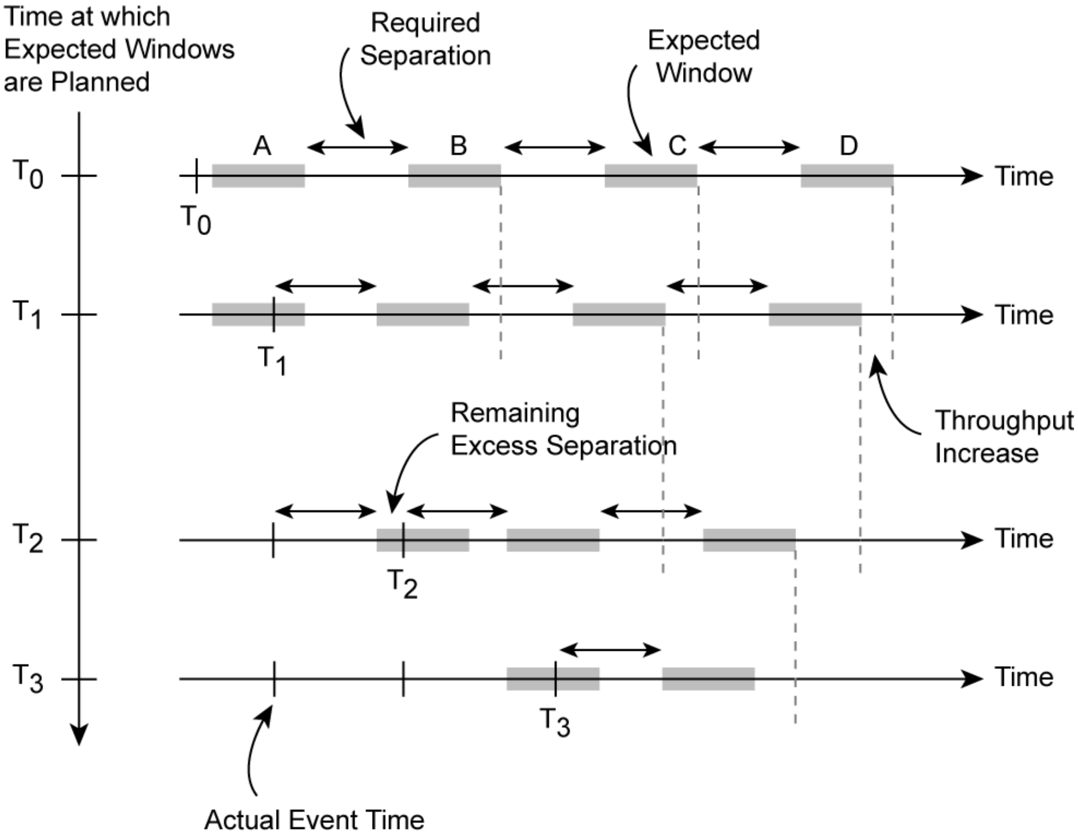

Figure 5. Throughput Benefit of Re-Planning Based on Actual Events in Absence of a Freeze Horizon

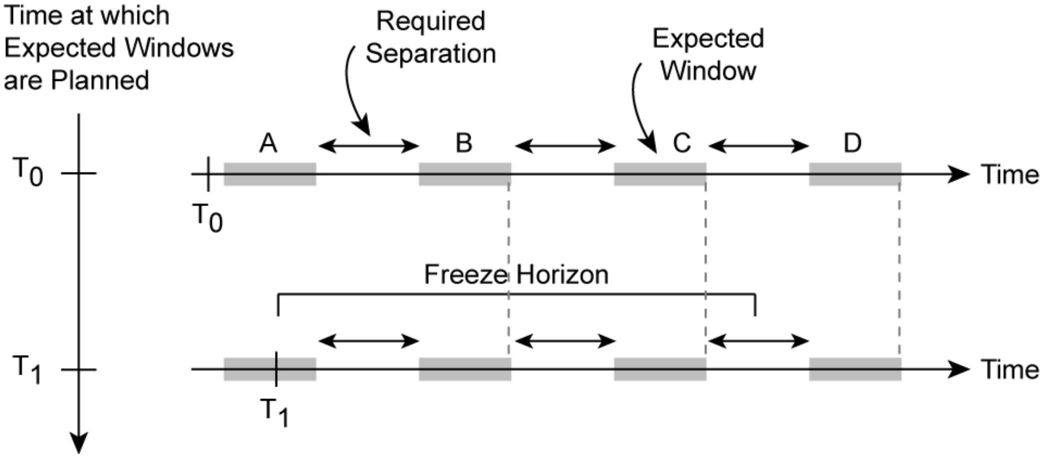

Figure 6. Freeze Horizon Prevents Re-planning in Response to Actual Event Times

In the surface planning problem, there may be a freeze horizon associated with setting the planned window in coordination with other planning systems, while the expected window (that describes the possible actual event times relative to a planned time) may be small relative to the planned window and be allowed to move within the planned window, as depicted in Fig. 7. In some cases, there may be a separate freeze horizon that restricts when the planned time may be moved within the planned window, or there may be a constraint on how far the planned time may be moved as a function of how far into the future the change is being made.

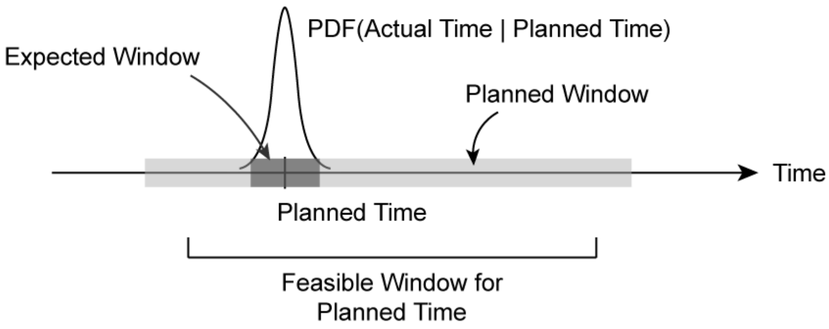

Figure 7. Re-planning Event Within Coordinated Planned Window

This situation (shown in Fig. 8) is a combination of the situations shown in Fig. 5 and Fig. 6. Within the freeze horizon, planned times (i.e., expected windows) may be adjusted within the limits of the frozen planned windows. Outside the freeze horizon, both the expected windows and the planned windows may be adjusted. Exceptions must be handled outside the freeze horizon. A simple example in the current NAS is the management of departures to comply with Expected Departure Clearance Time (EDCT) takeoff time restrictions. A flight assigned an EDCT is required to takeoff within a 10-minute window centered on the EDCT; this would be the planned window. Air traffic controllers at the airport may freely control the flight's sequence relative to other flights and takeoff time within the planned window. A flight's EDCT may be changed but doing so requires coordination. The freeze horizon in this example is not a fixed number of minutes but the amount of time needed to complete the required steps.

The first row of Fig. 8 shows an a priori plan at time T_0 for five events at a resource. Each event has a planned window as well as an expected window, within the planned window, defined by the planned time and the uncertainty. Required separation between the events is applied between the expected windows. The second and third rows in the figure each show the actual time at which the next event occurs and how the plan for subsequent events may be changed. When event A occurs at time T_1, the planned windows for events B and C are within the freeze horizon. However, the expected windows for these events may be moved within the frozen planned windows. The expected window for event B is shifted left to maintain the required separation between the actual event A time and the event B expected window, for example. The planned windows and expected windows for events D and E are shifted left in response to the change to the expected window for event C. Note that the planned window limits how much the expected window may be moved within the freeze horizon, reducing the possible benefit of being able to re-plan. The resulting resource throughput is between the limiting cases shown in Fig. 5 and Fig. 6.

Uncertainty may not decrease uniformly as the planning horizon decreases. For example, the uncertainty in when an arrival will land may decrease continuously as the aircraft approaches the runway. This allows consecutive arrivals to a runway to continuously adjust their arrival times by maintaining proper relative spacing and thereby efficiently use the runway. In contrast, the uncertainty in when a departure will take off may decrease at specific points in time or possibly not until the aircraft begins its takeoff roll. Consequently, mixed arrivals and departures on a runway require the planned arrival times to consider the departure time uncertainty in advance, since by the time the actual takeoff time of a leading departure is known, a following arrival will not be able to adjust its arrival time by more than possibly a few seconds.

Multiple uncertainties combine, increasing not only the total uncertainty but also making understanding how uncertainty and design requirements affect efficiency more complex. For example, if gate departure time and taxi time are random numbers, and takeoff time equals gate departure time plus taxi time, then takeoff time is also a random number. The expected takeoff time equals the sum of the expected gate departure time and the expected taxi time; gate departure time and taxi time may be, but are not required to be, independent random numbers.

However, the uncertainty in the takeoff time will be larger than the gate departure time and taxi time uncertainties. Although the variance of takeoff time equals the sum of the variances of gate departure time and taxi time when gate departure time and taxi time are at least linearly independent, in general the variance of takeoff time requires a convolution of the probability density functions describing the random processes from which gate departure time and taxi time are sampled. The ability to frequently re-plan helps reduce the compounding of uncertainties.

Future work will apply these general concepts to specific surface planning operational concepts and algorithms. Designing the details for NextGen airport traffic management will require understanding both the amount of control available – e.g., how much can an arrival's landing time be varied at various amounts of time before landing – and the amount of uncertainty – e.g., how much variability will exist in the actual time at which a departure begins its takeoff roll relative to a planned time. The remainder of this paper begins to examine the variability in surface operations that must be accommodated by NextGen surface traffic management.

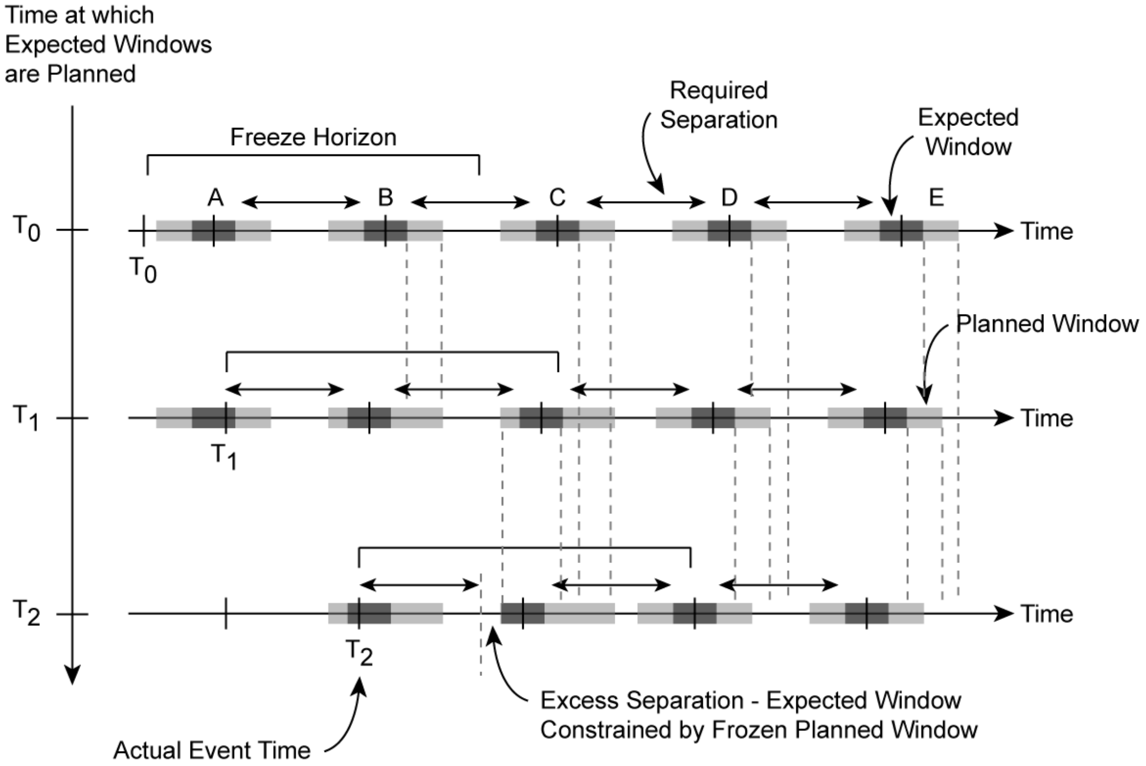

Figure 8. Re-planning Event Times and Planned Windows in the Presence of a Freeze Horizon

III. Quantification of Current Surface Operations Variability

Many aspects of surface operations exhibit variability that may affect optimal planning of surface operations. A few examples include arrival runway occupancy time, departure runway occupancy time after a takeoff clearance is provided, the taxiway used to exit the arrival runway, how long an aircraft takes to cross an active runway, the taxi time between two points, and the actual block out time relative to the scheduled block out time. Some aspects of surface operations that currently exhibit variability, such as the taxi time between points on the surface, may be controlled in the NextGen environment. However, 4DST planning algorithms will need to know the range of feasible values. Other aspects of surface operations, such as the departure runway occupancy time after the departure clearance is issued, will not be controllable. Understanding the characteristics of the variability is critical to designing planning algorithms that are robust to this uncertainty.

The Surface Operations Data Analysis and Adaptation (SODAA) tool, previously developed by Mosaic ATM, Inc., was used to study variability in current surface operations.[4 – 6] SODAA ingests raw airport surveillance data (e.g., from ASDE-X or ADS-B) and/or log files from the Surface Management System (SMS)[7] into a database and calculates a variety of derived data of interest to airportal researchers, such as runway occupancy time and taxi route used. The SODAA client application provides easy tools for understanding the patterns that exist in airport operations. Through a graphical user interface, researchers may use query templates to define database queries without needing to know a database programming language. Query results may be graphed, plotted on a map of the airport, displayed in tabular format, or exported to file for further manipulation in other applications.

This section presents an introduction into the variability observed in current surface operations, specifically runway occupancy time, taxi time around a corner, time between the arrival runway threshold and reaching an runway crossing, runway crossing time, and taxi path. These analyses were conducted using SODAA.

A. Runway Occupancy Time

A primary uncertainty in surface operations is how long each aircraft will occupy the runway. Figure 9 shows the runway occupancy and taxiway exits used by 226 arrivals to runway 18R at Dallas-Fort Worth International Airport (DFW) on February 22, 2007. Plotting the aircraft tracks on the airport surface map suggests that the runway exit used will significantly affect the runway occupancy time. Table 1 shows the number of arrivals that exited the runway at each taxiway, along with the mean and standard deviation of the runway occupancy times for the flights that used that exit. Runway occupancy times are measured as the time between crossing the runway threshold and exiting the runway. In this analysis, altitude data was not used to determine the point along the runway at which the wheels touched down. As expected, aircraft that exited farther from the runway threshold have, on average, longer runway occupancy times. Also expected, aircraft that exit on high-speed exits (e.g., E3, E6) have shorter runway occupancy times than aircraft that exit on a taxiway perpendicular to the runway (e.g., WK, WL). Not expected is the noticeably larger runway occupancy time for flights turning right (West) than those turning left (East) on the same perpendicular crossing taxiway (e.g., WK, WL), although data sample size is smaller for those runway exits. Although the air traffic controller may request the flight use a particular runway exit, procedures allow the pilot to select the runway exit. The landing clearance includes a clearance to exit the runway and hold short of the next taxiway intersection. Other taxiing aircraft will not be blocking taxiway exits and are not believed to influence runway occupancy time.

Taxiway Exit	Count	Mean (seconds)	Std. Dev. (seconds)	Minimum Value (seconds)	Maximum Value (seconds)
WK East	42	42.9	3.7	35	51
WK West	2	52.0	8.5	46	58
E3	53	40.5	5.7	33	64
E4	78	47.2	4.1	40	58
WL East	3	58.7	6.1	52	64
WL West	4	68.0	16.0	55	89
E6	35	54.5	3.5	49	64
WM East	0				
WM West	0				
E7	9	66.9	7.4	60	82
All Flights	226	47.3	8.4	33	89

Table 1. DFW Runway 18R Arrival Runway Occupancy Times

Overall, arrival runway occupancy times vary substantially, even within flights using the same runway exit. This pattern was also observed in data for other airports and runways. Five days of arrivals at Louisville International Airport (SDF) were also studied. Figure 10 shows the exits used from runway 35L. Table 2 lists the runway exit and occupancy statistics for arrivals to this runway. The trends – exits farther from the runway threshold have longer average runway occupancy times and the sharper the turn off the runway the longer the average runway occupancy time – are consistent with the DFW observations. Currently, controllers may request aircraft use a particular runway exit, but the runway exit choice is at the pilot's discretion. By pre-planning the runway exit, a NextGen surface traffic management concept could noticeably reduce the runway occupancy variability. However, some variability will remain.

The minimum runway occupancy time for a flight that exited at taxiway G was 58 seconds; the maximum was 120 seconds. This variability presents a substantial challenge for a NextGen planning system that plans subsequent uses of the runway, motivating research into controlling runway occupancy time, simultaneous runway use, and runway occupancy time prediction. Observations were not consistent with an initial hypothesis that heavy aircraft would have longer runway occupancy times and use exits farther from the runway threshold. Aircraft type was not a good predictor of runway exit used. Exit G had the highest percentage of non-heavy aircraft, which may have been related to the location of the aircraft parking gates. The passenger terminal is located North of runway 11; almost no heavy jets park at the passenger terminal. The United Parcel Service ramps, where the heavy jets park, are located South of runway 11.

Taxiway Exit	Count	Mean (seconds)	Std. Dev. (seconds)	Minimum Value (seconds)	Maximum Value (seconds)
B7	3	84.3	4.5	80	89
G	89	76.3	11.9	58	120
F	20	68.9	6.4	58	80
B6	119	49.2	8.0	40	63
B5	85	44.4	9.1	26	60

Table 2. SDF Runway 35L Arrival Runway Occupancy Times

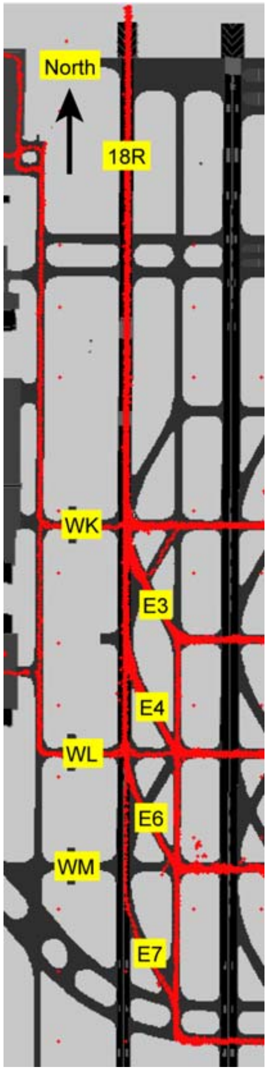

Figure 9. Runway Exits Used by Arrivals to Runway 18R at Dallas-Fort Worth International Airport (DFW)

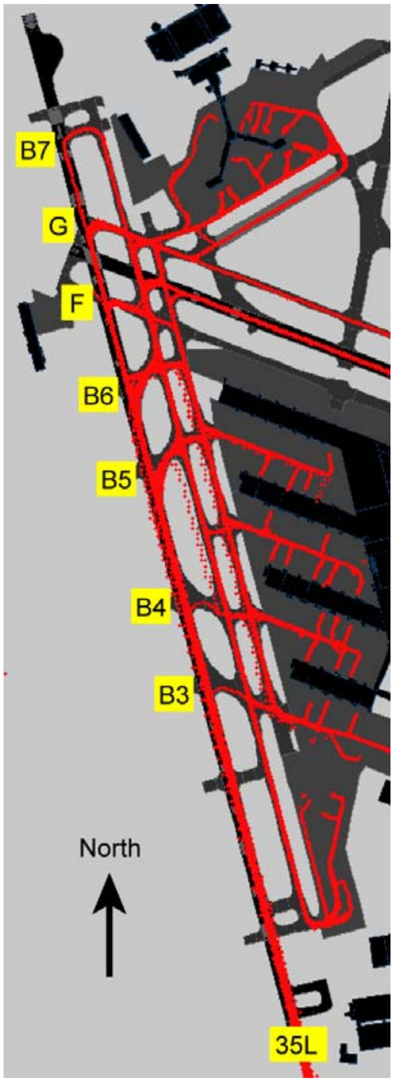

Figure 10. SDF Runway 35L Exits

B. Taxi Time Around Corner

Within the concept of 4DSTs in NextGen, whether taxi trajectories will be defined continuously in four-dimensions or by specifying required times (or windows) at specific points on the airport surface has not yet been determined. The planned 4DSTs must be feasible and efficient. Large variability in taxi times creates risk that a planned taxi trajectory will either be infeasible or inefficient. A short planned taxi time for a flight whose actual taxi time is long would result in an exception and possibly disrupt subsequent portions of the surface plan. Planning a long taxi time for every flight would cause many flights to incur longer than necessary taxi times – delay. Current variability in taxi time along a common path segment may be an upper-bound on pilots' ability to comply with 4DSTs.

Figure 11 shows the taxi paths of aircraft that landed on runway 13R at DFW airport. The time required for aircraft to taxi around the corner from taxiway B onto taxiway C was studied. Figure 12 is a histogram of the taxi time of 42 flights around this corner. The taxi time for this short distance exhibits remarkable variability, ranging from 23 seconds to 43 seconds (mean 30 seconds; standard deviation 5.2 seconds). The location of this corner makes the presence of other surface traffic an unlikely cause of the variability; the weather and visibility was constant throughout the data sample. Possible factors to which taxi time is correlated include aircraft type and airline. Further research is required to understand the fundamental cause of this variability, whether the taxi time could be controlled in a 4D concept, and the implication for NextGen surface traffic management.

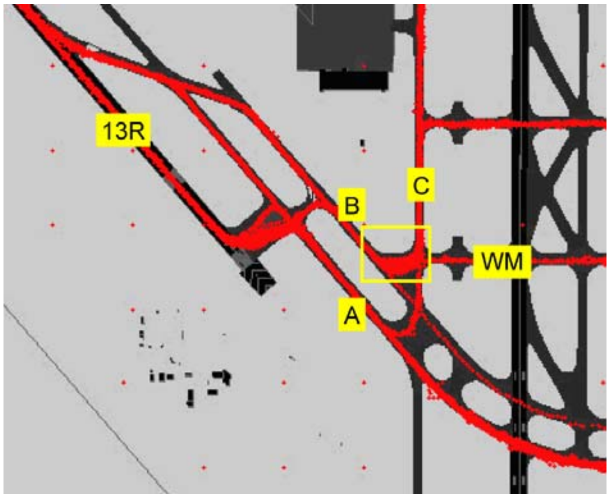

Figure 11. Surface Tracks Exiting DFW Runway 13R

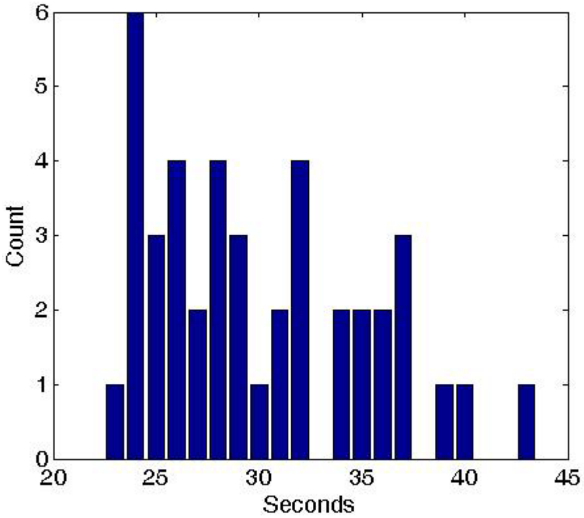

Figure 12. Taxi Time Around Corner from Taxiway B to Taxiway C

Although variability in taxi time along this taxiway segment may not disrupt an overall surface plan, variations in taxi time through an intersection being shared by crossing traffic could disrupt a surface plan. Future analysis will study taxi time to and through an intersection and sequence at a crossing intersection. Ways to improve robustness to taxi time variability, such as minimizing crossing traffic and allowing revisions to the planned sequence in which flights use an intersection based on updated measurements of aircraft progress toward the intersection should be considered in taxi planning systems.

C. Time To Reach Runway Crossing

Uncertainty accumulates over longer prediction horizons. This section studies the combination of runway occupancy time and taxi time along a path. Large variability is exhibited in the time between arrival aircraft crossing the threshold of runway 17L and reaching the intersection with runway 17C on taxiway ER. Figure 13 plots track data for arrivals to runway 17L at DFW.[††] Figure 14 shows the total time (for a sample of 60 aircraft)

[††] Errors in the position measurements of aircraft on taxiway ER just East of 17C illustrate the common phenomena that the position measurement noise increases for stopped or slowly moving aircraft.

between crossing the runway threshold and reaching the intersection at 17C via taxiway ER. The mean time is 240 seconds; the standard deviation is 73 seconds.

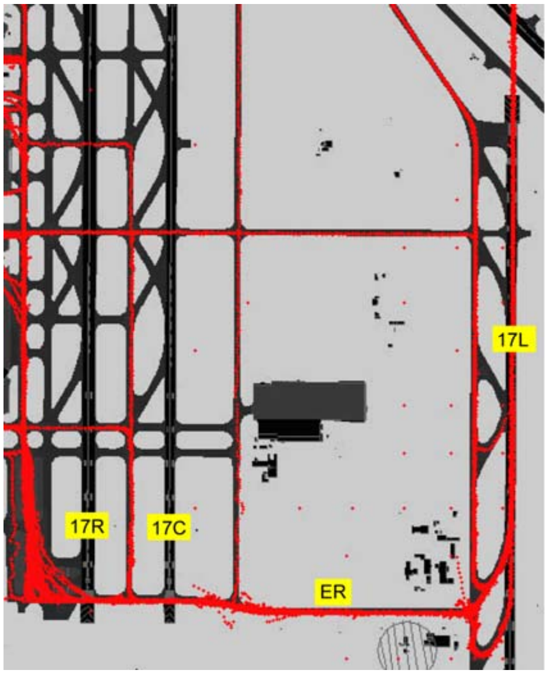

Figure 13. Taxi Paths for Arrivals to DFW Runway 17L

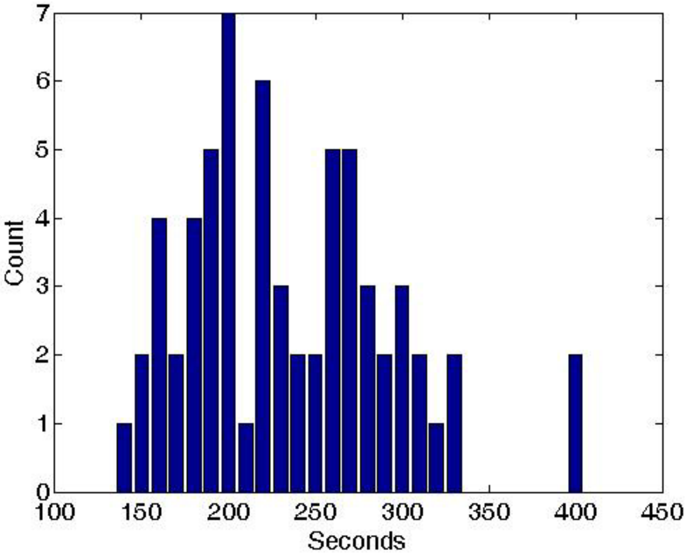

Figure 14. Variation in Time between Arrivals Crossing DFW Runway 17L Threshold and Reaching the Intersection with Runway 17C Via Taxiway ER

One of the objectives of NextGen surface traffic management is to minimize delays crossing active runways and minimize the number of times an aircraft must stop while taxiing only to subsequently start again, which is costly in terms of fuel burn and environmental impact compared to continuous taxi.[8] The results from this study show large variability – excluding outliers almost 3 minutes between the shortest and longest times – and suggest that precise timing of runway crossing may not be possible very far in advance (i.e., at or before crossing the runway threshold). Other taxi traffic is not likely to be an underlying cause of this variability, based on knowledge of the airport operations. Time spent in the queue to cross runway 17C was not included in Fig. 14. Additional research is needed to understand where and why this variability occurs. For example, a flight might be held if its parking gate is not available, while other variability may be correlated to aircraft type.

Planning the pair of aircraft in the runway 17C schedule between which the runway 17L arrival may cross runway 17C may need to wait until after the runway 17L arrival has landed and is closer to the runway crossing. These results suggest a hypothesis that planning active runway crossings should not be done until the aircraft is much closer to the runway to be crossed. As a result, systems providing taxi guidance to pilots must allow for changes to the taxi trajectory at shorter times into the future and pilots must be capable of accepting partial taxi trajectories that may be updated.

In addition, outliers may need to be accommodated through exception handling. Surface traffic management concepts and algorithms must be designed to handle outlier as well as nominal cases.

D. Runway Crossing

Figure 15 shows taxiway ER between runways 35C/17C and 35L/17R. Arrivals to runway 17C exit the runway and use other taxiways to cross runway 35L/17R. Many arrivals to 17L use taxiway ER to cross 35C/17C and then 35L/17R. The amount of time flights spent on ER between 35C and 35L is shown in Fig. 16 (for 64 aircraft), along with the taxi speed profile for each flight. The taxiway occupancy time (left half of Fig. 16) varies substantially, depending on the time waiting to cross 35L. The phenomena of queuing to cross runway 35L is illustrated in the aircraft speeds, shown in the right half of Fig. 16. The taxi speed crossing 35C varies from about 15 knots to about 35 knots, as seen on the left half of the graph. For many aircraft the speed then drops to zero, representing the aircraft is stopped, waiting to cross 35L or waiting behind other aircraft waiting to cross 35L. Noise in the surveillance data results in non-zero speed values for stationary aircraft. Close examination of the speed data shows incremental movement along the taxiway when queued behind other aircraft. The speed increases as the aircraft accelerates to cross the runway.

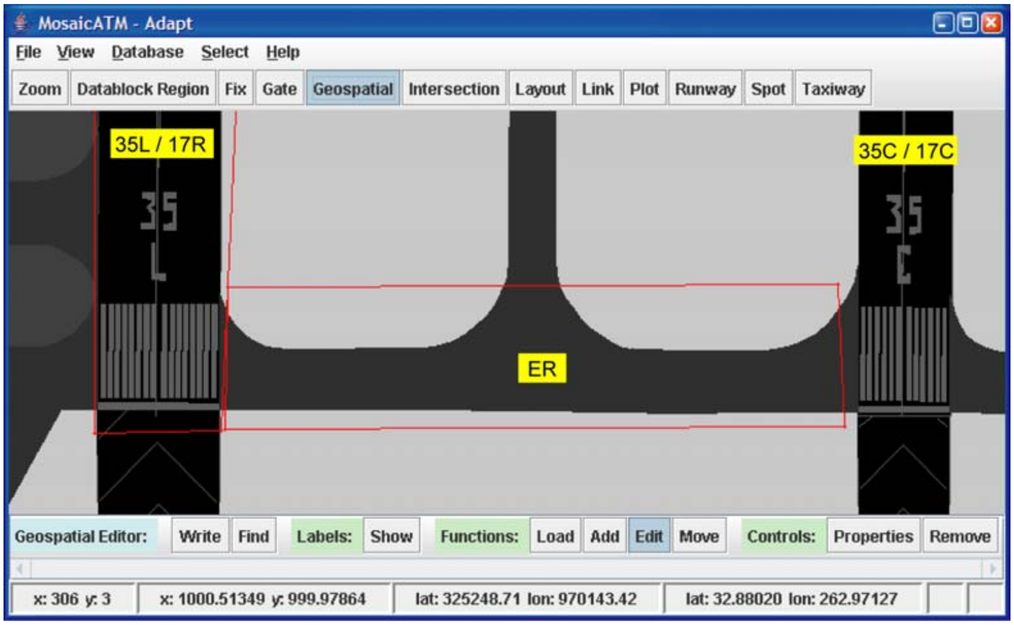

Figure 15. Taxiway ER Between Runways 35C/17C and 35L/17R at DFW

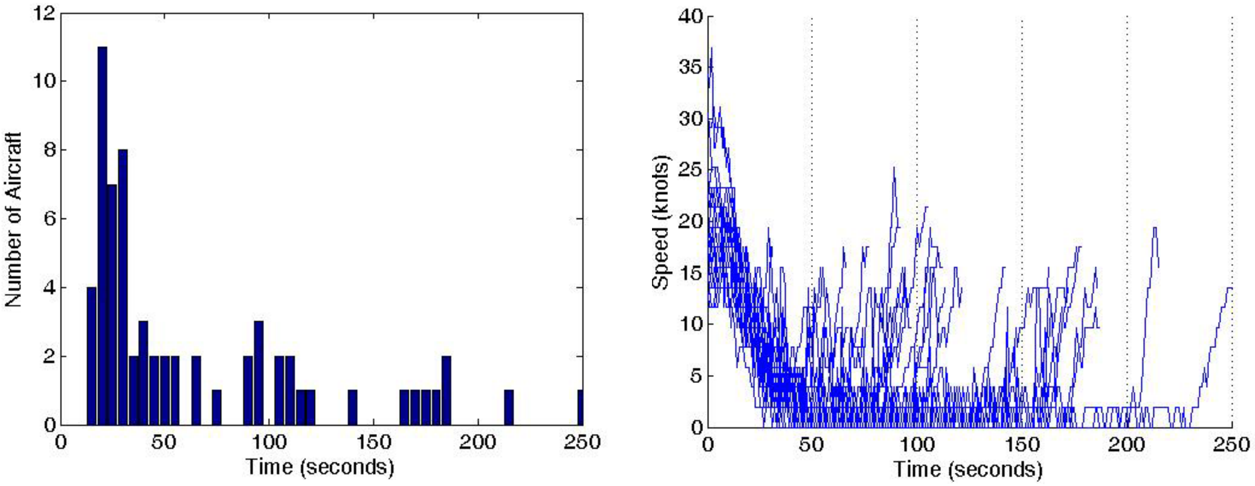

Figure 16. DFW Taxiway ER Occupancy Time Between Runways 35C/17C and 35L/17R (left) and the Speed Profile for Each Aircraft (right)

Figure 17 presents a histogram of the runway occupancy times for aircraft crossing runway 35L, in the left half of the figure, and the aircraft speed profiles while crossing the runway in the right half of the figure. The red line in the right half of Fig. 17 highlights one flight as an example. The occupancy time in the sample exhibits only about a 7 second range between the shortest and longest times and depends on the aircraft speed. The speeds crossing runway 35L vary from 10 knots to 35 knots; this was also seen in the speed crossing runway 35C in Fig. 16. Additional research on the dependence of crossing time on aircraft type and pilot procedures is warranted to understand whether NextGen concepts could result in more consistent crossing speeds and occupancy times. Additional research on the delay between a clearance being issued and the aircraft entering the runway is also needed.

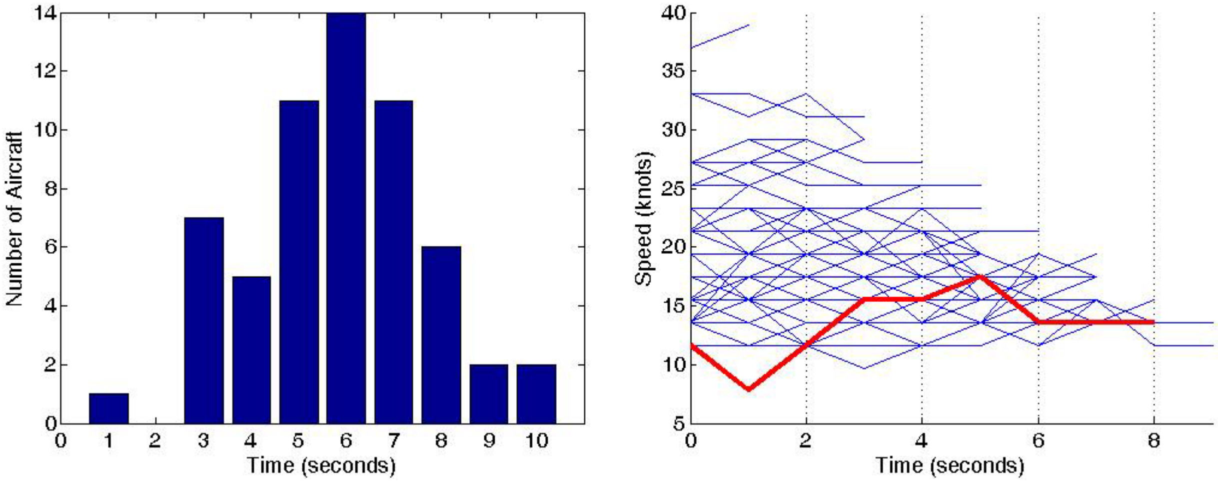

Figure 17. DFW Runway 35L Occupancy Time by Aircraft Crossing at Taxiway ER (left) and the Speed Profile for Each Aircraft (right)

Aircraft that stop on taxiway ER generally reach a speed of 15 to 20 knots before entering runway 35L. Figure 18 graphs the taxi speed at which flights that stopped on taxiway ER enter runway 35L. Figure 19 plots the speed increase (for all flights that crossed the runway) while crossing runway 35L/17R – the difference between the maximum speed while on the runway and the speed when entering the runway. A total of 75 percent of the flights accelerate less than 2 knots while crossing the runway. Taxi speeds remain nearly constant while occupying the runway and, therefore, the aircraft speed upon entering the runway determines the crossing time. The implication for NextGen surface management concepts may be that to reduce variability in runway occupancy time pilot taxi guidance systems need to advise the speed, and possibly the acceleration, profile at which the aircraft should taxi.

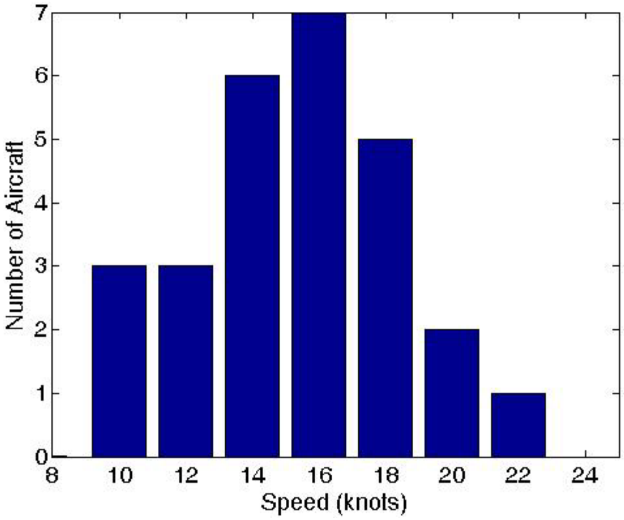

Figure 18. Taxi Speed Entering DFW Runway 35L/17R by Aircraft Crossing the Runway at ER and which Had Stopped on Taxiway ER

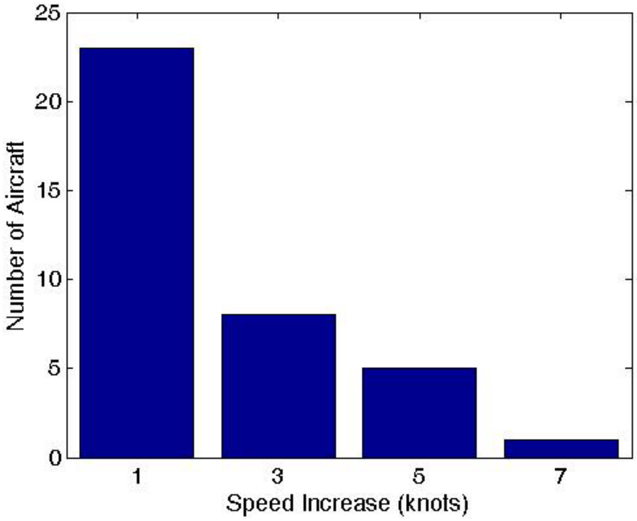

Figure 19. Speed Increase While Crossing DFW Runway 35L/17R at ER

E. Taxi Path

4DST concepts allow for each flight to be given a unique taxi path. However, during transition to the eventual NextGen concept, taxi routes that resemble current practices may be needed. The taxi paths used between two points on the airport surface can depend on a number of variables including the controller issuing the taxi clearances. Figure 20 illustrates that for a 12 hour period of time, all of the departures from the United Parcel Service ramps at

Louisville International Airport used consistent taxi paths – every flight from a particular ramp to a particular runway followed the exact same route. The figure uses a different color for each ramp/runway pair. Consistent taxiways may improve safety through both controller and pilot familiarity. In addition, consistent taxiways and keeping traffic from different runways separate may reduce controller workload by helping controllers remember the call signs for a series of aircraft. In contrast, Fig. 21 shows that arrivals to runway 18R at DFW followed different taxi paths to reach the Terminal A ramp, as well as to cross runway 18L. Inconsistent routing contributes to taxi time variability and surface conflict predictability. The reasons for consistent or variable routings needs to be understood so that surface planning systems produce feasible and acceptable taxi paths.

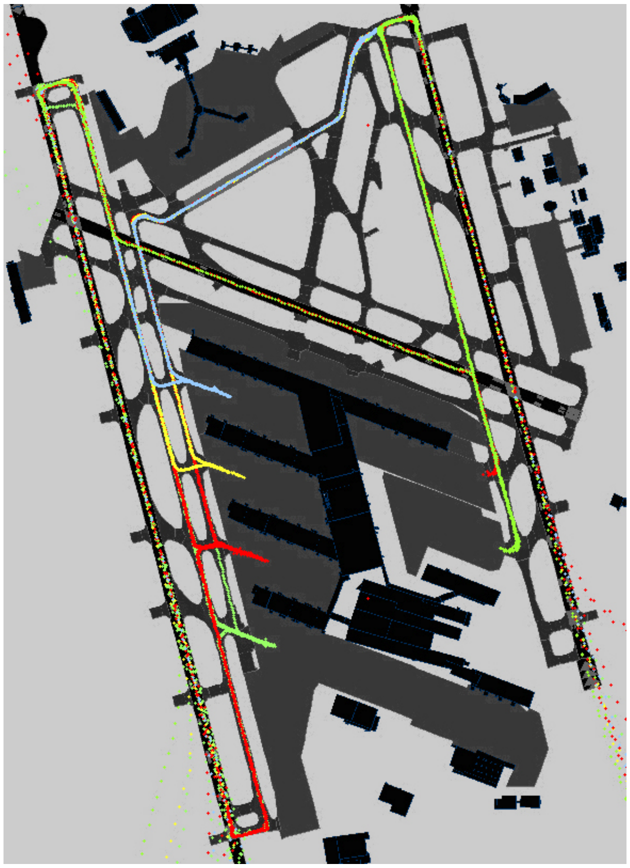

Figure 20. Consistent Taxi Paths at Louisville International Airport

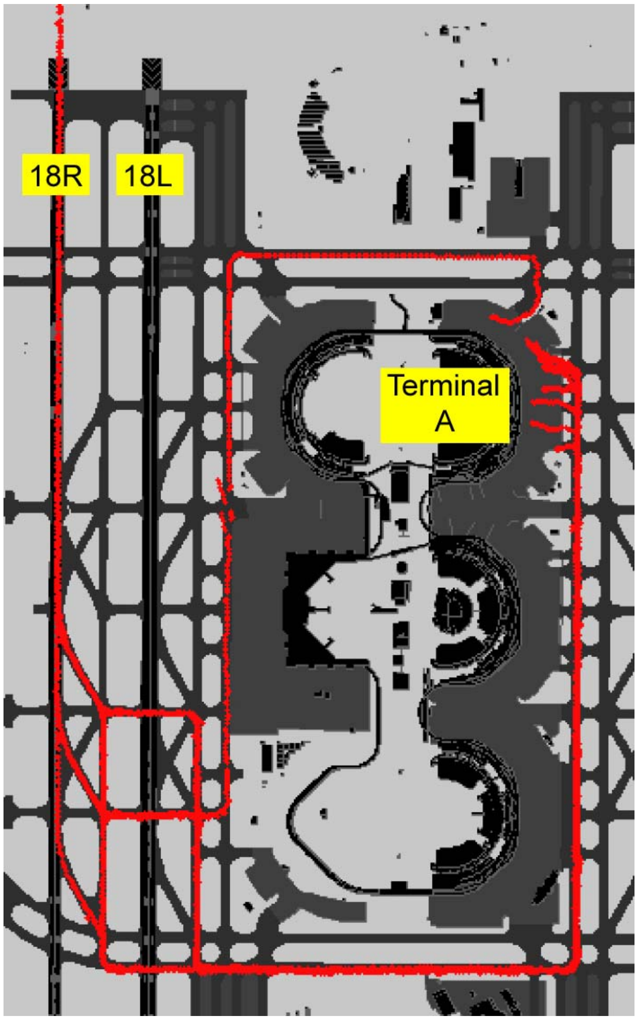

Figure 21. DFW Runway 18R Arrivals Parking at Terminal A

The purpose of these five examples was to illustrate the extent of surface movement variability, which is not widely recognized. Substantial variation between airports and with weather conditions should also be expected. Additional and more focused research is required to establish models of variability that could be used in simulating taxi trajectories and testing 4DST concepts. Some surface movement variability will be controlled through 4DSTs while other variability will appear as compliance errors. The concept of four-dimensional surface trajectories as part of NextGen has received broad acceptance without first completing studies demonstrating the feasibility or benefits of particular approaches. This paper has also shown the relationship between reduced flexibility in 4DSTs relative to current operating procedures and uncertainty in determining airport capacity. Further studies on specific 4DST concepts are needed to add details to the NextGen airport surface concept.

IV. Conclusions and Future Work

Errors in aircraft following a 4DST are anticipated to be greater than those that occur in airborne phases of flight when normalized to account for the smaller separation between aircraft on the airport surface. Consequently, compliance errors will have a larger effect on surface planning systems. However, the variability in surface movement times is poorly understood, in part due to the fact that detailed surveillance of surface operations is only gradually becoming available. This paper began to explore the variations in surface movements and the implications for designing NextGen surface traffic management concepts and algorithms, including how they are integrated with airborne traffic management concepts. Initial results demonstrated the variability currently observed, as a bound on the compliance errors that may be expected in aircraft following 4DSTs, and suggested how surface traffic management concepts might be influenced by the magnitude of variability. For example, the runway occupancy time in a sample of 226 flights using one runway at Dallas-Fort Worth International Airport varied from 33 seconds to 89 seconds. A correlation with the runway exit that was used suggested the need to control or predict the runway exit that would be used. Variation in runway occupancy time for flights that used the same runway motivates additional research to identify the causes of the variations. Significant variability in the taxi time around a corner (42 flights varied between 23 and 43 seconds) and the need for planned taxi trajectories to be feasible and efficient suggested a hypothesis that taxi trajectories should be defined as discrete points and required times at those points, rather than as continuous functions of position and time. However, the taxi trajectories will likely need to be revised frequently. Variation in time to cross an active runway (from 3 seconds to 10 seconds) was shown to result from different speeds entering the runway; aircraft speed tended to not change while crossing the runway. Aircraft that stopped prior to crossing the runway had longer crossing times than aircraft that did not stop.

The paper also generically explored the relationship between uncertainty (or errors in 4DST compliance), re-planning frequency, planning freeze horizon, and aircraft controllability (i.e., how much an aircraft's trajectory may be modified at various amounts of time in the future). This exercise illustrated how uncertainty in when an aircraft will occupy a runway or taxiway intersection relative to a planned time requires excess separation between aircraft using that resource. Moreover, restrictions (such as freeze horizons or required coordination with other planning systems) on modifying the planned resource usage times in reaction to observed events locks in the excess separation. Flexibility similar to current operations must be preserved to maintain capacity in the presence of uncertainty. Interoperability with airborne 4DT planning systems will require longer planned windows for coordinated events (e.g., takeoff) where the surface planning system may re-plan frequently, moving scheduled times within those frozen windows. Future work will apply these abstract relationships between design parameters to concrete examples of surface planning concepts.

Future research will study in greater detail the causes of variation in surface operations to help understand whether these variations will persist in NextGen concepts or may be controlled as part of those future surface traffic management concepts. For example, the reasons why the taxi times along a taxiway segment are different for aircraft will be examined thoroughly. Furthermore, the design of NextGen surface traffic management systems will likely require focused studies to characterize the variations in particular types of surface movements. Therefore, another area of future work will be to collaborate with the designers of NextGen surface concepts to identify what aspects of surface movements need to be understood in more detail.

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