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Kinematic Airport Surface Trajectory Model Development

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Airport surface trajectory models are a key component of current airport surface decision support tools as well as future surface traffic research concepts such as optimized taxi scheduling. These automation tools and concepts, however, commonly use constant speed based airport surface trajectory models even though aircraft do not taxi at a constant speed. This paper describes the development of an empirical kinematic airport surface trajectory model that was derived from the study of actual taxiing speed and acceleration characteristics on specific segments of a taxi route, such as straights and turns. A limited validation study showed this empirical surface trajectory model predicted unimpeded taxi times an average of only 9 percent earlier than the actual mean while modeling speed and acceleration variations observed in actual surface traffic movement. This was approximately 30 percent better than the constant speed based surface trajectory model to which it was compared.

I. Introduction

AIRPORT surface operations have been identified as one of the limiting factors in expanding National Airspace System (NAS) capacity. Airports have relied on human controllers to make complex decisions regarding surface operations with limited assistance from automation. Recent airport surface operations research has emphasized the development of automated scheduling tools and concepts as a means of increasing airport surface capacity and efficiency.[1,2] Although surface automation tools and concepts vary, surface trajectory models are a key component for them all. An example of surface trajectory based automation is the Surface Management System (SMS). SMS is a decision support tool for airport surface scheduling and management that has been successfully used to improve efficiency of surface operation.[3,4] SMS utilizes a surface trajectory model based on constant speed and instantaneous acceleration to calculate taxi times to a specific airport resource such as a departure runway. These taxi times are used to predict the schedule and sequence of aircraft arriving at the runway. Controllers would use these predictions to assist them in managing demand for airport resources. More advanced surface research concepts, such as taxi scheduling optimization, use constant speed trajectory models to not only establish the initial schedule and sequence of aircraft at a runway, for example, but also to a number of taxiway intersections along the route. The initial constant speed based schedules and sequences serve as the basis to which the optimization algorithms are applied.[5,6]

Surface trajectory models have also been implemented into airport surface simulation tools. The Surface Traffic Limitations Enhancement (STLE) model developed for the Airspace Concept Evaluation System (ACES) simulation is a fast time airport surface simulation that can be used to evaluate the impact of future surface traffic concepts on the NAS. In this case, surface traffic movement is simulated with a surface trajectory model based on constant taxi speed and instantaneous acceleration.[7] However, intuition as well as actual surface traffic data to be presented subsequently will show aircraft do not taxi at constant speed. Inaccurate modeling of surface movement may result in errors in the scheduling and sequencing of aircraft at a specified location and, therefore, adversely affect optimization or simulation results. Higher fidelity airport surface simulations such as the Airspace Target Generator (ATG) model surface movement more realistically with the incorporation of acceleration, and specific straight and turn speeds in their trajectory models, but have not been rigorously validated against real surface traffic data.[8]

Since airport surface concepts and surface simulation tools intended to evaluate them are dependent on scheduling and sequencing predictions derived from surface trajectory models, an opportunity exist to improve their performance by modeling surface trajectories more realistically. There has been research to better understand uncertainties associated with predicting airport surface movement.[9] However, many of these uncertainties are related to unexpected operational factors (i.e., congestion) which cause aircraft to vary from their predicted

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trajectories. That study identifies the need for frequent trajectory updates in order to adapt to errors associated with varying conditions instead of improving accuracy of a given trajectory prediction. The objective of this study is to improve surface trajectory prediction accuracy by developing an empirical kinematic surface trajectory model that is more realistic than the commonly used constant speed model and validate its accuracy.

The paper is organized into three sections that describe the effort to develop and validate an empirical kinematic surface trajectory model. The first section discusses the methodology used to analyze surface movement data from thousands of actual aircraft for speed and acceleration characteristics along different types of segments of a taxi route such as straights and turns. The second section describes the application of the empirical kinematic surface trajectory model derived from the taxiing characteristics discovered in the previous section. The third section shows validation results for several empirical surface trajectory model predictions and compares them to trajectory predictions from a constant speed model used in a fast time airport surface simulation.

II. Methodology for Characterizing Surface Traffic Movement

Due to the variability in taxiing behavior of actual aircraft, it was necessary to develop a methodology to analyze a large number of data samples in order to effectively characterize surface traffic movement. It is generally accepted that the taxi speed of an aircraft varies depending on whether the aircraft is on a straightaway or a turn. This characteristic was studied in more detail with the intention of finding additional relationships beyond simply a straight or turn speed. This method of analysis was developed to efficiently identify straight, turn, and stop segments in the track data of a large number of aircraft and to function with basic parameters derived from surface position data (e.g., speed, heading). In this study, the analysis of taxiway movement was limited to the area between the ramp area and the runways. Movement to and from the gates through the ramp area, and takeoff and landing of aircraft on the runways were not studied.

The characterization of surface traffic movement was accomplished with a two step method. In the first step, raw surface traffic data for thousands of individual aircraft were processed and key segments of their taxi routes (e.g, straights, turns) were extracted for further analysis. Key segment data from all aircraft were then separated by type and each taxi route segment type characterized as an aggregate in step two. Distinctions between taxiing characteristics of arrival and departure aircraft were made as needed. Two days of traffic data were used for this characterization, May 2, 2008, when Dallas/Fort Worth Airport (DFW) was operating primarily in the north flow runway configuration, and May 5, 2008, primarily south flow runway operations. It should be noted rain was reported in the area during a one hour period on May 5, 2008. The use of data with potential weather effects was inadvertent. However, a cursory analysis showed the data not to be biased by the rain event. Although this study analyzed several aircraft types in detail, the majority of the results presented were focused on MD80 series aircraft, the most common aircraft type at DFW.

A. Raw Surface Traffic Data Processing

Surface traffic data were initially processed with the Surface Operations Data Analysis and Adaptation tool (SODAA).[10] SODAA stores aircraft
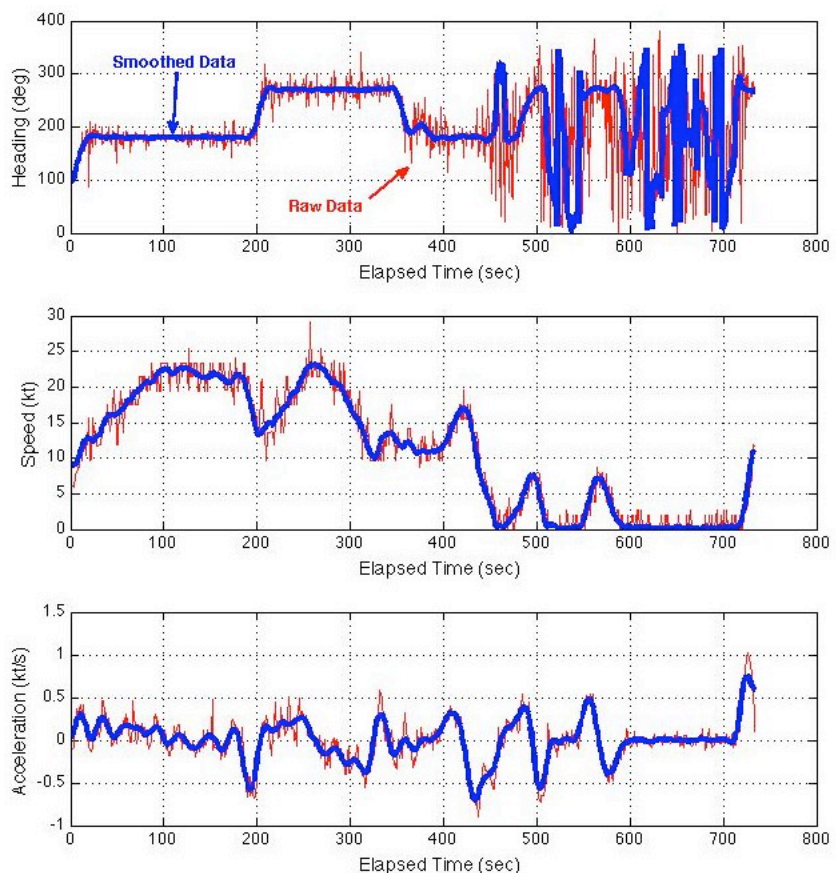

Figure 1. Raw Airport Surface Data Processing – MD80 Departure

position and airport configuration (i.e., adaptation) data in a database. In addition, SODAA uses these data to derive additional data elements such as spot used and runway entry time. The source surveillance data, Airport Surface Detection Equipment – Model X (ASDE-X), were noisy and required additional smoothing in order for it to be effectively analyzed. Version 1.9 of SODAA used for this analysis did not provide the necessary smoothing capability. Therefore, simple smoothing techniques were developed and applied using Matlab. A moving, cubic spline curve fit was applied to the raw position data. The moving data window was made up of fifteen data points (i.e., 15 seconds) forward and fifteen points aft of the data point to be fitted. The raw data within the window were fitted with a cubic spline. The resulting curve fit was then used to calculate a new value for the data point of interest. The data window was then moved to the next raw data point and the fitting process was repeated. After all the position data were fitted, path distance, speed, acceleration, as well as heading were calculated. Additional smoothing was applied, as appropriate, to each of the derived parameters using a moving average technique. Figure 1 shows an example of the results of the smoothing for a MD80 departure. The raw data are represented by the thin red line while the smoothed data are shown with the bold blue line. Note the values for heading were erratic while the aircraft was stopped because of the noise in the position data from which the heading values were derived. In addition, the smoothing technique applied in this analysis could be improved to better handle fluctuations between heading values near zero and 360 degrees while the aircraft was stopped.

Once the raw surface data were smoothed, key segments in each aircraft's taxi route were identified. Straight taxi segments were identified by analyzing the smoothed heading data for segments with at least ten consecutive data points with a heading difference of no more than five degrees. The straight segments identified for the sample MD80 departure are highlighted by a wide green line in Fig. 2. Mean speed, path distance, and other metrics were then calculated for each straight segment.

Turn segment identification in this analysis was dependent on the straight segments indentified earlier.

Figure 2. Straight and Turn Segment Identification– MD80 Departure

Only turns connecting two known straights were analyzed. The method for turn identification compared the heading at the end of a known straight segment to the heading at the start of a subsequent straight. The minimum heading difference was set to 30 degrees and the maximum turn distance (i.e., distance between the two straights) was limited to 1000 feet in order to minimize false turn segment identification. For the example shown in Fig. 2, the first straight (elapsed time 19-194 sec.) ends with a heading of about 180 degrees while the subsequent straight (elapsed time 210-349 sec.) starts with a heading of about 270 degrees. In addition, the distance between these two straights was 371 feet, calculated in the analysis but not shown here. Turn segments are pointed out and highlighted in magenta on the example in Fig. 2. This method was able to identify the majority of the turn segments successfully. However, poor quality data prevented some turns from being identified. This occurs in the example shown in Fig. 2 between elapsed times 470 and 508 seconds. In this case, erratic heading data prevented the identification of the turn.

Stop segments were identified by analyzing the smoothed speed data for at least ten consecutive points with a maximum speed of no more than one knot. Due to the noise in the data, identification of stop segments using a maximum speed threshold of less than one knot proved to be inconsistent. Three stop segments identified for the example MD80 departure are highlighted in red in Fig. 3.
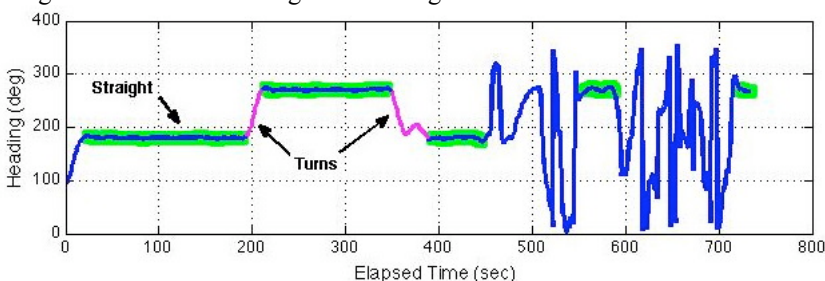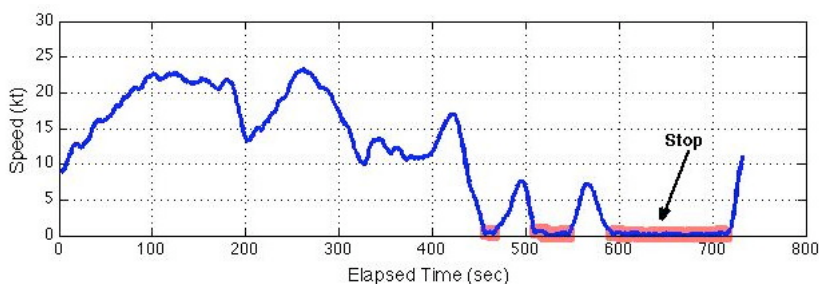

Figure 3. Stop Segment Identification– MD80 Departure

B. Characterizing Taxi Route Segments

Taxi route segments extracted from the individual aircraft surface tracks with the method described in the previous section are analyzed in this section. All taxi route segments were categorized by type (e.g., straight, turn)

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and then analyzed in an aggregate manner for characteristics that could contribute to the development of a surface trajectory model. Taxiing aircraft often have to stop for operational reasons such as avoiding other surface traffic. These operational factors cannot be predicted solely with a trajectory model. In order to minimize the influence of operational factors inherent to actual surface traffic data being used to develop the trajectory model, it was necessary to distinguish those aircraft that taxi without stopping, referred to as unimpeded herein. Depending on the type of segment being analyzed, only data from unimpeded aircraft were used for the characterization.

1. Straight Taxiways

MD80 departures from the two-day DFW data set described above consisted of a total of 489 aircraft, 162 of which taxied unimpeded. Only the unimpeded departures were used in the analysis of straight taxiway segments resulting in a total of 610 straight segments. The analysis revealed a relationship between the mean taxiing speed and the length of the straight segment. Figure 4 shows the mean speed increasing from approximately 4 knots for the shortest of segments up to 17 knots for the longest straights. These data support the notion aircraft would taxi slower on short connecting taxiways than they would on the longer main taxiways. In addition, these data show a single straight taxiway speed used by the constant speed trajectory models may not adequately model surface movement. Standard deviation of the curve fit was 3.2 knots. The effects of surrounding surface traffic on the speed of the unimpeded departures were not considered and could have possibly contributed to the data scatter.
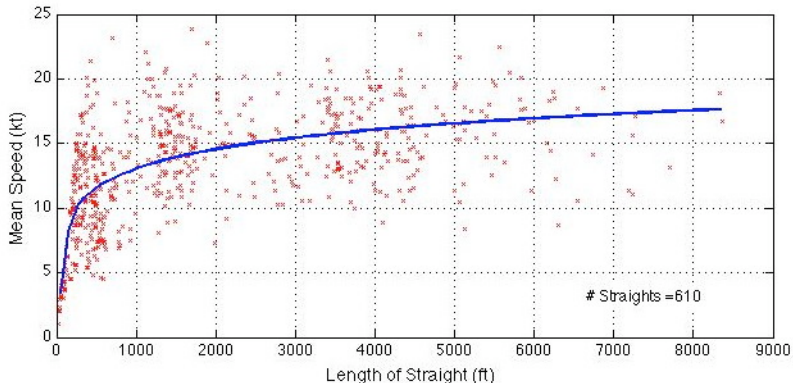

Figure 4. **Mean Straight Taxiway Speed – Unimpeded MD80 Departures**

The mean straight taxiway speed for other departure aircraft types are shown in Fig. 5. With the exception of the CRJ regional jets which were up to 3 knots faster, mean straight taxiway speeds could be considered essentially the same as the MD80 given the level of uncertainty.

Mean straight taxiway speeds for MD80 arrivals were also analyzed. In addition to limiting the analysis to unimpeded arrivals, straight taxiway segments starting at the runway exit were excluded so the data were not biased by high speed arrival runway exits which will be analyzed separately. The two-day DFW data set consisted of a total of 577 MD80 arrivals of which 289 were unimpeded. A comparison of mean straight taxiway speed of MD80 arrivals and departures is shown in Fig. 6. Arrival aircraft taxied up to three knots faster than the departures. Standard deviation of the arrival curve fit was 4.2 knots.
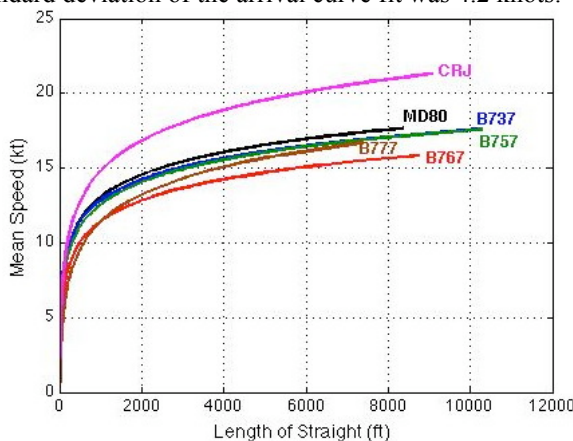

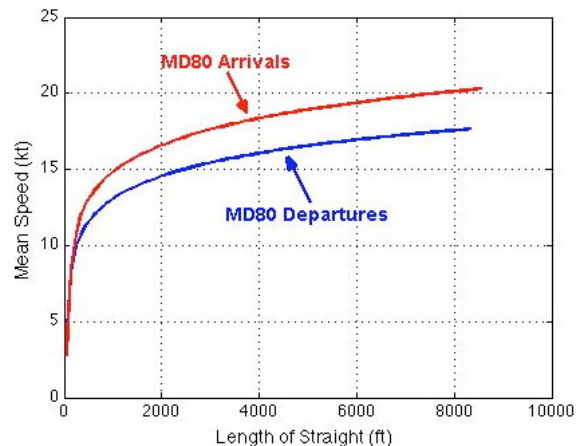**Figure 5. Mean Straight Taxiway Speed – All Unimpeded Departures**

Figure 6. Mean Straight Taxiway Speed – Arrival vs. Departures

2. Turns

Turn segments for unimpeded MD80 departures were analyzed. The 162 unimpeded MD80 departures yielded 277 turn segments for analysis. Figure 7 shows the mean turn speed to be a function of the speed of the aircraft on the straight prior to the turn or "pre-turn" straight. For example, the data show an aircraft taxiing at 20 knots on the pre-turn straight slowed down and negotiated the turn with a mean speed of 14 knots, while an aircraft taxiing at 12 knots only slowed down 2 knots to taxi around the turn at a mean speed of approximately 10 knots. The standard deviation of the curve fit was 2.2 knots. The turn analysis supports the need to model turn speed with more than the one value typically found in constant speed trajectory models. It should be noted that the taxiway configuration at DFW was such that the majority of the turns are 90 degrees. There were a limited number of shallower angled turns to analyze. Initial analysis of the shallower turns showed aircraft did not slow down to negotiate them, however, further study is needed.

Mean turn speed for other departure aircraft types are shown in Fig. 8. These data show turn speeds were similar for other aircraft types. Analysis of turn segments for unimpeded MD80 arrivals showed the same characteristics as the departures, therefore, were not presented.
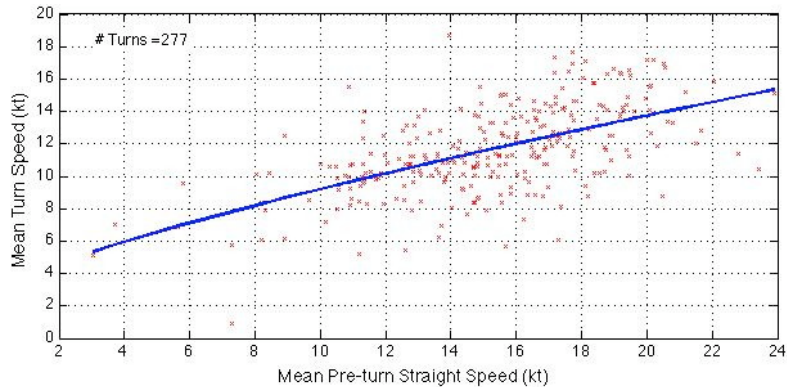
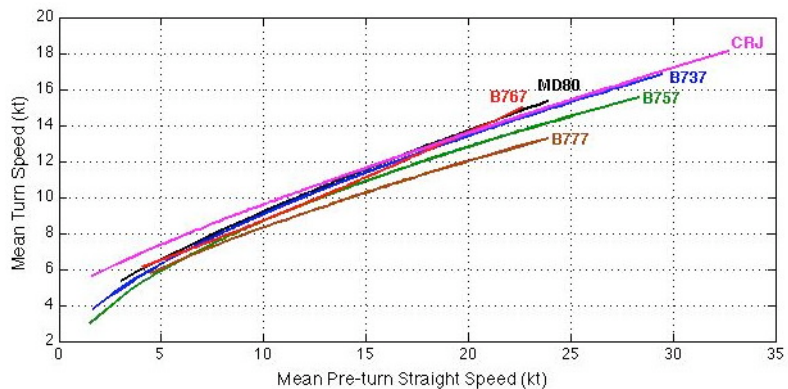

Figure 7. Mean Turn Speed – Unimpeded MD80 Departures

Figure 8. Mean Turn Speed – Unimpeded Departures

3. Acceleration and Deceleration

The acceleration of taxiing aircraft constantly varied as a result of speed perturbations, intentional or not, throughout the taxi route. In Fig. 1, the acceleration can be seen to vary along a straight segment (elapsed time 100-180 sec.) when the aircraft was probably trying to maintain a constant speed. The challenge of the acceleration analysis was to select discrete segments of data during which the aircraft's intent was known to be either accelerating or decelerating. For this reason, the acceleration analysis was focused on segments before and after a stop segment. The assumption was an aircraft would intentionally decelerate (i.e., braking) before a stop segment and intentionally accelerate to a taxi speed after the stop segment.

Deceleration characteristics before a stop segment, i.e., pre-stop, were measured for segment starting from the peak speed point prior to the stop to the first point of the stop segment. For the first stop segment shown in Fig. 3, the pre-stop maximum speed was 17 knots and occurred at elapsed time of 421 seconds. The resulting pre-stop deceleration segment spanned from an elapsed time of 421 seconds to 455 seconds, the first point of the stop segment. The post-stop acceleration segment was defined in a similar manner, from the last point of the stop segment to the peak speed after the stop segment. In the example shown in Fig. 3, the first post-stop acceleration segment spanned from elapsed time of 469 seconds to 495 seconds with a peak speed of 7.6 knots. The resulting deceleration and acceleration characteristics for MD80 departures, as well as other departure aircraft types, shown in Fig. 9 and 10 were found to be a function of the pre- and post-stop speeds, respectively. The standard deviation of both the deceleration and acceleration curve fits was approximately 0.07 kt/s. The data show aircraft applied brakes harder (i.e., greater deceleration) when the taxi speeds were higher, as well as, accelerated more when higher taxi speeds needed to be attained.
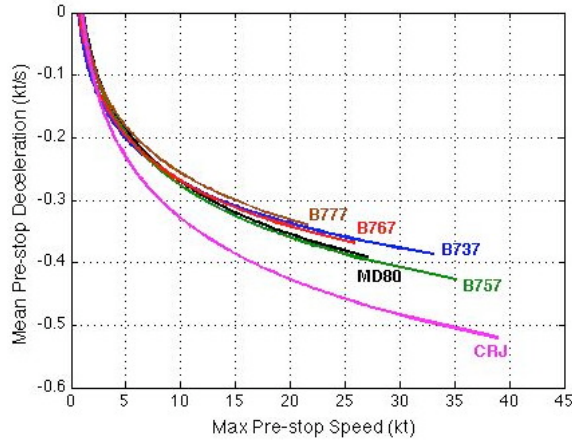
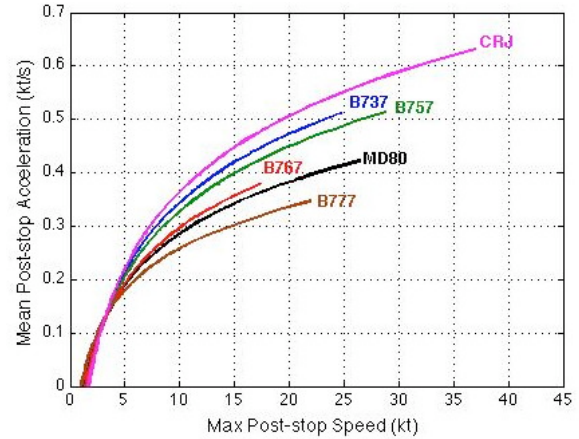**Figure 9. Departure Aircraft Deceleration**

Figure 10. Departure Aircraft Acceleration

4. High Speed Arrival Runway Exits

Taxiing characteristics on a high speed arrival runway exit were analyzed separate from the other taxiways. High speed arrival runway exits are specific taxiways configured to allow arrival aircraft to taxi off of runways at speeds higher than that of a typical taxiway. MD80 arrivals landing on DFW south flow runways 17C and 18R, and north flow runways 35C and 36L were analyzed. These are the primary arrival runways for DFW. For this data set, all arrivals exited the runway on one of the high speed taxiways. Maximum high speed arrival runway exit speeds are shown on Fig. 11. The 448 MD80 arrivals exited with an average maximum speed of approximately 30 knots with a standard deviation of 5.7 knots.

Arrival aircraft typically decelerate to a normal taxiway speed immediately after exiting the runway. Deceleration was measured over the first 500 feet of the high speed arrival runway exits which are on the order of 1000 feet in length. The resulting mean deceleration is shown in Fig. 12. The mean deceleration for the data set was -0.58 kt/s with a standard deviation of 0.28 kt/s. Deceleration on the high speed runway exits was greater than that observed on a normal taxiway (Fig. 9).
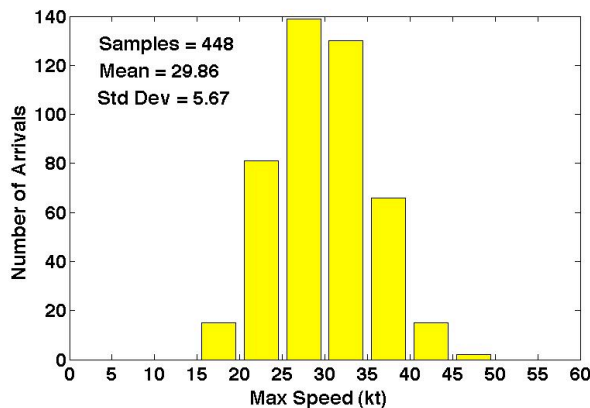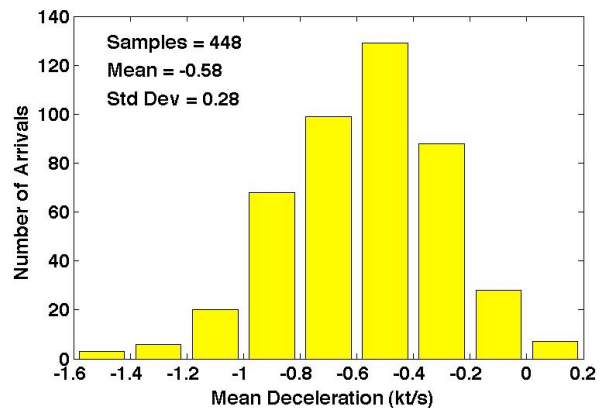

Figure 11. MD80 Runway Exits, Maximum Speed

Figure 12. MD80 Runway Exits, Mean Deceleration

III. Empirical Kinematic Surface Trajectory Model

The surface movement characteristics described in Section II were used to develop an empirical surface trajectory model. This trajectory model calculates the unimpeded taxi time along a specified taxi route between the runway to the "spot" for arrivals and vice versa for departures (the "spot" marks the transition point between the ramp area and taxiway). As an example, Fig. 13 shows actual surface track data of a number of MD80 arrivals exiting DFW runway 17C and taxiing along a specific taxi route to the gate via spot 23. The empirical surface

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trajectory model would calculate the unimpeded taxi time for the portion of the route between the runway exit and the spot shown in yellow.

The empirical surface trajectory model has not been incorporated into an algorithm at this time, so its application was demonstrated by calculating the taxi times manually. Unimpeded taxi time was calculated by summing up times for specific taxi route segments (i.e., straight, turn, etc.). For the MD80 arrival example shown in Fig. 13, the taxi route was broken into six segments based on segment type. The corresponding segment descriptions are listed in Table 1. All accelerations/decelerations were assumed to occur on the high speed runway exit or straight taxiways only. The example MD80 arrival exited runway 17C onto high speed runway exit segment 1 and decelerated from a speed of 29.9 knots at -0.58 kt/s (Fig. 11 and 12) to the taxi speed of segment 2. Segment 2 was classified as a shallow turn. As mentioned in the turn analysis in Section II-B2, there were limited data indicating aircraft did not slow down when taxiing through shallow turns. Therefore, the segment 2 turn speed was assumed to be the same as that of the subsequent straight, segment 3. The straight speed for segment 3 and the shallow turn segment 2 was determined to be 15.4 knots based on a straight distance of 1278 ft (Fig. 6). Turn speed for segment 4 was determined to be 11.7 knots from Fig. 7. This was based on the pre-turn straight (i.e., segment 3) speed of 15.4 knots. Deceleration of -0.38 kt/s from the pre-turn

Figure 13. Taxi Route Segments, MD80 Arrival - Runway 17C to Spot 23

straight speed of 15.4 knots to the turn speed of 11.7 knots was determined from Fig. 9 and was accounted for in Table 1 as the end condition of segment 3. The speeds and accelerations for segments 5 and 6 were determined in a similar manner. Individual segment times were then calculated by integrating the speed and acceleration over the segment distance. For the MD80 arrival example shown in Fig. 13, total unimpeded taxi time derived from the empirical surface trajectory model was 208 seconds.
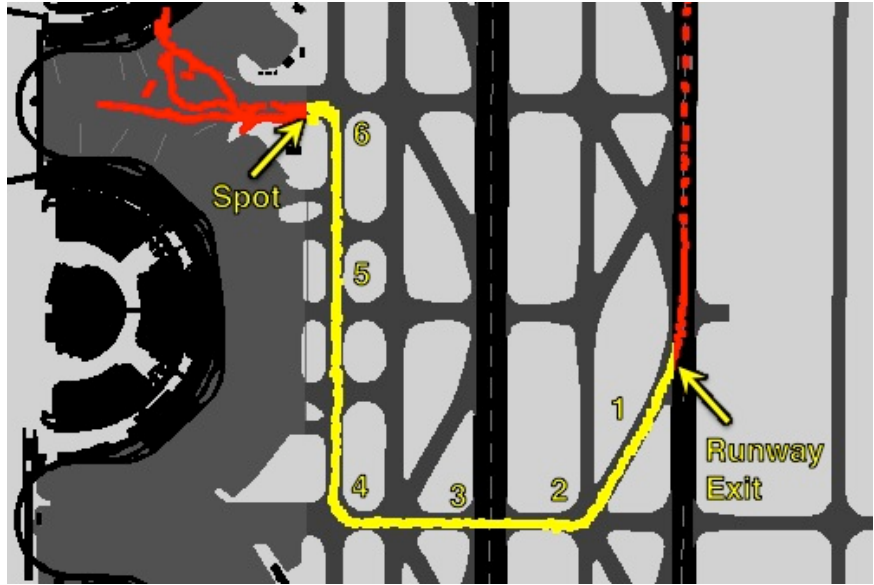
Segment Number	Segment Type	Segment Distance (ft)	Start Conditions Spd (kt)	Accel (kt/s)	Segment Spd (kt)	End Conditions Accel (kt/s)	Spd (kt)	Segment Time (seconds)
1	Rwy Exit	960	29.9	-0.58	15.4	0	15.4	25.1
2	Shallow Turn	266	15.4	0	15.4	0	15.4	10.2
3	Straight	1278	15.4	0	15.4	-0.38	11.7	63.1
4	Turn	261	11.7	0	11.7	0	11.7	13.2
5	Straight	2301	11.7	0.41	16.9	-0.40	12.3	84.1
6	Turn	261	12.3	0	12.3	0	12.3	12.6
Total		5327						208

Table 1. Empirical Model Unimpeded Taxi Time Calculations, MD80 Arrival - Runway 17C to Spot 23

IV. Empirical Kinematic Surface Trajectory Model Validation and Comparison

A limited set of unimpeded MD80 taxi times calculated with the empirical kinematic surface trajectory model described in Section III were validated against taxi times measured from actual MD80 surface traffic data. A different set of DFW surface data, independent of the set used for taxiing characterization, was collected and analyzed to determine actual taxi times along four common taxi routes; two for departures and two for arrivals. As noted earlier, taxi time was measured from the runway to the spot for arrivals and vice versa for departures. These data were collected from thirty-one days during September and October 2008 when DFW was operating primarily in the south flow runway configuration. It should be noted there were no differences observed in the taxiing characteristics of DFW north and south flow surface traffic.

Unimpeded taxi times from the September 2008 version of the ACES Surface Traffic Limitations Enhanced (STLE) model, a fast time airport surface simulation, were calculated for comparison. STLE is an airport surface model that can be used to represent one or more airports in a system-wide ACES simulation. Airport configuration is represented in STLE by a node-link graph. Node-link representation of airports is common for surface simulations of various fidelities. A typical node-link representation would place nodes at points of interest such as taxiway intersection, for example, and connect them with links. In this case, links would represent the taxiways between intersections. A kinematic trajectory model based on constant speed and instantaneous acceleration along the taxiway links is implemented in STLE. Link speeds in STLE were predefined for a given node-link graph and could be defined differently for each link. In this version of STLE, taxi routes were predefined as a series of nodes and links. The STLE taxi times were determined by simulating one aircraft at a time for each of the four validation routes. This was done to ensure taxiing was unimpeded.
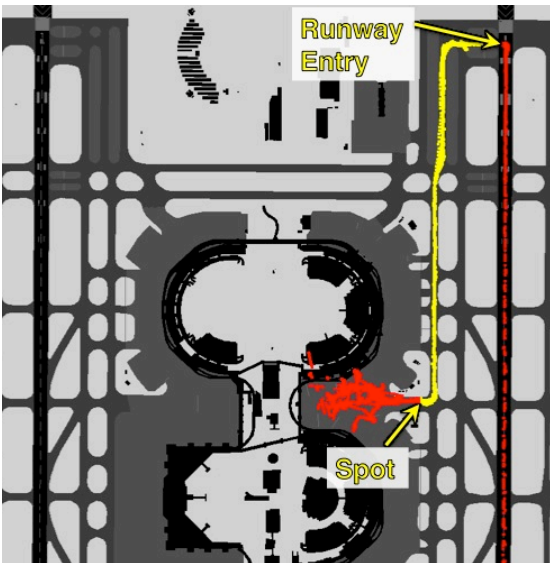

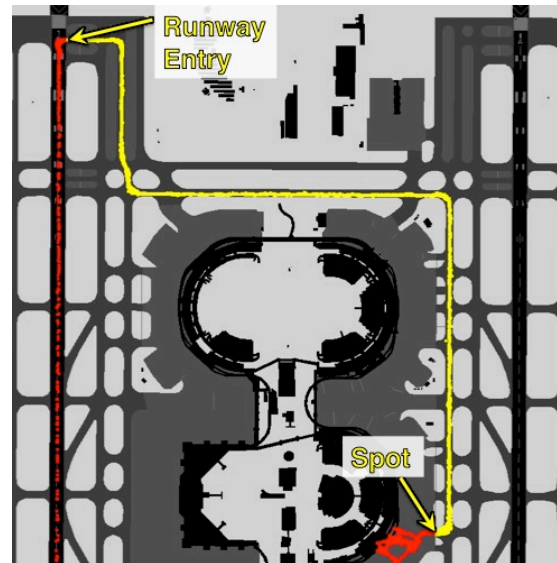**Figure 14. MD80 Departure Taxi Route, Spot 22 to Runway 17R**

Figure 15. MD80 Departure Taxi Route, Spot 36 to Runway 18L

The two common taxi routes used to validate unimpeded departure taxi times are shown in Fig. 14 and 15. Figure 14 shows actual surface track data for MD80 departure aircraft departing from gates at DFW terminals A and B, entering the taxiway via spot 22, and taxiing to runway 17R. For departures, taxi time was measured starting from the spot and ending at the runway entry point shown in yellow. Figure 15 depicts track data on the other departure validation route for MD80 departure aircraft taxiing to runway 18L via spot 36.

Processed track data for each flight were analyzed to identify those aircraft that were unimpeded during their taxi to the runway. Figure 16 shows a histogram of the unimpeded taxi time for 53 MD80 departure aircraft taxiing to runway 17R via spot 22. Mean unimpeded taxi time was 313 sec with a standard deviation of 58 sec. Maximum unimpeded taxi time was 452 sec. For the sake of comparison, the mean taxi time for all MD80 aircraft on this taxi route, unimpeded and impeded, was 445 sec, with a maximum taxi time of 1,141 sec. For this maximum time case, further analysis showed the aircraft appeared to be delayed in a queue at the runway, moving and stopping incrementally four times before entering the active runway. This case was impeded by operational conditions and would not have been predicted by a trajectory model alone. For this reason, only unimpeded taxi times were used in

this analysis. Figure 17 shows the unimpeded taxi time for 32 MD80 departures taxiing to runway 18L via spot 36. The mean unimpeded taxi time on this taxi route was 553 sec with a standard deviation of 88 sec.

The corresponding unimpeded taxi times calculated with the empirical surface trajectory model were 268 and 505 seconds, 14 and 9 percent earlier than the actual mean unimpeded taxi time, respectively (Fig. 16 and 17). Unimpeded taxi times between the corresponding spots and runways for the STLE simulations of the runway 17R and 18L departure cases were 176 and 356 seconds, respectively. These taxi times were 44 and 36 percent earlier than the actual mean taxi time of 313 and 553 seconds shown in Fig. 16 and 17. Moreover, unimpeded departure taxi times predicted by the empirical model developed in this study was approximately 28 percent more accurate than the constant speed based STLE model.
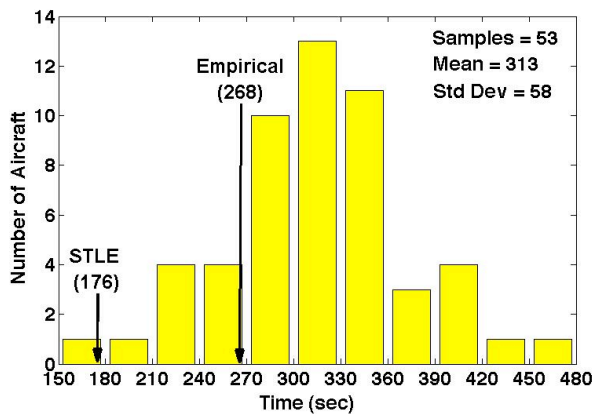

Figure 16. MD80 Unimpeded Departure Taxi Time, Spot 22 to Runway 17R
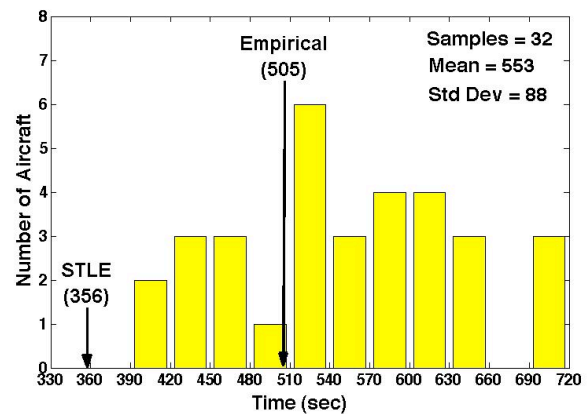

Figure 17. MD80 Unimpeded Departure Taxi Time, Spot 36 to Runway 18L.

A similar validation was performed for two sets of MD80 arrivals. The first arrival validation taxi route was used earlier to describe the application of the empirical surface trajectory model in Section III. Figure 13 shows the track data for 53 MD80 arrival aircraft which exited runway 17C and taxied to the terminal via spot 23. Taxi times for arrivals were measured along the route between the runway exit and the spot, shown in yellow. The second set of surface tracks for 64 MD80 arrivals taxiing from runway 18R to spot 23 is shown in Fig. 18.

The unimpeded taxi times for the 17C arrival set is shown in Fig. 19. Mean taxi time was 228 sec with a standard deviation of 38 sec. For the 18R arrival set, mean unimpeded taxi time was 581 sec with a standard deviation of 84 sec (Fig. 20). Unimpeded MD80 arrival taxi times were calculated with the empirical surface trajectory model. For the two arrival routes, unimpeded taxi times were 208 and 562 seconds (Fig. 19 and 20), or 9 and 3 percent earlier than the actual mean unimpeded taxi time, respectively. As with the departure routes, the STLE unimpeded taxi times for the arrival routes were also significantly earlier than the actual mean. Unimpeded STLE taxi times for the runway 17C and 18R arrival routes were 108 and 405 second, or 53 and 30 percent earlier than the actual mean unimpeded taxi times, respectively (Fig. 19 and 20). The unimpeded arrival taxi times determined by the empirical trajectory model were approximately 35 percent more accurate than those calculated with STLE.
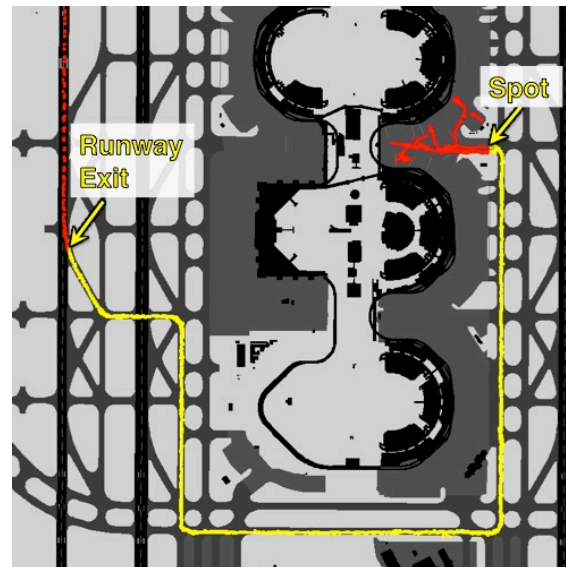

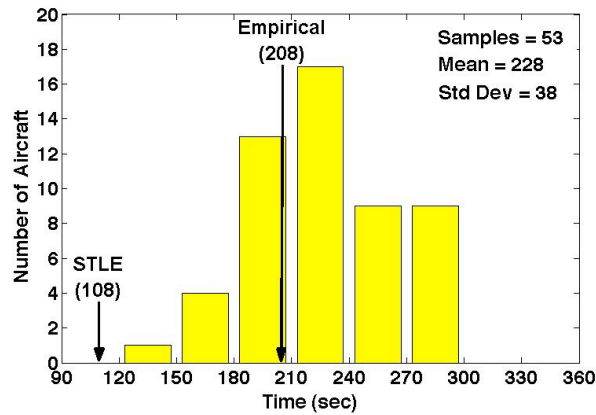**Figure 18. MD80 Arrival Taxi Route, Runway 18R to Spot 23.**

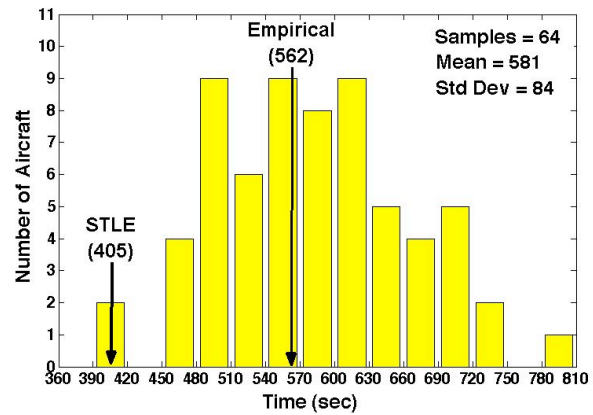**Figure 19. MD80 Unimpeded Arrival Taxi Time, Runway 17C to Spot 23**

Figure 20. MD80 Unimpeded Arrival Taxi Time, Runway 18R to Spot 23.

Further analysis of the STLE link speeds revealed almost all of the links representing the taxiways were set to 22 knots. Coincidentally, a link speed of 22 knots would be appropriate for an MD80 arrival taxiing on the longest of straight taxiways shown on Fig. 6. However, the modeling of constant taxiway speeds in the trajectory model used by STLE consistently predicted unimpeded taxi times at least 30 percent earlier than actual.

Results from of a STLE evaluation of limited scope was documented in Ref. 7. This evaluation showed a correlation between the resulting takeoff and landing rates from a simulation in which STLE was used to model surface traffic at Newark International Airport (KEWR) and actual KEWR takeoff and landing rates. However, the ability of the trajectory model implemented in STLE to model movement along specific taxiways was not directly evaluated in Ref. 7.

The limited validation results for the empirical model showed a bias in the unimpeded taxi time predictions. For all cases, the predicted unimpeded taxi time was earlier than the actual mean taxi time by an average of 9 percent. The source of the bias was not investigated and will be a subject for future study. Therefore, there was no attempt compensate for the bias by adjusting the empirical model presented in this study.

The unimpeded taxi time analysis performed in this study only evaluated the ability of the trajectory models to predict the time between two taxi route end points (i.e., spot and runway for departures, vice versa for arrivals). However, it is expected the empirical model will be able to better predict time to intermediate points along the taxi route (e.g., intersections) than a constant speed model would because it considers segment characteristics throughout the entire taxi route. Time prediction accuracy to intermediate points is an important aspect of surface scheduling optimization research because the initial schedules and sequences of aircraft to which the optimization algorithms would be applied are dependent on these predictions. Therefore, measuring trajectory prediction accuracy at intermediate points along the taxi route would be worthy of future study.

This study only used airport surface data from one airport, DFW, to characterize surface traffic movement. Although the concept of predicting unimpeded surface trajectories based on key taxi route segment characteristics proved to be valid, investigating the potential effects of different airports and weather conditions are topics for future study.

V. Concluding Remarks

An empirical kinematic airport surface trajectory model was derived from the study of taxiing characteristics on specific segments of a taxi route. These characteristics showed the speed and acceleration of a taxiing aircraft varied depending on specific taxiway segment types such as straights and turns. Such characteristics are not considered by the constant speed surface trajectory models commonly used in airport surface research. A limited validation study showed the empirical surface trajectory model predicted unimpeded taxi times an average of 9 percent earlier than the actual mean while modeling speed and acceleration variations of actual surface traffic movement. This empirical trajectory model showed an improvement of 28 and 35 percent in unimpeded taxi time prediction accuracy for MD80 departures and arrivals, respectively, over the constant speed model used in STLE.

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