A Framework for Coordinated Surface Operations Planning at Dallas-Fort Worth International Airport

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An Integer Programming formulation is developed for optimizing surface operations at Dallas-Fort Worth airport, with the goal of assessing the potential benefits of taxi route planning. The model is based on operations in the eastern half of the airport under the most frequently used configuration. The focus is on operational concepts that optimize taxi routes by utilizing different control points on the airport surface. The benefits of two different concepts for optimizing taxiway operations, namely *controlled pushback* and *taxi reroutes* are analyzed, for both current data and a projected data set with approximately twice the traffic density. The analysis estimates that: (1) for current traffic densities, controlled pushback would reduce the average departure taxi time by 17% without altering runway schedule conformance, while the benefits of taxi reroutes would be minimal; and (2) for high-density operations, controlled pushback would reduce the average departure taxi time by 18%, while incorporating taxi reroutes would reduce the average arrival taxi time by 14%. Other benefits analyzed for these control strategies include a decrease in the average time spent in runway crossing queues.

Nomenclature

$\mathcal{F}$	set of all flights.
$\mathcal{J}$	set of all (capacity-constrained) resources (links and nodes).
$\mathcal{J}_2$	set of all bidirectional links with capacity greater than 1.
$\mathcal{T}$	set of time periods, i.e., $\{1, \cdots, T\}$, where T is the planning horizon.
d_f	earliest pushback time of departing flight f; landing time of arriving flight f.
r_f	scheduled departure queue time (from departure planner) of flight f.
$C_j(t)$	capacity of resource (link or node) j at time t.
c_f^{on}, c_f^{off}	cost of holding flight f with engine on/off for unit time.
$t_{fj}^{\min}$, $t_{fj}^{\max}$	minimum/maximum time spent by flight f in link (or node) j.
T_f^j	set of feasible times for flight f to arrive at link (or node) j. $T_f^j = [\underline{T}_f^j, \overline{T}_f^j]$.
P_f	surface route of flight f, as a sequence of nodes and links. $P_f = [P(f,1) \ \cdots \ P(f,N_f)]$.

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I. Introduction

The Next Generation Air Transportation System (NGATS) is projected to have a demand that is 2-3 times the levels witnessed in the current system. Even with the runway projects that are currently underway as part of the Federal Aviation Administration's Operational Evolution Plan (OEP), it has been recognized that the required increase in airspace and airport capacities for the NGATS can only be achieved through enhanced levels of automation and new concepts of operation.[1,2] This has motivated research into techniques that enhance the capacity of the airspace system, especially in terminal areas. To support the increased traffic density, along with the planning of airspace operations, it is also imperative that surface operations be coordinated efficiently. The coordination of surface operations in high- and super-density terminal areas will only be possible through the implementation of new operational concepts on the surface. One aspect of surface movement planning, namely the coordination of taxiway operations using various optimization approaches and different control points on the airport surface, has been proposed as a potential operational concept.[3–5]

Modeling complex airport processes through observations, including the identification of flow constraints and potential control points is an important step toward developing optimization and decision support tools for surface operations.[6] In addition, there has been much research in techniques for the automation of surface operations, ranging from the automatic control of taxiing aircraft[7] to the development of cockpit displays and pilot interface formats that enable 4D taxi clearances.[8,9] Prior surface traffic optimization research includes Dynamic Programming-based taxi route optimization using Dijkstra's algorithm,[10] applied sequentially to all the aircraft of interest within the time horizon, and Time-Dependent Shortest Path techniques.[5] There has also been prior work on algorithms for taxi routing using various approaches such as Genetic Algorithms and the A^* search by Brinton et al.[4] and Mixed Integer Linear Programming by Visser and Roling.[11] Similar Integer Programming formulations have also been used in the context of routing aircraft in the National Airspace System.[12] Most of the previous research on the optimization of taxi operations has been limited to demonstrations on small, constructed examples, and not studies on network models of an actual airport. The large-scale nature of the real system also imposes requirements on the optimization formulation. For example, Visser and Roling model bidirectional taxiways with capacity greater than one by dividing them into several smaller links, each of capacity one. While this is technically possible, in a large airport with long bidirectional taxiways this would result in a large and computationally demanding optimization problem.

The focus of the research described in this paper is to compare different control strategies during the optimization of taxiway operations, that is, to determine what the control points (or variables) in the optimization should be. The solution approach is to develop a model of surface operations at the Dallas-Fort Worth (DFW) airport, and to use the model to assess the benefits of potential optimization-based concepts for taxiway operations. To obtain a meaningful comparison of the outcomes of different control mechanisms, the formulation presented in this paper models different airport environments (in terms of fleet mixes, equipage levels, separation requirements, airport procedures, etc.) Holding these factors constant, the benefits of employing different control strategies can be compared; this paper focuses on two of them, controlled pushback and taxi reroutes.

This paper is the first attempt, to the best of our knowledge, to formulate and assess the relative benefits of different control approaches for surface traffic optimization (that is, the use of different control points on the airport surface[6]) on a real, large-scale, airport model using observed surface operations data. We first present a formulation that can be used to optimize taxi operations under different fleet mixes, taxiway procedures (unidirectional and bidirectional), control strategies and routing options. We then focus on two concepts, namely controlled pushback and taxi reroutes, and assess the benefits of employing these strategies for different levels of airport traffic density. We also comment on some architecture issues, such as the interaction between the taxiway, runway and ramp schedulers.

II. Optimization architecture

The main function of the airport taxiway system is to deliver aircraft from their gates or the ramp area to the appropriate runways, and vice versa. As such, any taxiway scheduler must interface with both the ramp (or gate) schedulers and the runway schedulers. The ramp and runway schedules impose constraints on the potential start and end times of an aircraft's taxi operations.

The times when aircraft are ready to pushback are determined by a combination of airline schedules, turnaround operations and gate processes. As a result, there is considerable uncertainty associated with them. This work assumes that airlines (or the gate/ramp scheduler) provide the taxiway scheduler with an estimate of the earliest possible pushback time. A moving half-hour window is considered, which means that airlines would need to estimate their earliest pushback times 30 min in advance. However, it is proposed that the schedule be recomputed every 10 min, at which time airlines will be allowed to revise their estimates of the pushback times. Aircraft that conform to their previously estimated schedule will not be rescheduled (i.e., penalized), while aircraft that miss their "slot" will have to wait their turn, thereby providing incentive for the accurate reporting of pushback times. In the current system, aircraft take-offs are typically scheduled in a First-Come-First-Served (FCFS) order, depending on their arrival at the departure queue. However, this is not an efficient sequence of departures, since the sequence of take-offs determines the required separation between aircraft, and aircraft departure times may depend on downstream constraints such as traffic flow management advisories.[13–15] For this reason, in the proposed optimization architecture the runway scheduler would determine the most efficient departure sequence incorporating the downstream (airspace) constraints, and the taxiway scheduler would deliver aircraft to the runway accordingly. There would, however, be considerable interaction and coordination between the two components, as shown in Figure 1 (left). The landing times for aircraft are assumed to be known 30 min in advance, although these too can be revised every 10 min. Improved prediction of landing times would be enabled by the integration of Center-TRACON Automation System (CTAS) arrival capabilities with the Surface Management System (SMS).[16]

Runway schedules also determine the times when aircraft can conduct active runway crossings. In the current system, active runway crossings are coordinated by the Local Controllers who are also responsible for the operations on the runway. A frequently observed technique is the use of the gap in the departure sequence following the departure of a B757 or a "Heavy" aircraft in order to accommodate an active runway crossing. While this is carried out manually in the current system, there has also been prior research in the development of techniques for scheduling active runway crossings.[17] The development of a runway scheduler that accounted for active runway crossings would result in a scheduled runway crossing time for an aircraft. In the absence of such a scheduler, the formulation proposed in this paper identifies the gaps in the runway schedule and coordinates active runway crossings at those times. The results of this research show that while these gaps in the schedule exist in current operations, high-density operations would result in long periods of time with no gaps in the runway schedule, resulting in long waits for aircraft in runway crossing queues. This was the motivation behind the development of a runway scheduler, which not only accommodates active runway crossings, but also schedules them.[18] This proposed change in the interaction between the taxiway and runway schedulers is shown in Figure 1 (right).

III. Problem formulation

This paper considers surface operations at the Dallas/Forth Worth International airport. The airport diagram for DFW is shown in Figure 2, showing the runways, taxiways and terminals.

The airport surface is modeled as a network of links and nodes. The authors have developed such a model for the East side operations at DFW, using the adaptation of SMS for that airport. The node-link model is shown in Figure 3. Time is discretized into 5 sec intervals, called time periods. The choice of time period reflects the tradeoff between the problem size (which grows as the fidelity of the time discretization increases) and the need to capture the important features of an aircraft's taxi path. A time period of 5 sec

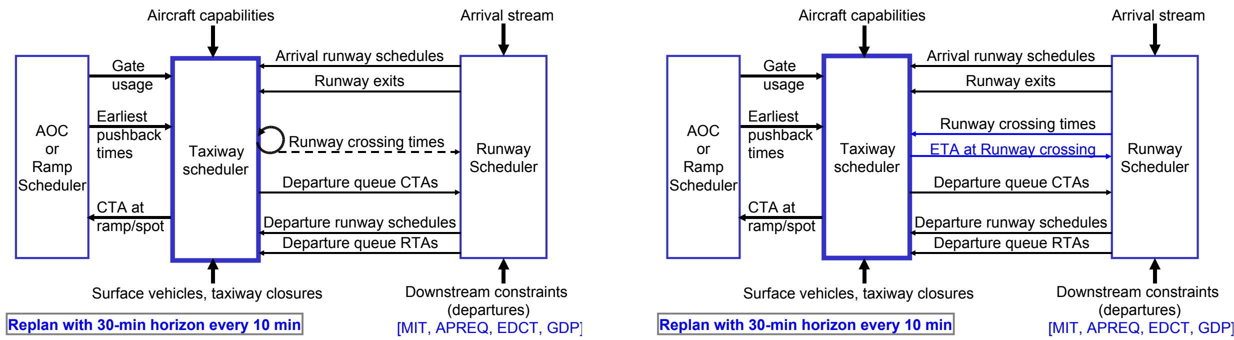

Figure 1. (Left) Optimization architecture diagram, showing interactions between ramp, taxiway and runway schedulers. (Right) Potential modification of interaction between runway and taxiway schedulers.

ensures that every intersection and link in the taxi route is captured (that is, aircraft take at least 5 sec to complete any link in the airport surface model). This allows the derivation of an Integer Programming formulation for the surface traffic routing problem. Let $\mathcal{F}_a$ be the set of all arrivals, and $\mathcal{F}_d$ be the set of all departures. It is assumed that every aircraft has a set of preferred routes ($\mathcal{P}_f$), each expressed as a sequence of links and nodes $P_f \in \mathcal{P}_f$. The first segment of a departing aircraft's path begins at its gate; the last segment terminates at the departure runway. That is, $P(f,1)$ is a gate and $P(f,N_f)$ is a departure runway queue for any departing aircraft $f \in \mathcal{F}_d$. Conversely, an arriving aircraft's path begins at the arrival runway and ends at its gate.

The binary decision variable w^j_{ft} is used to decide if flight f arrives at link (or node) j by time t. It is defined as

$$w^j_{ft} = \begin{cases} 1, & \text{if flight } f \text{ arrives at link (or node) } j \text{ by time } t, \\ 0, & \text{otherwise.} \end{cases}$$

A. Objective function

The cost of a unit of delay is categorized based on whether the engine is on or off. In general, the cost of a unit of delay is greater when the engine is on than when the engine is off ($c^{\text{on}}_f > c^{\text{off}}_f$). This paper assumes that $c^{\text{off}}_f = 0$, and that an aircraft pushes back from its gate and immediately turns its engines on. Given a scheduled pushback time (d_f, also the earliest pushback time) and a scheduled time of arrival at the runway (r_f, determined by the runway scheduler) for each aircraft, the objective is to find surface routes and pushback times for all flights such that the total cost ($\sum_f c^{\text{on}}_f \times$time spent on the airport surface with the engines on) is minimized. In addition, a large penalty ($\mathbf{P}$) is enforced when the aircraft is not at the runway before its scheduled departure queue time. This total cost for departures can be expressed as

$$\begin{aligned} Q(\text{Departures}) \quad = \quad & \sum_{f \in \mathcal{F}_d} c^{\text{on}}_f \{ \max[\sum_{t \in T^k_f, k=P(f,N_f)} t(w^k_{ft} - w^k_{f,t-1}), r_f] - \sum_{t \in T^k_f, k=P(f,2)} t(w^k_{ft} - w^k_{f,t-1}) \} \\ & + \mathbf{P} \max[\sum_{t \in T^k_f, k=P(f,N_f)} t(w^k_{ft} - w^k_{f,t-1}) - r_f, 0]. \end{aligned} \quad (1)$$

The form of this objective as a function of the pushback time and the time of arrival at the runway is illustrated in Figure 4 [left].

Similarly, for arrivals, the taxi time is defined as the time between an aircraft landing on the runway and reaching its assigned gate. The cost per unit delay is assumed to be twice as much for arrivals as for

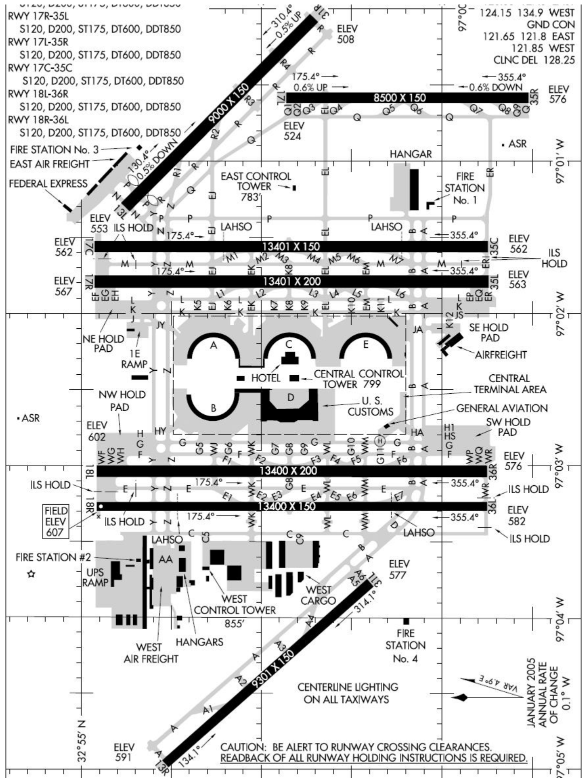

Figure 2. Airport diagram of Dallas-Fort Worth International (DFW).[19]

departures, that is, $c^{\text{on}}_{f_a} = 2c^{\text{on}}_{f_d}$, if f_a is an arrival and f_d is a departure. This is done to reflect a greater sense of urgency for arrivals, and because many airlines have operational procedures in which they do not turn all their engines on while taxiing out, thereby reducing the taxi cost of departures. Future work will investigate the sensitivity of the solution to this parameter. The engine-off costs are assumed to be zero. Therefore, the total cost for arrivals can be expressed as

$$Q(\text{Arrivals}) \quad = \quad \sum_{f \in \mathcal{F}_a} c^{\text{on}}_f \{ \sum_{t \in T^k_f, k=P(f,N_f)} t(w^k_{ft} - w^k_{f,t-1}) - d_f \} \tag{2}$$

This objective is a function of the total taxi time which is measured as the time between landing (On) and arriving at the gate (In), as shown in Figure 4 [right].

B. Control points

The pushback sequence and ramp exit sequence were identified by Idris et al.[6] as potential control points to influence the departure sequence. This work assumes that the departure sequence is determined by a Departure Runway scheduler, which accounts for downstream constraints such as Miles-in-Trail (MIT), Approval Requests (APREQ), Estimated Departure Clearance Time (EDCT) and other constraints imposed by the airspace. The taxiway scheduler then attempts to conform to this departure sequence by controlling pushback times and the arrival times (Controlled Times of Arrival or CTAs) at intersections. Control of the ramp exit sequence is similar to the strategy currently employed by SMS, in which aircraft are sequenced

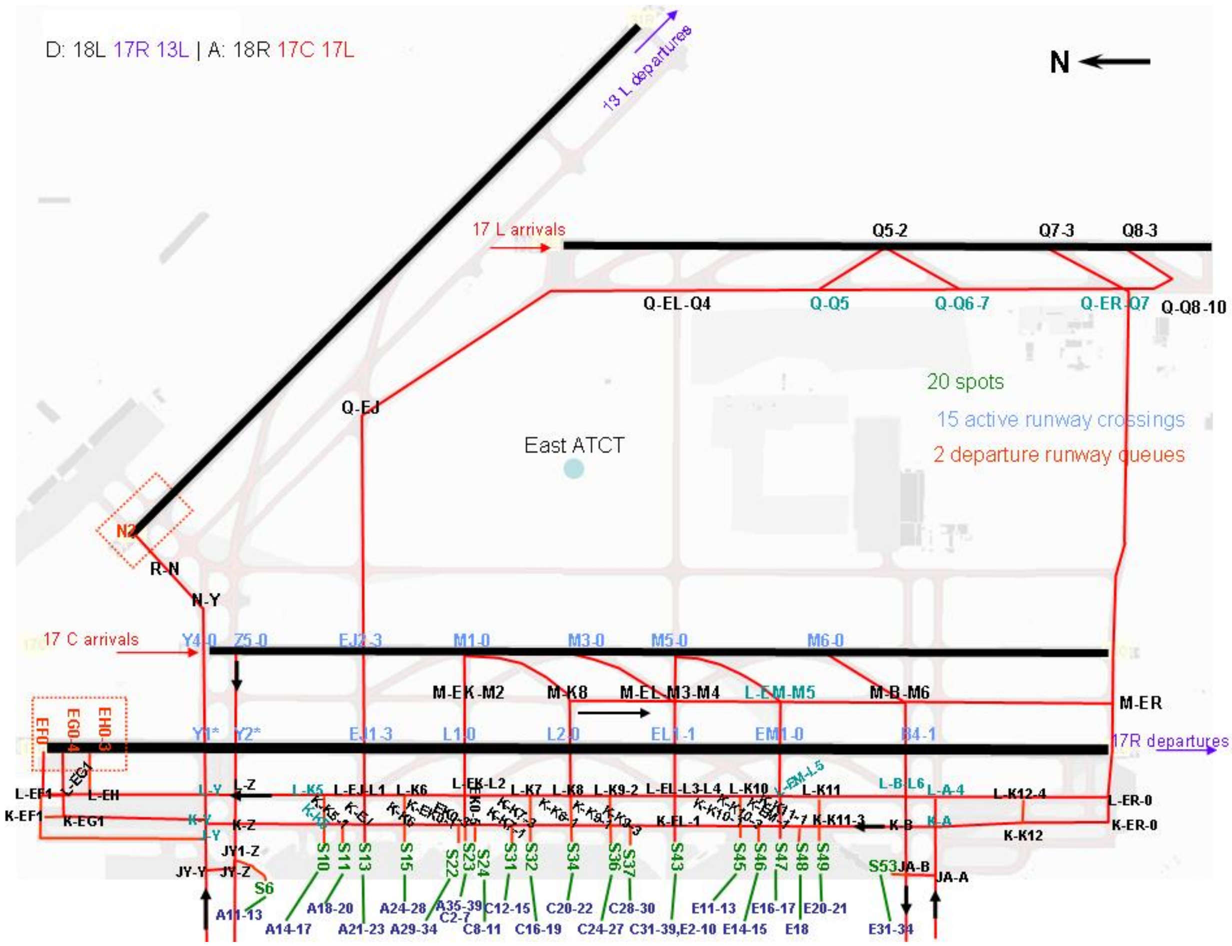

Figure 3. Node-link model of Eastern half of DFW in A 17LC, 18R, 13R/D 17R, 13L, 18L configuration, showing the taxiways, runways and intersections. The intersection labels those used by the SMS adaptation for DFW.

at their Spots (the hand-off point between the ramp area and the taxiway system). While the formulation presented in this paper does implicitly regulate the ramp exit sequence, this is not the primary control point. The motivation for controlling the pushback times of aircraft is the potential savings in fuel. From the air traffic control perspective it results in shorter queues on the surface, particularly at the Spots. From an airline perspective, controlling only the ramp exit sequence would mean waiting at the Spot with engine(s) on, when the delay could have been absorbed at the gate with engines off.

Arrivals are usually routed to their gates as soon as they land on their runways. There is potential for using the choice of runway exit as a control point. However, the choice of exit is currently at the discretion of the pilot and depends on variables such as aircraft weight and braking characteristics. While there is on-going research on Flight Management Systems that can be assigned runway exits,[20] the adoption of these systems requires a safety analysis, and is beyond the scope of this work.

Some of the possible degrees of freedom that can be used to control the surface traffic flow of aircraft are the pushback times, the times spent on each link or at an intersection (which translate to taxi speed profiles), and the specification of taxi routes. Taxi speed control is enforced as a CTA at an intersection. A

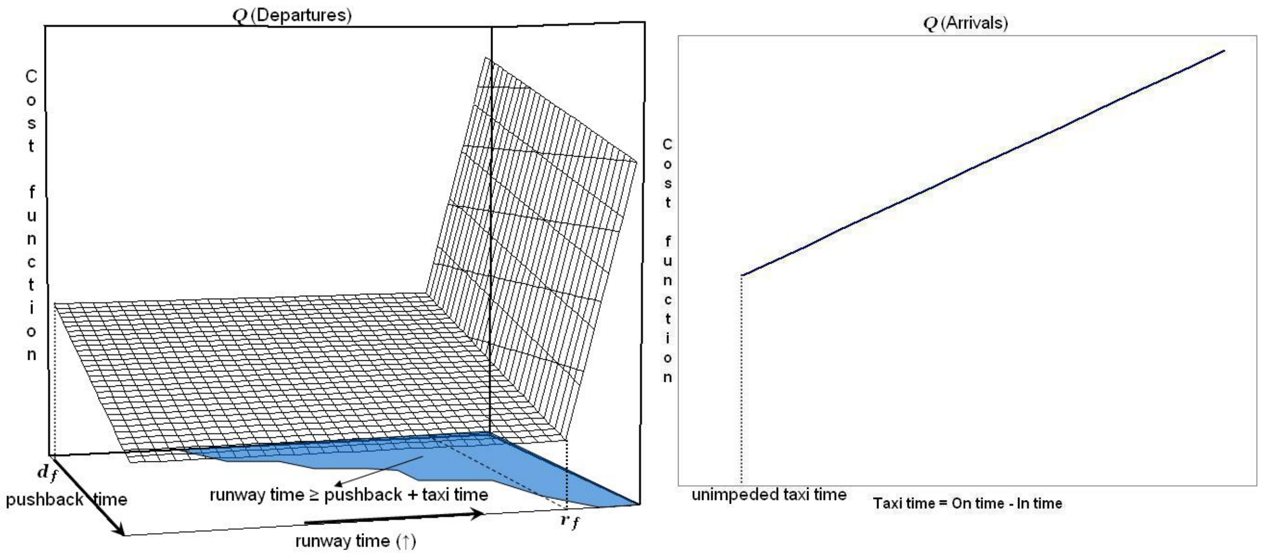

Figure 4. [Left] Form of objective function, Q(Departures)**. The shaded region denotes the feasible set of pushback and runway times. [Right] Cost function for arriving aircraft,** Q(Arrivals)

maximum speed limit of 40 knots on high-speed taxiways (runway exits), 16 knots along the taxiways and 8 knots in the ramp area is imposed, and the CTAs at intersections are computed such that the speed limits are satisfied on all links. In addition, a minimum speed along some of the taxiways is also imposed to avoid stagnation. This minimum speed is assumed to be half the maximum speed limit on taxiways and ramps, allowing aircraft to come to a halt only at gates, designated holding areas and runway crossing queues.

C. Minimum separation requirements

As aircraft taxi, they must maintain separation for safety. There seem to be few available standards for the minimum separation required between taxiing aircraft. The minimum separation requirement that is used while scheduling operations depends on the uncertainty in taxi speeds and the ability to achieve controlled times of arrival. For example, to ensure safety, the separation between two aircraft that are not capable of precision taxiing must be large enough to account for the uncertainty in their trajectories. As aircraft become capable of precise taxiing, these separation buffers can be reduced. Until then, there needs to be sufficient distance between taxiing aircraft. This safety distance is added to the physical dimensions of an aircraft to obtain the length of taxiway that is allocated to a single aircraft while it is taxiing. This length is assumed to be 200 m, as suggested by Visser and Roling.[11] The capacity of a link of the taxiway (capacity = $\lfloor$length/(space allocated per aircraft)$\rfloor$) can then be computed. The separation requirements can therefore be translated to capacity constraints. When the capacity of a link is greater than 1, traffic is metered at the intersection leading into the link so that the taxiing aircraft are separated by the required amount. It is to be noted that this buffer is used only for taxiing aircraft, and not for aircraft in runway crossing queues or departure queues.

The length of taxiway that needs to be reserved for an aircraft (the space "occupied" by it) depends on the uncertainty in its trajectory, which in turn depends on its equipage. For example, an aircraft that is equipped for precision taxi is likely to require less buffering than one that is not equipped.

Suppose that an aircraft that is capable of precision taxiing requires α times the length of taxiway as one that is not equipped, where $\alpha \leq 1$. Let $C_j(t)$ be the capacity of a link, measured in terms of the number of unequipped aircraft. Let $\mathcal{F}_{\text{equipped}}$ be the set of equipped aircraft and $\mathcal{F}_{\text{unequipped}}$ be the set of unequipped aircraft. Then, the capacity constraint is given by

$$\alpha(\text{Number of equipped aircraft}) + \text{Number of unequipped aircraft} \leq C_j(t), \tag{3}$$

which can alternatively be written as,

$$\sum_{\substack{f \in \mathcal{F}_{\text{equipped}}: \\ P(f,i)=j, P(f,i+1)=j', \\ i<N_f}} \alpha(w_{ft}^{j} - w_{ft}^{j'}) + \sum_{\substack{f \in \mathcal{F}_{\text{unequipped}}: \\ P(f,i)=j, P(f,i+1)=j', \\ i<N_f}} (w_{ft}^{j} - w_{ft}^{j'}) \leq C_j(t). \tag{4}$$

The same approach can be used if aircraft are of substantially different sizes and hence occupy different lengths of taxiway (for example, an Airbus A380 and a small, general aviation aircraft). However, adding constraints of the above form alters the structure of the Integer Program substantially.

D. Two-way links

The possibility of having bidirectional taxiways is also considered in the proposed model. At any given instant, it is desirable all the aircraft on the taxiway to be moving in the same direction. This is to avoid situations in which two aircraft may be heading in opposite directions on the same taxiway, and while there may be no danger of a collision, it can be disconcerting to the pilots. Instead, the intent is to have a system in which taxiways are unidirectional, but the direction of a taxiway can change depending on the traffic flow.

Clearly, this is not an issue when the capacity of the taxiway is equal to one, since the direction of the aircraft on it specifies the direction of the taxiway. The case where the capacity of the link is more than one aircraft therefore needs to be addressed.

Let link $J \in \mathcal{J}_2$ be a bi-directional link with capacity $C_J(t)$ greater than 1. Then, we define the variables $x_t^{L,J}$ and $x_t^{R,J}$ that determine the direction of the flow on J at time t.

$$x_t^{L,J} = \begin{cases} 1, & \text{if flow is to the left on } J \text{ at time } t, \\ 0, & \text{otherwise.} \end{cases}$$

$$x_t^{R,J} = \begin{cases} 1, & \text{if flow is to the right on } J \text{ at time } t, \\ 0, & \text{otherwise.} \end{cases}$$

$$x_t^{L,J} + x_t^{R,J} = 1 \; \forall t.$$

Let $\mathcal{F}^{L,J}$ be the set of aircraft that go left on link J and $\mathcal{F}^{R,J}$ be the set of aircraft that go right on link J. Then,

$$\begin{aligned} \sum_{f \in \mathcal{F}^{L,J}, P(f,i)=J, P(f,i+1)=j', i<N_f} (w_{ft}^{J} - w_{ft}^{j'}) &\leq C_J(t) \cdot x_t^{L,J}, \; \forall t \\ \sum_{f \in \mathcal{F}^{R,J}, P(f,i)=J, P(f,i+1)=j', i<N_f} (w_{ft}^{J} - w_{ft}^{j'}) &\leq C_J(t) \cdot x_t^{R,J}, \; \forall t. \end{aligned}$$

E. Active runway crossings

Aircraft cannot cross a runway while it is being used by an arriving or departing aircraft. This implies that the crossings need to be carried out during breaks in the arrival or departure flows. It is assumed that the departure scheduler assigns the runway times and sequences, with the appropriate wake vortex separation between aircraft. The estimated arrival times are also known. A runway occupancy time (roll-time) of 55 sec is assumed. This would imply that there would be zero capacity for runway crossings for 55 sec after every takeoff or touchdown. Runway crossings are assumed to take 40 sec for the first aircraft in the runway crossing queue, and 10 sec-in-trail spacing for every subsequent aircraft in that queue.[21] For example, if a runway crossing queue contains 4 aircraft, it can be completed 125 sec after an arrival touches down on the runway. Since the wake vortex spacing minimum for a heavy aircraft leading a large aircraft is 157 sec, the runway crossing can be easily carried out at such a point in the arrival sequence, that is, after the heavy aircraft lands. Similar spacing requirements can also be utilized to schedule runway crossings at appropriate points in the departure sequence.

F. Problem statement

The objective is to minimize the total cost (from (1) and (2)) subject to constraints such as link capacity and speed restrictions identified above. The case in which every aircraft has a single route $P_f = [P(f,1) \;\; P(f,2) \;\; \cdots \;\; P(f,N_f)]$ is first considered.

$$\text{minimize} \quad Q(\text{Departures}) + Q(\text{Arrivals})$$

$$\text{subject to} \quad \sum_{\substack{f\,:\,P(f,i)=j,\,P(f,i+1)=j',\\ i<N_f}} (w_{ft}^{j} - w_{ft}^{j'}) \leq C_j(t),\ \forall j \in \mathcal{J} \setminus \mathcal{J}_2, \forall t \in \mathcal{T} \tag{5}$$

$$\sum_{\substack{f \in \mathcal{F}^{L,J},\,P(f,i)=J,\\ P(f,i+1)=j',\,i<N_f}} (w_{ft}^{J} - w_{ft}^{j'}) \leq C_J(t) \cdot x_t^{L,J},\ \forall t \in \mathcal{T},\ \forall J \in \mathcal{J}_2 \tag{6}$$

$$\sum_{\substack{f \in \mathcal{F}^{R,J},\,P(f,i)=J,\\ P(f,i+1)=j',\,i<N_f}} (w_{ft}^{J} - w_{ft}^{j'}) \leq C_J(t) \cdot x_t^{R,J},\ \forall t \in \mathcal{T},\ \forall J \in \mathcal{J}_2 \tag{7}$$

$$x_t^{L,J} + x^{R,J} = 1,\ \forall t \in \mathcal{T},\ \forall J \in \mathcal{J}_2 \tag{8}$$

$$w_{ft}^{j} - w_{f,t+t_{fj}^{\min}}^{j'} \geq 0, \forall f \in \mathcal{F},\ t \in T_f^j,\ j = P(f,i),\ j' = P(f,i+1),\ i < N_f \tag{9}$$

$$w_{ft}^{j'} - w_{f,t-t_{fj}^{\max}}^{j} \geq 0, \forall f \in \mathcal{F},\ t \in T_f^j,\ j = P(f,i),\ j' = P(f,i+1),\ i < N_f \tag{10}$$

$$w_{ft}^{j} - w_{f,t-1}^{j} \geq 0,\ \forall f \in \mathcal{F},\ j \in P_f,\ t \in T_f^j \tag{11}$$

$$w_{ft}^{j} \in \{0,1\},\ \forall f \in \mathcal{F},\ \forall j \in P_f,\ t \in T_f^j \tag{12}$$

$$x_t^{L,J},\ x_t^{R,J} \in \{0,1\},\ \forall J \in \mathcal{J}_2,\ t \in \mathcal{T} \tag{13}$$

Constraints (5)-(8) above are capacity constraints, for unidirectional and bidirectional links. Constraints (9) and (10) enforce the maximum speed (minimum amount of time spent on a link) and minimum speed restrictions respectively, and constraint (11) enforces continuity in time. The decision variables are defined in (12) and (13).

The problem, as described above, is an Integer Program with a linear cost function. For the analysis of the data from DFW in this paper, a simplified cost function that imposes the same cost per unit delay at all times that only depends on whether the aircraft is an arrival or a departure is considered; the formulation can employ any cost that is a function of the particular flight, time when the delay is incurred, or the region on the airport surface where the delay is incurred, all without changing the structure of the problem. The problem described above is NP-hard, from arguments presented for the Traffic Flow Management Problem.[12]

1. *Output*

The solution to the problem defined in Section III-F is the optimal value of the decision variable w_{ft}^{j}. This is used to compute the pushback times, trajectory with CTAs at intersections, the times of arrival at the runways and gates. These are computed, for flight f, using the following relations:

$$\begin{aligned}
\text{OUT_time}(f) &= \sum_{t \in T_f^k, k=P(f,2)} t(w_{ft}^k - w_{f,t-1}^k), \; \forall f \in \mathcal{F}_d && (14)\\
\text{Runway_time}(f) &= \sum_{t \in T_f^k, k=P(f,N_f)} t(w_{ft}^k - w_{f,t-1}^k), \; \forall f \in \mathcal{F}_d && (15)\\
\text{CTA_on_link_or_node_}j &= \sum_{t \in T_f^j} t(w_{ft}^j - w_{f,t-1}^j), \; \forall f \in \mathcal{F} && (16)\\
\text{IN_time}(f) &= \sum_{t \in T_f^k, k=P(f,N_f)} t(w_{ft}^k - w_{f,t-1}^k), \; \forall f \in \mathcal{F}_a. && (17)
\end{aligned}$$

The CTAs at various intersections define the 4D trajectories for the aircraft on the taxiways. These may be inputs to the FMS (or FARGO[20] system) for precision taxiing, or may be presented to pilots as control advisories. The advisories may be presented either as required times of arrival, or speed advisories, or a combination of the two.[9]

IV. Data generation

To assess the benefits of different operational concepts, two sets of traffic density scenarios are analyzed. The first represents the traffic density of current operations, while the second looks at a high-density scenario with approximately twice the traffic of present-day operations. Both data sets only consider arrivals and departures that utilize the runways on the eastern half of the airport. Recorded data from SMS at Dallas Fort Worth[22] were used. The data were recorded on July 3, 2006 between 1630 hrs and 1950 hrs. The total number of operations during this period (for the runways on the east side of the airport) was 162, consisting of 92 departures and 70 arrivals. During this period, the airport was in a South flow configuration, with arrivals on 17L, 17C, 18R and 13R, and departures from 17R, 13L and 18L. This is the most frequent configuration of DFW, and is used 71% of the time during optimal conditions, 57% of the time during marginal conditions.[23]

The data set for current operations is generated as follows: For departing aircraft, the pushback times recorded by SMS are used as the earliest pushback times for the aircraft. A nominal taxi time, based on the distance of the departure runway queue from the aircraft gate and a nominal taxi speed (16 kts) is used to compute the arrival time at the runway. The appropriate inter-departure times for runway operations are then enforced if necessary, depending on the aircraft maximum take-off weight class, while maintaining the order of departures. The minimum inter-departure spacings for wake separation are given in Table 1. The departure runway schedule is determined in this manner, and the take-off times corresponding to this schedule are defined as the scheduled departure runway times. For arrivals, the landing times are set equal to the values observed by SMS. The runway assignments are also obtained from SMS. The average time between departures in this data set is about 134 sec for Runway 17R and about 20 min for Runway 13L. The average time between arrivals is about 149 sec for 17C and about 14 min for 17L.

The gate assignments for both arrivals and departures are obtained from SMS when available; in the absence of SMS records, the gate assignments are inferred from the web sites of the appropriate airlines. The aircraft that depart/arrive on one of the East runways but are assigned gates on the West half of the airport are routed from/to the midpoint of the Alpha, Bravo, Yankee or Zulu taxiways that bridge the two halves of the airport.

The high-density data set is generated as follows: The runway assignments and order in the runway schedule are assumed to be the same as the current assignments. The inter-departure and inter-arrival spacings are set to the larger of half the corresponding value in the current data, and 55 sec. The value of 55 sec is chosen because it is the estimate of the runway occupancy time for current operations,[24] and

	Leading Aircraft		
Trailing Aircraft	Large	Heavy	B757
Large	55	110	90
Heavy	75	100	75
B757	55	110	60

Table 1. Minimum time separations (in seconds) between departures on the same runway.

also the smallest of the inter-departure spacing requirements for a runway. Altering the data in this manner results in 17R operating nearly at capacity (that is, the inter-departure spacing between a large fraction of consecutive departures is 55 sec). For the high-density set, the average inter-departure spacing is about 69 sec for Runway 17R and about 9 min for Runway 13L. The arrivals are generated similarly, with the average inter-arrival time equal to about 80 sec for 17C and about 7 min for 17L. The density (as measured in the number of operations per unit time) of the data set is approximately double (about 1.96 times for the arrivals and 1.74 times for the departures) that of current operations.

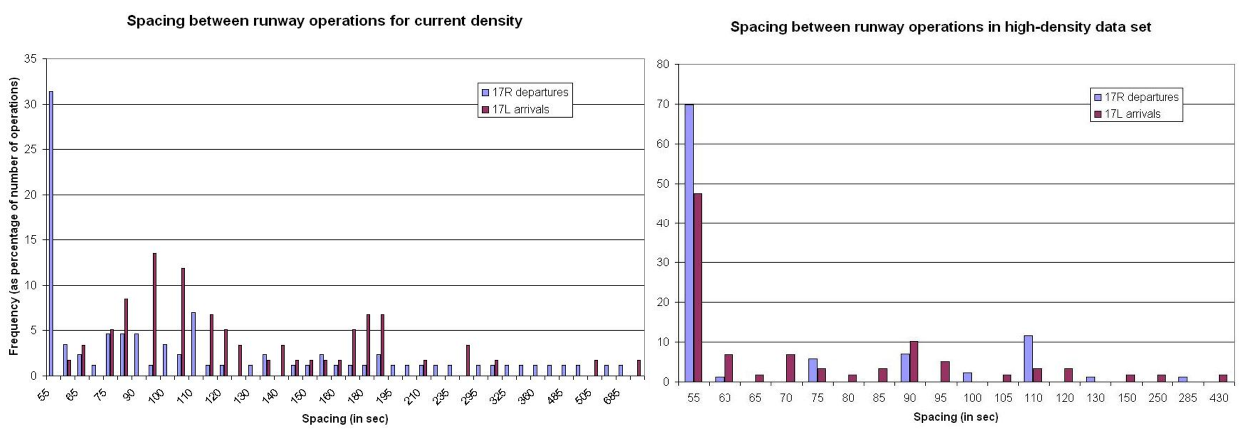

Figure 5. Histogram of inter-arrival and inter-departure spacings for current operations (left) and the high-density data set (right). Note that the scales are not the same.

V. Operational concepts

The objective of this research is to build a framework to assess the benefits of different future operational concepts. While proposing a new operational concept, it is important to bear in mind current procedural factors and pilot/controller considerations. For this reason, the effect of bidirectional taxiways, which would be a substantial deviation from current procedures, is not investigated in detail. Similarly, while it is possible to route aircraft dynamically through the surface (a path-planning problem), this could potentially result in complicated taxi routes that would be undesirable to a pilot. Instead, a predetermined set of alternate routes for every aircraft that would be acceptable to both pilots and controllers is considered, and the optimal route from within this set is selected.

A. Controlled pushback

The main idea behind controlled pushback is that aircraft need not pushback early from their gates and queue at the taxiways, expending fuel and adding to the congestion. Instead, by coordinating the pushbacks based on the surface traffic and runway schedules, it is possible to achieve runway conformance and expend less taxi time and fuel.

In airports without a significant ramp area (such as Boston Logan), aircraft pushback into the taxiway system, while in airports like DFW, pushbacks are coordinated by Ramp Controllers or the Airline Operations Center. The Ramp Controllers clear aircraft for pushback and coordinate their movements until they reach their assigned Spot, where the aircraft is handed off to the Ground controller (who coordinates taxi operations). The issue of whether controlled pushback strategies would be acceptable to the AOCs needs to be considered. The proposed formulation can be used to compute the optimal taxiway schedule from the Spots to the runways and vice versa, given the Spot times of the aircraft. However, this would result in aircraft being put on hold at their Spots with engines on, until it is their turn to enter the taxiway system. It is therefore plausible that the proposed alternative, wherein aircraft are cleared for pushback so that they have a relatively unimpeded taxi route, would be acceptable to the airlines due to the potential for substantial savings in fuel. In situations in which an arriving aircraft is assigned a gate that is still occupied by a departure, there is a tradeoff between delaying the pushback to decrease the taxi-out time, and clearing the gate in order to decrease the taxi-in time. The optimal controlled pushback time then minimizes the sum of the costs incurred by both the arriving and departing aircraft.

B. Taxi reroutes

The possibility of assigning alternate routes to those typically used is also investigated. Under current operations at DFW, taxi routes are generally generated based on runway and gate assignments. Taxi routes are also affected by procedural considerations of the particular airport: for example, at Boston Logan airport, Ground Controllers attempt to route departures through the outer taxiway and arrivals through the inner taxiway;[25] SMS data at DFW suggest that arrivals are routed through the outer taxiway (Lima) and the departures through the inner taxiway (Kilo). Both the Kilo and Lima taxiways are one-way (South to North). To minimize deviation from current procedures, the direction or the uni-directional nature of the taxiways is not altered.

The main effect of congestion on taxi delay is an increase in the runway crossing times. This is mitigated by adding alternate routes that maintain the directionality of the taxiways, but allow aircraft to bypass active runway crossings by taxiing through peripheral taxiways. The uni-directional nature of the Kilo and Lima taxiways prevents departures from bypassing active runway crossings; however, arrivals can be rerouted efficiently. For example, an aircraft that lands on 17C and needs to reach Gate E16 usually crosses 17R at EM1-0 (a taxi length of 0.9 nm), an alternate route is to go around 17R using taxiway Echo-Romeo which is treated as a peripheral taxiway (a taxi length of 2.3 nm) in this work, as shown in Figure 6.[a] While the taxi distance increases, it is found that for high-density traffic, it is more efficient (in terms of time) for an aircraft to taxi on the considerably longer alternate route than to wait in the runway crossing queue for a gap in the departure sequence.

[a] We note that taxiway ER is not a peripheral taxiway in reality. Peripheral taxiways have been proposed at DFW as part of the DFW Airport Perimeter Taxiway (DAPT) project.[26] As per this proposal, the peripheral taxiways will extend well beyond the runway end. The resultant taxi *distance* for arrivals on 17C is expected to increase substantially, while the taxi distance for arrivals on 17L is expected to remain approximately the same. We note that this property is true in our model as well.

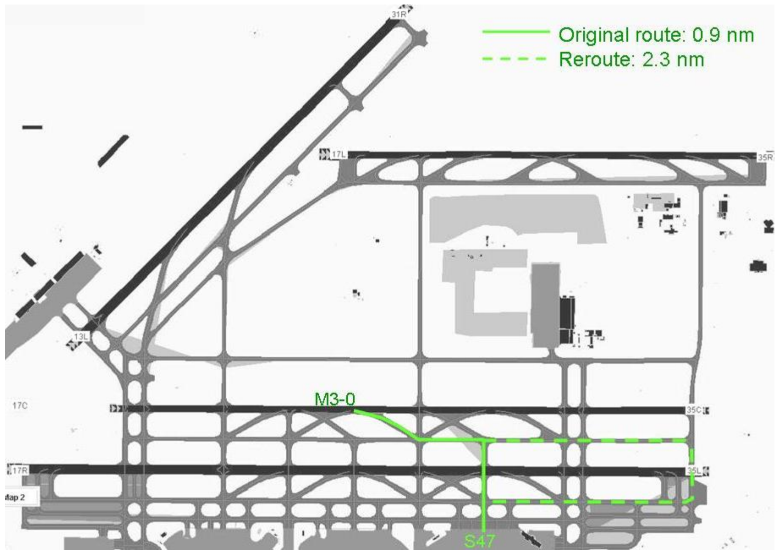

Figure 6. An example of a taxi reroute from runway exit M3-0 to Spot 47 (Gate 16). The original route is 0.9 nm long, while the alternate route is 2.3 nm long.

VI. Results

1. Optimizing over 30-min moving windows

Using the data collected using SMS observations from July 3, data for 30-min intervals is generated. 18 such intervals for current density traffic are generated, and the arrival and departure taxi times, as well as the 4D trajectories that result from optimizing different control strategies are estimated. The first concept is controlling pushback times, and the second is changing taxi routes in addition to the pushback times. As seen in Section V-B, the unidirectional nature of taxiways Kilo and Lima will prevent departures from bypassing active runway queues by using ER as a peripheral taxiway. Therefore, the present study focuses on rerouting arrivals from their runway exits to their assigned gates. To keep the runway crossing times under control, the runway crossing time (time spent waiting in queue to cross an active runway) is constrained to be less than 500 sec. The amount of delay that can be incurred at the gate is also limited, that is, the amount of time between the actual (controlled) pushback and earliest pushback is constrained to be less than 2 min 30 sec for all departures. This is to ensure some degree of fairness, such that no aircraft accrues a disproportionately large value of gate delay. In reality, this would also depend on Ground Delay Programs, Expected Departure Clearance Times, etc. as decided by the runway scheduler.

To make a meaningful comparison, the effects of controlled pushback and taxi reroutes need to be identified, keeping all other factors constant. This is achieved by first computing the optimal arrival and departure taxi times, and 4D routes, when all the aircraft pushback (that is, turn their engines on) at their earliest possible pushback times. The departure taxi time is defined as the time between pushback and take-off, and the arrival taxi time is defined as the time between the arriving at the runway exit and reaching the gate. The average arrival and departure taxi times, and the average time spent waiting to cross an active runway are given in Table 2 for the scenario in which all aircraft pushback at their earliest possible times. The average taxi time (averaged over all the 30-min intervals) is 7.8 min for arrivals and 7.1 min for departures, while the average runway crossing wait time is about 40 sec.

Next, the strategy of controlled pushback is considered for the current density data set. The average arrival and departure taxi times, and the average active runway crossing times for controlled pushback are

Time window	Number of flights			Avg. taxi (min)		Avg. wait to cross runway (min)
	All	Arr.	Dep.	Arr.	Dep.	
16:30 – 17:00	5	0	5	—	6.2	—
16:40 – 17:10	10	0	10	—	6.7	—
16:50 – 17:20	16	3	13	6.8	6.8	0
17:00 – 17:30	28	9	19	7.1	7.5	<0.1
17:10 – 17:40	34	14	20	8.8	7.4	1.6
17:20 – 17:50	36	17	19	9.8	7.5	1.4
17:30 – 18:00	34	18	16	9.7	6.7	0.6
17:40 – 18:10	29	17	12	9.9	7.1	0.4
17:50 – 18:20	27	15	12	8.1	7.4	0.3
18:00 – 18:30	24	12	12	5.5	8.0	<0.1
18:10 – 18:40	29	17	12	6.8	8.0	0.2
18:20 – 18:50	34	17	17	6.9	7.5	0.5
18:30 – 19:00	39	18	21	7.2	7.3	0.4
18:40 – 19:10	35	15	20	6.0	7.1	0.4
18:50 – 19:20	33	12	21	6.0	6.9	0.3
19:00 – 19:30	25	8	17	6.3	6.6	0.2
19:10 – 19:40	29	8	21	9.0	6.5	1.7
19:20 – 19:50	21	6	15	10.6	6.2	2.6

Table 2. Average arrival/departure taxi and active runway crossing times for different time-windows, for current-density data set when all aircraft pushback at their earliest possible times, and take the nominal taxi routes (baseline).

given in Table 3. It is found that the average taxi time (over all time windows) is 7.8 min for arrivals and 5.9 min for departures, while the average runway crossing time is about 40 sec. This corresponds to a 16.9% decrease in the average departure taxi time over a 30-min interval (17.2% when weighted by the number of arriving aircraft in the interval), and a 0.26% decrease in the average arrival taxi time over a 30-min interval (0.18% weighted by the number of departures in the interval).

Next, a combination of controlled pushbacks and taxi reroutes on the current-density data set is considered. As mentioned before, the main purpose of rerouting arrivals is to bypass the active runway crossing queues. The average arrival and departure taxi times, and the average active runway crossing times for controlled pushback with reroutes are given in Table 4. It is calculated that the average taxi time (over all time windows) is 7.6 min for arrivals and 5.9 min for departures, while the average runway crossing time decreases to about 26 sec. This corresponds to a 16.9% decrease in the average departure taxi time over a 30-min interval (17.2% when weighted by the number of departing aircraft), and a 2% decrease in the average arrival taxi time over a 30-min interval (2.1% weighted by the number of arriving aircraft), which is not a considerable gain in arrival delay benefit over simply using controlled pushback. However, the average runway crossing time decreases by 35%.

The exercise is repeated for the high-density data set, with nine time intervals. The level of congestion on the surface results in the problem becoming “infeasible” under the current operating concepts. This is an artifact of the formulation and/or the runway and gate schedules, since the actual problem cannot be infeasible. This modeling artifact is resolved by allowing the formulation to recommend flight “holds,” where a “hold” means that the aircraft will have to be put in a holding area and scheduled in the next 30-min interval. Holding areas will therefore be required under this operating concept.

As in the case of the current-density data, the scenario in which all departures pushback at their earliest possible time is considered first. The average arrival and departure taxi times, and the average active runway crossing times for this high-density case are given in Table 5. The average taxi time (averaged over all the 30-min intervals) is 12.2 min for arrivals and 7.3 min for departures, while the average runway crossing time is about 3.8 min. This average runway crossing time is substantially higher than the values seen in the

Time window	Number of flights			Avg. taxi (min)		% decrease from baseline		Avg. wait to cross runway (min)
	All	Arr.	Dep.	Arr.	Dep.	Arr.	Dep.	
16:30 – 17:00	5	0	5	——	5.5	0.0	11.6	——
16:40 – 17:10	10	0	10	——	5.7	0.0	14.8	——
16:50 – 17:20	16	3	13	6.8	5.6	0.0	17.3	0.0
17:00 – 17:30	28	9	19	7.1	5.9	0.0	20.83	<0.1
17:10 – 17:40	34	14	20	8.8	5.8	0.0	22.2	1.7
17:20 – 17:50	36	17	19	9.8	5.9	0.0	20.8	1.4
17:30 – 18:00	34	18	16	9.7	5.5	0.0	17.8	0.4
17:40 – 18:10	29	17	12	9.9	5.9	0.1	17.7	0.6
17:50 – 18:20	27	15	12	8.1	6.2	0.1	16.3	0.3
18:00 – 18:30	24	12	12	5.5	6.7	0.2	16.8	<0.1
18:10 – 18:40	29	17	12	6.8	6.8	0.0	14.4	0.2
18:20 – 18:50	34	17	17	6.9	6.4	0.0	14.5	0.5
18:30 – 19:00	39	18	21	7.2	6.4	0.2	13.2	0.5
18:40 – 19:10	35	15	20	6.0	6.4	0.1	10.5	0.3
18:50 – 19:20	33	12	21	5.9	5.9	0.8	15.1	0.2
19:00 – 19:30	25	8	17	6.2	5.4	1.5	18.2	0.1
19:10 – 19:40	29	8	21	8.9	5.2	1.0	20.8	1.5
19:20 – 19:50	21	6	15	10.6	4.9	0.0	21.1	2.7

Table 3. Average arrival/departure taxi and active runway crossing times for different time-windows, for current-density data set with controlled pushback.

current-density data set, and also higher than the current recommended maximum of 3 min.[21] It is also noticed that at some time-intervals, a few of the aircraft need to be placed on hold, that is, need to be sent to a holding area.

Next, the effect of employing controlled pushback under high-density conditions is considered. The results are summarized in Table 6. It is found that in doing so, the average taxi time remains 12.2 min for arrivals and decreases to 6.0 min for departures, while the average runway crossing time is still about 3.8 min. This corresponds to a negligible change in the arrival taxi time, and an 17.9% decrease in the average departure taxi time over a 30-min interval (18.5% when weighted by the number of departures in the interval). There are still aircraft that need to be sent to the holding area, although the added flexibility of controlled pushback reduces the number of aircraft that need to be placed there.

Finally, the benefits of employing both controlled pushback and taxi reroutes under high-density conditions are considered. The average arrival and departure taxi times, and the average active runway crossing times for this high-density case are given in Table 7. In contrast to the current-density scenarios, the benefits of taxi reroutes under high-density conditions are significant. This is because surface congestion and runways operating at capacity lead to large runway crossing times; as a result it is more efficient for an aircraft to adopt the longer reroute that bypasses an active runway crossing than to wait in queue. The average taxi time (averaged over all the 30-min intervals) decreases to 10.4 min for arrivals and 6.0 min for departures, while the average runway crossing time is about 2.7 min. This corresponds to a 13.8% decrease in the average arrival taxi time in any 30-min time-window (16.1% when weighted by the number of arrivals in the interval), an 18.1% decrease in the average departure taxi time over a 30-min interval (17.6% when weighted appropriately), and a 31% decrease in the average runway crossing time. The recourse of sending aircraft to holding areas is also avoided.

2. Optimizing over the entire dataset

It is also possible to compute what the average taxi times and routes would be were we to optimize over all the flights in the dataset simultaneously. This corresponds to a 3hr 20 min time-window for current-density

Time window	Number of flights			Avg. taxi (min)		% decrease from baseline		Avg. wait to cross runway (min)
	All	Arr.	Dep.	Arr.	Dep.	Arr.	Dep.	
16:30 – 17:00	5	0	5	——	5.5		11.6	——
16:40 – 17:10	10	0	10	——	5.7		14.8	——
16:50 – 17:20	16	3	13	6.8	5.6	0.0	17.3	0.0
17:00 – 17:30	28	9	19	7.1	5.9	0.0	20.8	<0.1
17:10 – 17:40	34	14	20	8.8	5.8	7.9	22.2	1.7
17:20 – 17:50	36	17	19	9.8	5.9	6.1	20.8	1.4
17:30 – 18:00	34	18	16	9.7	5.5	0.0	17.8	0.4
17:40 – 18:10	29	17	12	9.9	5.9	1.1	17.7	0.6
17:50 – 18:20	27	15	12	8.1	6.2	1.5	16.3	0.3
18:00 – 18:30	24	12	12	5.5	6.7	0.2	16.8	<0.1
18:10 – 18:40	29	17	12	6.8	6.8	0.0	14.4	0.2
18:20 – 18:50	34	17	17	6.9	6.4	0.0	14.7	0.5
18:30 – 19:00	39	18	21	7.2	6.4	0.2	13.2	0.5
18:40 – 19:10	35	15	20	6.0	6.4	-0.2	10.7	0.3
18:50 – 19:20	33	12	21	5.9	5.9	0.8	15.1	0.2
19:00 – 19:30	25	8	17	6.2	5.4	1.5	18.2	0.1
19:10 – 19:40	29	8	21	8.9	5.2	6.8	20.8	1.5
19:20 – 19:50	21	6	15	10.6	4.9	6.6	21.0	2.7

Table 4. Average arrival/departure taxi and active runway crossing times for different time-windows, for current-density data set with both controlled pushback for departures and arrival reroutes.

operations and a 1 hr 50 min time-window for the high-density operations. It is found that for the data recorded on July 7, 2006, controlled pushback results in an approximately 0.2% decrease in arrival taxi time and a 17.1% decrease in departure taxi time, while controlled pushback with arrival taxi reroutes results in a 2.7% decrease in arrival taxi time and a 17.3% decrease in departure taxi time. The level of conformance to the runway schedules remains unchanged, one flight is 25 sec late to its departure runway (13L), but this is true even when all the aircraft pushback at their earliest possible pushback times.

3. Computing environment

The Integer Program was formulated and solved using OPL[27] (a modeling language) and CPLEX (version 10.0), a commercially available optimization software.[28] The computation is conducted on a personal computer with a 3GHz Intel Pentium 4 CPU on a Microsoft Windows platform and 1.24GB of RAM. The

Time interval	Number of flights			Avg. taxi (min)		Average wait for runway crossing (min)	Holding area
	All	Arr.	Dep.	Arr.	Dep.		
16:30 – 17:00	28	11	17	9.0	6.8	1.7	
16:40 – 17:10	42	19	23	10.7	7.4	2.7	
16:50 – 17:20	57	30	27	12.6	7.6	3.3	1 (A)
17:00 – 17:30	61	27	34	15.8	7.6	5.7	3 (2A, 1D)
17:10 – 17:40	66	32	34	15.9	7.4	5.8	1 (D)
17:20 – 17:50	58	31	27	12.6	7.8	4.4	1 (A)
17:30 – 18:00	53	26	27	11.4	8.2	4.0	3 (A)
17:40 – 18:10	52	20	32	11.0	6.7	3.6	
17:50 – 18:20	35	11	24	11.1	6.5	3.5	

Table 5. Average arrival/departure taxi and active runway crossing times for different time-windows, for high-density (≈2x) data set when all aircraft pushback at their earliest possible times.

Time window	Number of flights			Avg. taxi (min)		% decrease from "earliest" OUT		Average wait for runway crossing (min)	Holding
	All	Arr.	Dep.	Arr.	Dep.	Arr.	Dep.		
16:30 – 17:00	28	11	17	9.0	5.7	0.0	15.7	1.8	
16:40 – 17:10	42	19	23	10.7	5.9	0.0	20.0	2.9	
16:50 – 17:20	57	30	27	12.6	6.1	0.0	20.0	3.4	1 (A)
17:00 – 17:30	61	27	34	15.8	6.6	0.0	18.1	5.2	2 (A)
17:10 – 17:40	66	32	34	15.9	6.1	0.0	17.1	5.7	1 (D)
17:20 – 17:50	58	31	27	12.6	6.4	0.0	18.5	4.3	1 (A)
17:30 – 18:00	53	26	27	11.4	6.4	-0.1	22.2	3.7	3 (A)
17:40 – 18:10	52	20	32	11.0	5.6	0.0	16.7	3.5	
17:50 – 18:20	35	11	24	11.1	5.3	0.0	17.9	3.4	

Table 6. Average arrival/departure taxi and active runway crossing times for different time-windows, for high-density (≈2x) data set with controlled pushback.

Time window	Number of flights			Avg. taxi (min)		% decrease from "earliest" OUT		Average wait for runway crossing (min)	Holding
	All	Arr.	Dep.	Arr.	Dep.	Arr.	Dep.		
16:30 – 17:00	28	11	17	8.4	5.7	7.1	15.7	1.4	
16:40 – 17:10	42	19	23	9.6	5.9	11.0	20.0	1.8	
16:50 – 17:20	57	30	27	11.1	6.0	12.3	21.4	2.2	
17:00 – 17:30	61	27	34	11.6	6.2	26.7	23.4	2.8	
17:10 – 17:40	66	32	34	11.1	6.5	30.4	11.7	3.0	
17:20 – 17:50	58	31	27	10.8	6.6	14.3	15.7	3.9	
17:30 – 18:00	53	26	27	11.4	6.2	0.2	24.7	3.8	
17:40 – 18:10	52	20	32	9.5	5.6	13.9	16.7	2.3	
17:50 – 18:20	35	11	24	10.2	5.3	8.4	17.9	2.6	

Table 7. Average arrival/departure taxi and active runway crossing times for different time-windows, for high-density (≈2x) data set with controlled pushback and taxi reroutes.

maximum total computation times (OPL formulation + CPLEX solution times) over the 30-min intervals generated are about 2 min for controlled pushback and 4 min for controlled pushback with reroutes, for the current density data sets. This makes the development of a real-time optimization tool that uses a moving 30-min window and recomputes every 10 min a feasible approach, especially for current traffic densities.

VII. Conclusions

A framework for modeling and planning taxiway operations to help enable coordinated surface movement optimization at airports was presented in this paper. Using observations from the Surface Management System, an Integer Programming formulation for operations at Dallas-Fort Worth airport was developed, current- and high-density traffic data were generated, and the benefits of two potential control strategies that have been proposed for taxiway operations planning: controlled pushback of departures and arrival taxi reroutes were assessed. The preliminary analysis estimates that controlled pushback would decrease the departure taxi times by 17% even for current traffic densities, while in high-density scenarios, taxi reroutes would decrease the arrival taxi time by about 14%. In addition, rerouting arrivals to bypass active runway crossings significantly decreases the time spent waiting in runway crossing queues. These results suggest that there are substantial benefits to the optimization of taxiway operations, both in terms of taxi times and queue lengths on the airport surface, and that the proposed formulation could be a valuable approach for gauging the benefits of future operational concepts. Extensions of the approach to a future system with mixed equipage, reduced separation requirements and bidirectional taxiways were also discussed. The model of aircraft taxi trajectory adopted in this paper assumed the same nominal speeds and speed limits for an aircraft throughout its route. It would be desirable to use a higher fidelity model that takes into account the variation in taxi speeds.[29,30] This feature can be incorporated quite easily into the proposed approach. In addition, decreased separation buffers and bidirectional taxiways can also be investigated using this framework. Future research plans include the investigation of potential optimization architectures, including an analysis of the interactions between the taxiway, runway and ramp schedulers.

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