Analysis of Taxiway Aircraft Traffic at George Bush Intercontinental Airport, Houston, Texas

Kai Yin, Chunyu Tian, Bruce X. Wang, and Luca Quadrifoglio

Serving one of the largest metropolitan areas in the United States, the George Bush Intercontinental Airport (IAH) in Houston, Texas, is one of the 10 airports with the longest average taxi-out and taxi-in times. This paper assesses the congestion at IAH by analyzing taxi times and flight data during different hours of the day. The capacity of IAH is investigated by examining the number of departing flights on the ground. IAH is operating close to capacity most of the time. Because increasing airport capacity can mitigate congestion, this report develops a surface operation model based on analyzed results to achieve this aim. A mixed-integer programming formulation is proposed to optimize total taxi times by finding optimal taxi routes and the related schedules. The model is applied to a sample from real data.

With increased air traffic demand in the past few years, many airports face severe congestion problems. Most major airports are operating close to capacity. According to data collected by the Bureau of Transportation Statistics for the year 2007, outbound and inbound taxi times increased noticeably in 2007 and surpassed the previous peak reached in 2000 (*1*).

Serving one of the largest metropolitan areas in the United States, the George Bush Intercontinental Airport (IAH) in Houston, Texas, is one of the 10 airports with the longest average taxi-out and taxi-in times (*1*). IAH needs to improve its overall capacity. It is recognized that increased airport capacity can be achieved through a new concept of operation (*2*). Hence, the objectives of this paper are to analyze departure and arrival data from IAH and to develop a model to optimize surface operations based on the analyzed results.

Because the longest taxi-out times occur in the summer (*1*), this study used departure and arrival data at IAH from June 1 to June 15, 2010. The data were obtained and combined from two sources: IAH airport and the Research and Innovative Technology Administration (*3*). The following information was gathered:

- Scheduled and actual pushback time (gate-out) of each departing flight,
- Scheduled and actual arrival time (gate-in) of each arriving flight,
- Wheel-on time of each arrival and wheel-off time of each departure,
- Flight code of each flight,
- Runway usage of each flight, and
- General information about gate usage.

This paper is organized as follows. First, general information about IAH is introduced. Then runway operations and taxi times are studied at different hours of the day. The capacities of departures and congestion are investigated by examining the number of departing flights on the ground. On the basis of the analyzed results, a mixed integer programming formulation is then proposed for optimizing surface operations. The model can optimize the total taxi times by finding the optimal taxi routes and the related schedules. In addition, the model is applied to a sample from real scheduled flight data.

ANALYSIS OF ARRIVALS AND DEPARTURES

Overview

The IAH airport configuration featured two sets of parallel runways and one single runway: 08L/26R, 08R/26L, 15L/33R, 15R/33L, and 09/27, as shown in Figure 1. By the time this study was completed, all the runways were used in a mixed arrival–departure mode to accommodate the increase in air traffic associated with the airport, unlike the prior operation strategy, which allowed only Runways 15L/R to serve departing aircraft (*4*). This runway usage strategy is shown in Table 1, which summarizes the arrival and departure information from June 1 to June 15, 2010.

Table 1 shows total arrivals and departures for each runway as well as the average value per day. Runways 27 and 26L/R handle most arriving aircraft, and Runways 15L/R deal with most departing aircraft, indicating that west flow operations occur most often at IAH. Rare use of Runway 09 for arrivals reveals that aircraft arriving on it would affect the aircraft departing from Runways 15L/33R and 15R/33L because of the need for a 2-mi clearance to protect airspace. Because of the longer distance between Runway 26R/08L and each terminal (see Figure 1), Runways 26L/08R and 27/09 are used more often than Runway 26R/08L. In addition, the total number of arrivals, 11,150, does not equal the total number of departures, 11,160 (not shown in Table 1) because some flight information is not reported.

Analysis of Arrivals

Airport surface operations consist of those in four areas: runways, taxiway system, ramp areas, and gates. Operations in each area are critical to each arriving and departing aircraft and could be a reason

Zachry Department of Civil Engineering, Dwight Look College of Engineering, Texas A&M University, College Station, TX 77843-3136. Corresponding author: K. Yin, yinkai1000@gmail.com.

Transportation Research Record: Journal of the Transportation Research Board, No. 2266, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 85–94.
DOI: 10.3141/2266-10

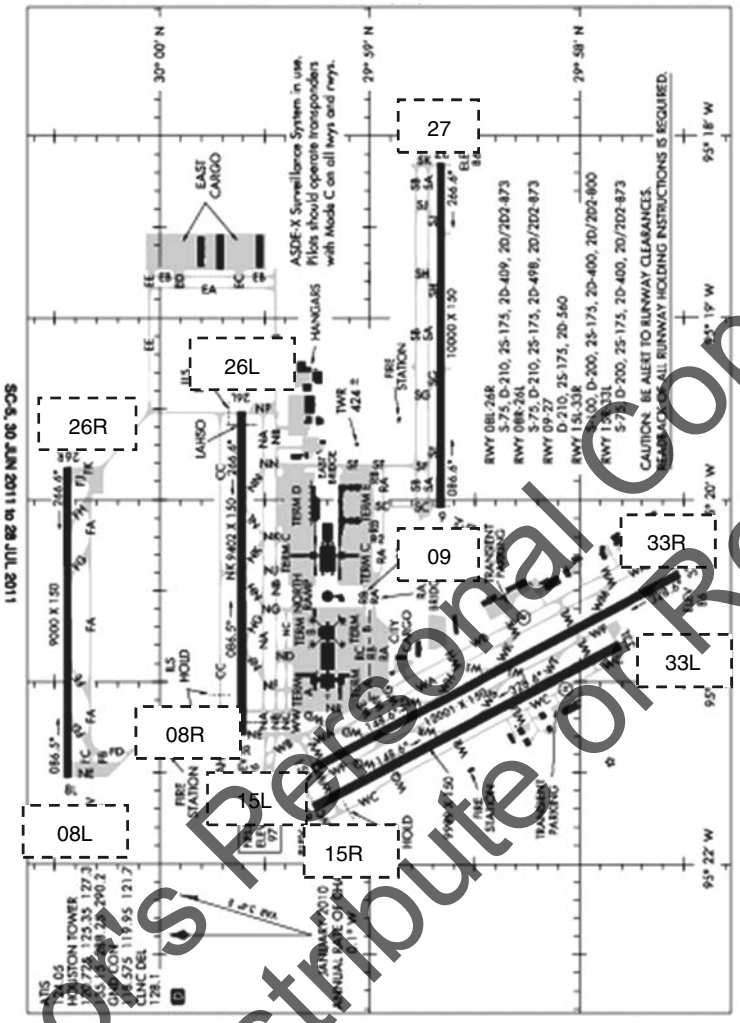

FIGURE 1 IAH airfield layout and runway system.

TABLE 1 Summary of Arrivals and Departures for Each Runway

Runway	Total Number of Arrivals	Average Arrivals/Day	Total Number of Departures	Average Departures/Day
15R	100	6.67	3,467	231.13
33L	0	0.00	101	6.73
15L	41	2.73	6,618	441.20
33R	4	0.27	174	11.60
09	102	6.80	452	30.13
27	4,436	295.73	40	2.67
08R	1,149	76.60	5	0.33
26L	3,966	264.40	207	13.80
08L	609	40.60	1	0.07
26R	732	48.80	85	5.67

for delay. For the arrival process, an arriving aircraft leaves the runway as soon as possible after touchdown and enters the taxiway system. Then it taxis to the terminal area and may wait on the ramp for a prepared gate. The taxi-in time of arriving aircraft measures the time between landing (wheel-on) and gate arrival (gate-in). For a runway with mixed usage, arriving aircraft might interact with departing aircraft in some way. Although Idris et al. (*5*) found a low correlation between taxi-out delay and arrivals, a reexamination by Clewlow et al. (*6*) indicated that the number of arriving aircraft did, as one might expect, affect taxi-out times. Hence, this section examines the number of arrivals each hour and the related taxi-in time.

The number of arrivals and departures can vary significantly at different times of day. The number of runway operations in 1 h may affect the number of departures or arrivals the next hour. To show the statistics of runway operations at different times of day, the mean value or the total number of arrivals can be used. However, a problem may occur in these two cases. Because there may be no records of arrivals for a particular hour on some days, a mean value averaging the total number of arrivals over the whole period may underestimate the real value. Likewise, using only the total number of operations does not reveal how busy the runway is for the whole period. To account for these factors, Table 2 uses a mean value equal to the total number of arrivals divided by the number of days when there is at least one arriving aircraft. The table shows the percentage of those days for the whole period as well. For example, 50% of days in use in Table 2 means that only 50% of the whole period (15 days in this study) for that particular hour had runway operations.

Table 2 shows the average number of arrivals on the most frequently used runways. All times used in this paper are local Houston local times. The busiest period for arrival operations is from 13:00 to 14:00 on most days. There are also two local arrival peaks from 16:00 to 17:00 and from 19:00 to 20:00. The airport operates all runways during these periods. Runways 27 and 26L are used most often and their busy periods extend from 10:00 to 17:00. Although the records show Runway 08R can handle 30 arrivals in 1 h, a detailed examination of the data indicates that the taxi-in times increase during these hours and that the optimal number of arrivals for this runway may be smaller, as it should not cause an increase in taxi times. The available data and the information in Table 2 suggest that the optimal maximum number of arrivals for Runways 08R/L and 27 is 25 aircraft per hour.

Figure 2 shows the average taxi-in times each hour of the day. There is no significant difference in taxi-in times between Runway 27 and 26L/08R; both are <10 min per aircraft. The Runway 08R taxi times have two peaks, around 11:00 and around 17:00. For Runway 26R/08L, the average taxi-in times are >10 min, which is

TABLE 2 Runway Operations for Arrivals Each Hour of Day

	Runway									
	27		08R		26L		08L		26R	
Hour	Mean	% of Days in Use	Mean	% of Days in Use	Mean	% of Days in Use	Mean	% of Days in Use	Mean	% of Days in Use
0:00	2.38	53	1.83	40	2.67	20	0.00	0	0.00	0
1:00	1.29	47	1.33	20	1.00	7	0.00	0	0.00	0
2:00	1.00	13	0.00	0	1.00	7	0.00	0	0.00	0
3:00	1.50	27	1.00	13	1.33	20	1.00	7	0.00	0
4:00	2.00	80	1.00	7	1.50	13	0.00	0	0.00	0
5:00	4.07	100	7.42	80	1.50	13	0.00	0	0.00	0
6:00	7.87	100	8.58	80	4.91	73	1.00	7	0.00	0
7:00	19.53	100	0.00	0	21.40	100	0.00	0	8.73	100
8:00	16.93	100	0.00	0	17.40	100	1.00	7	3.50	53
9:00	24.83	80	4.00	7	17.21	93	6.50	13	2.83	40
10:00	25.45	73	16.00	13	21.69	87	12.67	20	5.33	40
11:00	22.15	87	27.00	7	20.00	87	11.67	20	2.25	53
12:00	20.07	93	30.00	7	18.50	93	10.33	20	2.00	40
13:00	26.07	93	27.00	13	24.92	87	27.00	13	6.42	80
14:00	26.46	87	31.00	13	26.92	87	28.00	13	5.17	80
15:00	15.73	100	7.75	27	14.80	100	4.75	27	2.57	47
16:00	21.93	93	21.20	33	23.23	87	21.00	27	7.11	60
17:00	24.20	67	24.86	47	22.40	67	20.67	40	8.00	60
18:00	16.83	80	17.86	47	15.58	80	9.83	40	2.57	47
19:00	27.50	80	20.40	33	23.46	87	17.00	20	11.91	73
20:00	11.85	87	22.00	27	18.42	80	7.80	33	3.91	73
21:00	13.08	80	10.50	27	4.60	67	1.50	13	1.13	53
22:00	5.71	93	4.83	40	5.89	60	0.00	0	0.00	0
23:00	6.62	87	4.13	53	3.78	60	0.00	0	0.00	0

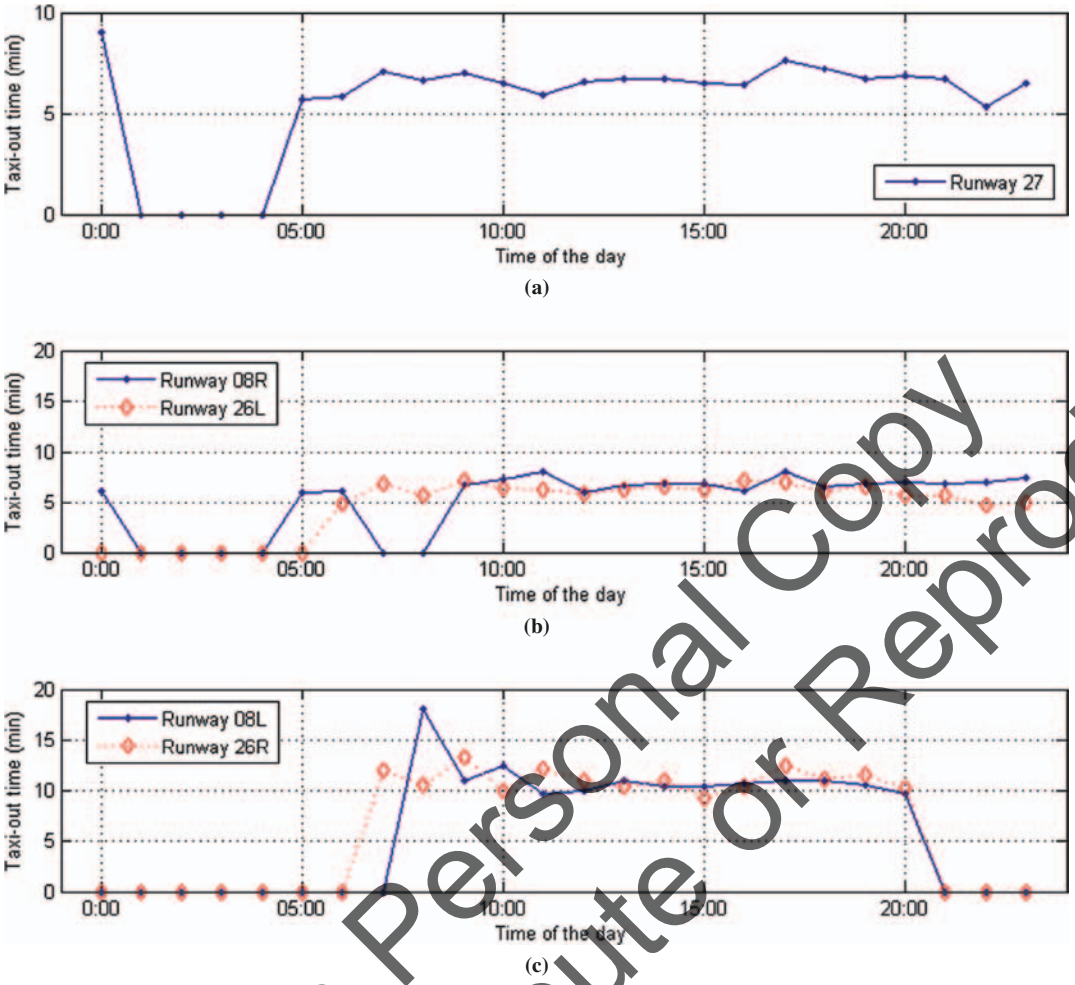

FIGURE 2 Taxi-in time at different hours of day.

not surprising as it is farther from the terminal than the other runways. One may wonder why there is a peak taxi-in time of >15 min for Runway 08L at about 9:00. A detailed examination of the data shows that there were abnormal operations on June 9: only Runway 08L served arrivals from 9:00 to 10:00, which caused taxi-in times to increase. Runway 26L/08R was closed for an unknown reason.

Congestion Determination

Most major airports face congestion that occurs when departure demand exceeds capacity (*7*). Although sometimes such phenomena are due to reduced capacity during bad weather or construction of runways, inefficient taxi operations for departing aircraft contribute the most time to congestion, especially at airports where a conservative taxi strategy is adopted. Without detailed data such as taxi routes, the analysis can be done only with macroscopic observations. Because better understanding of the taxi process for departures can help in analyzing congestion, the departure process is described first and factors affecting the taxi-out time from a macroscopic perspective are then discussed.

In contrast to the arrival process, departing aircraft would experience delay at each surface operation region. At the gate, they should wait for pushback because of a long pushback queue. They should wait with others at the ramp to enter the taxiway system; when they taxi to the runway, they may wait in a departure queue to take off. When there is a large departure demand, the queue can form in any of the above areas. Individual departing aircraft would experience a long taxi-out time, resulting in a large number of aircraft being kept on the airport surface, which indicates there is a saturation departure rate or a capacity at the airport. Although this concept is intuitively clear, in practice it is difficult to determine the capacity.

To determine the saturation departure rate at IAH, the approach used by Simaiakis et al. (*7, 8*) is adopted in this study. It considers the throughput of the departure runway with respect to the number of aircraft, denoted by *N,* on the ground after pushback from their gates. As *N* increases, the mean departure rate increases up to some maximum value. There is no additional increase in the mean throughput on average if *N* still increases. Such a maximum value can be seen as the capacity and the minimum number of *N* at capacity is defined as the saturation point (*7*). Conceptually, if the number of departing aircraft on the ground exceeds the saturation point, the airport experiences congestion. The weakness of such an approach needs to be pointed out. At a particular value of *N,* the takeoff throughput may vary significantly compared with the mean value. Even when *N* exceeds the threshold, the variance of throughput can be still large. It implies that many other factors affect the departure

throughput and a more precise method may be needed to obtain the capacity. However, because of limited data, this approach is easily implemented and can be accepted as a tool to estimate capacity in practice.

For the data used in this study, the average hourly departure throughput saturates at 50 when there are 43 departing aircraft on the ground. Here, capacity refers to the total maximum hourly throughput of Runways 33L/15R and 33R/15L. Hence, the saturation point is 43 and the capacity is 50 aircraft per hour. This departure capacity is for daytime only. The capacity at night cannot be obtained because of lack of data.

In Figure 3, solid bars show the mean values of the number of departing aircraft on the ground with respect to each hour of the day. Error bars denote standard deviation. This figure reveals that the number of departures is significantly larger than the saturation point of 43 aircraft for 2 h of the day: from 15:00 to 16:00 and from 19:00 to 20:00. However, except for these 2 h, there is no significant difference between the maximum number of departing aircraft and capacity. It is reasonable to argue that if the efficiency of taxi operations at IAH could be improved, congestion might mitigate during the above 2 h. Moreover, examination of the standard deviation suggests that the airport may experience congestion occasionally from 10:00 to 12:00 and from 14:00 to 15:00. A more detailed investigation shows that such occasional congested periods exist infrequently. The above analysis also suggests that the airport may benefit from controllers adopting a more efficient strategy.

Analysis of Departures

Due to the west flow of operations occurring most of the time at IAH, Runways 15L/33R and 15R/33L are used most often for departing aircraft. Table 3 shows the average number of departures on these runways. The meaning of "percentage of days in use" is the same as in Table 2. This table illustrates that there are three peak hours of the day at Runway 15R, when the number of departing aircraft per hour exceeds 20: 9:00 to 10:00, 13:00 to 14:00, and 18:00 to 20:00. However, it appears that Runway 15L keeps operating at a high throughput rate for most hours of the day. With information from Figure 3, a crude estimate of the capacity of Runway 15L is 30 aircraft per hour. Comparing the operations on Runways 15R and 15L, Runway 15L handles more aircraft, and Runway 15R cannot operate at a high throughput rate most of time. A possible reason is that, being closely spaced, these two runways are interdependent. In other words, departures from Runway 15R may depend on departures from Runway 15L. Runway 15L can still handle a large amount of departures per hour from 21:00 to 22:00, implying that lighting conditions do not influence the capacity of this runway.

The standard deviation of the number of departures is not shown in Table 3, as the values generally range from 5.00 to 8.00 for most periods. The only exception occurs from 11:00 to 12:00 when the standard deviation for both runways reaches up to 10.00, which indicates that departure demand fluctuates around noon. In addition, the data show that Runways 33R and 33L are occasionally used for departures. Since all terminals for passengers are close to the thresholds of Runways 15L and 15R as shown in Figure 1, the departures using Runways 33R and 33L could be cargo or other types of aircraft, whose information is missing in the current data.

Taxi-out times of departures on Runways 15R and 15L are also shown through their mean values and standard deviations in Table 3. In general, taxi-out times increase as the number of departures increases. During peak hours, taxi-out times from the gates to Runway 15L are >15 min per aircraft, and the taxi-out time to Runway 15R is >20 min per aircraft. There is a 5-min difference between them. It is also clear that the standard deviation is relatively large during busy hours, implying that congestion at the airport not only leads to increased taxi-out times but also brings about the uncertainty of handling departing aircraft. Moreover, the taxi-out time from the gate to Runway 15R is about 3 min longer than that to Runway 15L. On one the hand, this difference is simply because the aircraft require more time to reach the Runway 15R threshold. On the other hand, considering a 5-min difference during peak hours, one can reasonably infer that the queues at Runway 15L probably affect the aircraft taxiing to Runway 15R.

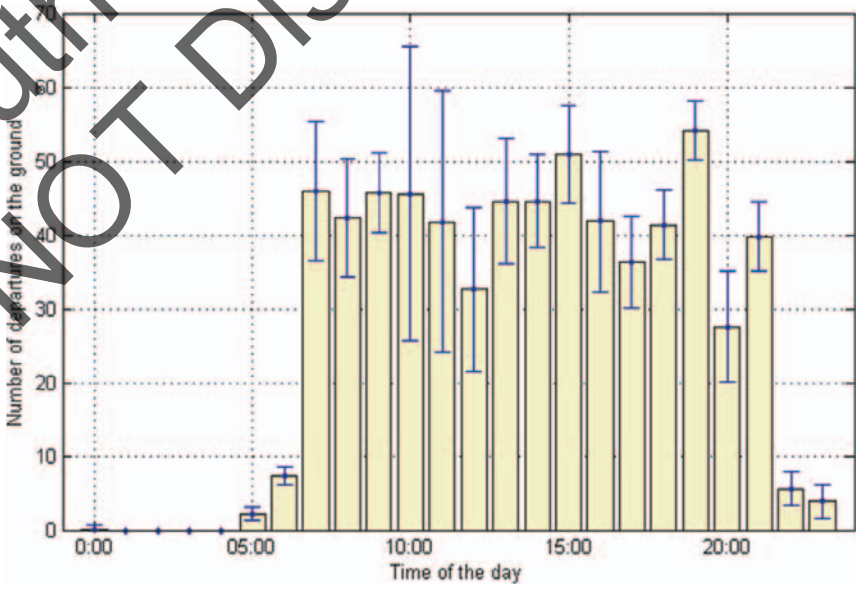

FIGURE 3 Number of departing aircraft on the ground each hour.

TABLE 3 Runway Operations for Departures and Taxi-Out Times Each Hour of Day

	Runway							
	15R				15L			
	Number of Departures		Taxi-Out Time, min		Number of Departures		Taxi-Out Time, min	
Hour (local)	Mean	% of Days in Use	Mean	SD	Mean	% of Days in Use	Mean	SD
0:00	1.00	7	0.00	0.00	2.30	67	0.00	0.00
1:00	0.00	0	0.00	0.00	3.00	7	0.00	0.00
2:00	0.00	0	0.00	0.00	2.00	7	0.00	0.00
3:00	0.00	0	0.00	0.00	1.00	7	0.00	0.00
4:00	1.00	13	0.00	0.00	1.00	7	0.00	0.00
5:00	1.00	7	0.00	0.00	2.40	100	10.33	2.75
6:00	2.14	47	12.50	3.99	11.00	100	12.82	3.34
7:00	13.07	93	17.27	3.05	24.00	100	14.11	1.03
8:00	13.80	100	23.56	10.80	22.67	100	15.92	6.95
9:00	21.73	100	22.00	10.00	34.40	100	16.61	4.43
10:00	17.50	93	17.38	5.74	28.07	100	16.93	6.15
11:00	17.43	93	16.26	2.81	29.93	100	17.31	5.14
12:00	10.42	80	15.67	2.26	24.00	93	13.52	1.07
13:00	20.00	93	17.45	4.24	32.00	93	15.29	2.88
14:00	14.40	100	15.78	1.85	29.80	100	13.54	2.03
15:00	17.57	93	17.47	4.86	28.40	100	14.73	4.45
16:00	18.87	100	21.41	8.42	27.93	100	19.23	7.93
17:00	10.00	73	21.34	11.52	25.00	93	13.85	4.23
18:00	23.07	93	18.50	2.95	30.79	93	14.45	2.39
19:00	22.93	100	17.87	2.78	33.93	100	15.78	2.04
20:00	6.93	93	15.62	4.50	20.60	100	11.44	1.21
21:00	12.47	100	20.09	8.78	29.73	100	14.08	2.63
22:00	3.50	53	24.42	13.05	7.60	100	11.14	2.34
23:00	1.00	27	8.67	1.25	5.08	87	10.82	3.17

NOTE: SD = standard deviation.

Taxi-out times vary from day to day, depending on congestion at the airport. This effect may influence the accuracy of estimating the mean value and result in a large standard deviation. For example, Figure 4 illustrates the mean taxi-out times to Runways 15R and 15L between June 1 and June 5, 2010. These 5 days were chosen because IAH was much busier than on other days in the available data of this study. The taxi-out times on those 5 days are generally longer than the overall average, especially around 10:00, 17:00, and 21:00. In Table 3, the difference of taxi-out times between Runways 15R and 15L is not significant at most times. However, this is not true in Figure 4, where the difference is significant most of the time. Figure 4 suggests that taxi-out times from the gates to Runway 15R could become excessive when the airport experiences congestion. This case suggests that one should take care when dealing with the data over a long period, and more insightful investigation is needed in future studies.

MODEL OF SURFACE OPERATIONS

The above analysis shows that the taxi times become longer during busy hours at IAH. Although this phenomenon is normal at most major airports, sometimes it might be due to an inefficient taxi operation strategy. This study proposed a model to optimize surface operations.

Modeling the taxi processes and determining taxi routes for arriving and departing aircraft are important for optimizing surface operations and developing related decision support tools (*9*). Optimization tools can help controllers navigate aircraft operations. Extensive research has been done in optimizing airport surface operations. While some studies apply dynamic programming with the shortest path algorithm (*10*), most authors use mixed integer linear (MIP) programming (*11–13*) to incorporate different types of control strategies. Some studies model surface operations through time–space network models (*12*), and some use network assignment techniques to decide on taxi routes (*14*). Among these models, control strategies and taxi route decisions are critical to performance, as most constraints such as link directions, time continuity, and order constraints are similar to the constraints in the traditional vehicle routing and scheduling problem. In the study of Smeltink et al. (*11*), each individual aircraft is assigned a fixed taxi route regardless of whether it is a departure or an arrival. The problem then becomes a scheduling problem, which requires aircraft to reach each segment of the taxi route at a scheduled time. Balakrishnan and Jung (*15*) chose taxi routes from a preferred set and assessed two controlled strategies: controlled pushback and taxi reroutes.

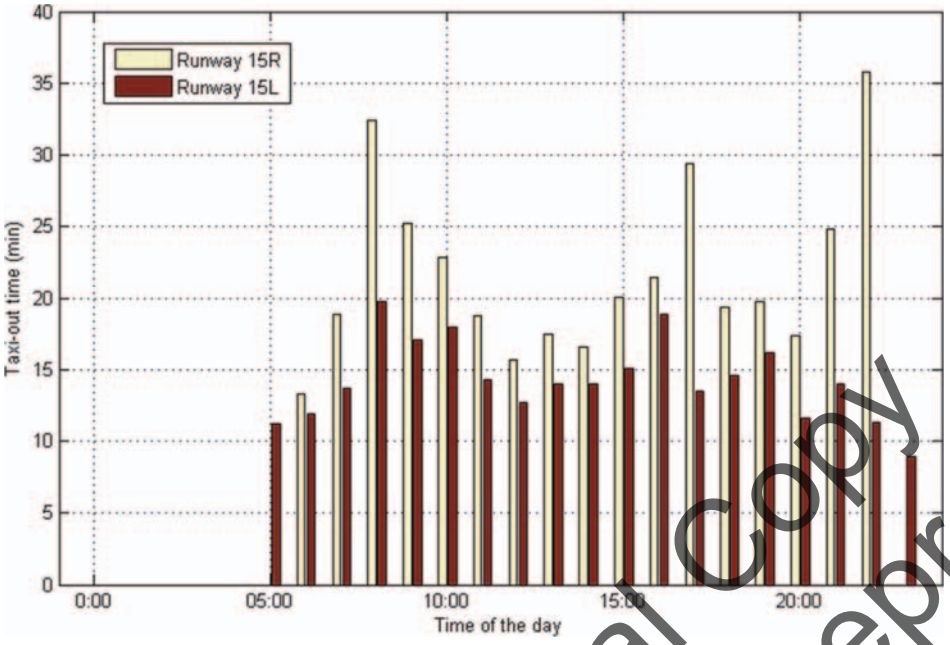

FIGURE 4 Taxi-out times from gates to Runways 15R/L between June 1 and June 5, 2010.

This taxi route strategy is more flexible than preassigned routes and enjoys an efficient computational time. The authors show that taxi-out times are reduced and the airport would benefit from these control strategies, especially for high-density operations. Although some studies (*9, 16*) recommended that several airport ground systems be considered together, the problems are too complex and not practical to implement.

This study proposes MIP programming and adopts a centralized control strategy to investigate taxi planning in good weather conditions. The proposed model aims at automatically providing non-conflicting taxi routes and scheduling plans for all aircraft on the airport grounds to minimize overall taxi times.

Taxi Route Decision and Control Strategy

In practice, taxiing aircraft have the option to take multiple taxi routes. If controllers realize that some taxiways are occupied by another aircraft during a busy period, they may assign the aircraft an alternative route to reduce congestion. Along this direction, the method of Marin (*12*) was adopted and only the origin and destination of each aircraft were fixed. With proper objectives and constraints in the model, the aircraft must follow the same taxi route to their destination when there is no congestion on the ground. If there is congestion on some links, the solution can search optimal routes for all aircraft as well as their schedules of using those routes. Because of increased variables and constraints, the computation time can be large and some heuristic methods should be adopted.

During congestion on the ground, aircraft are sometimes required to hold at some area along their route to wait for queue clearance. The most commonly used holding points are gates. If one aircraft frequently holds in the middle of the path with the engine on, the stop-and-go phenomenon would burn much fuel. From economic and environmental perspectives, it is desirable to hold aircraft at the gate if there is a need.

Model Formulation

The IAH airport surface is modeled as a graph of nodes and links, denoted by $G = \{N, L\}$. N is a set of nodes, which can represent gates, intersections of taxiways, runway crossing points, runway threshold, and runway exits. L is a set of directed links representing taxiways and other links connecting the nodes.

Let $F = \{D, A\}$ be the aircraft set where D is the set of departures and A is the set of arrivals. For each aircraft $i \in F$, the origin (denoted by ORI_i) and the destination (denoted by DES_i) are fixed. A taxi route for aircraft i is thus a sequence of nodes connecting the origin and the destination. For departure aircraft, the gate is the origin and the runway threshold is the destination. Similarly, for arrival aircraft, the origin is the landing runway exit and the destination is the assigned gate. A dummy node N_{air} is introduced in this model and can be understood as the outside of the airport ground network. Each departing aircraft reaches the destination and then enters this dummy node.

Let each aircraft associate with a sequence of planning periods, denoted by $\{E_1, E_2, \ldots, E_p\}$. Each E_j is a length of time. The fixed number p is chosen to guarantee every aircraft can finish the movement from the origin to the destination. When an aircraft leaves a certain node, a new planning period begins. It is assumed that all aircraft enter the dummy node within E_p planning periods, implying that they complete their paths. If the aircraft enters the dummy node in E_j where $j \neq p$, the left planning periods are set to 0. For each arriving or departing aircraft, the taxi time is between its first planning period and its last planning period.

Definition of Variables

- $R^j_{(i,n_1,n_2)}$ = route variable = 1 if aircraft i moves from node n_1 to node n_2 at planning period j, = 0 otherwise.
- $Z^n_{(i,j)}$ = order variable = 1 if aircraft i arrives at node n earlier than aircraft j, = 0 otherwise. The dummy node is not considered for this variable.

$C^{n_r}_{(i,j)} = 1$ if aircraft i_1 takes off earlier than the time when aircraft i_2 (if any) crosses the runway; otherwise it is 0. Notion n_r is the threshold of the runway;

t_i^j = starting time of planning period j for aircraft i; and

EPTi and EAT$_i$ = planned pushback time for departures and planned arrival time for arrivals, respectively.

Objective Function

The objective is to minimize the total cost and total taxi times by finding the taxi routes and schedules for all aircraft. It is expressed as Equation 1, where f_i is a cost variable associated with each departing and arriving flight. For different flights, f_i can be different according to the urgency of each individual flight.

$$\min \sum_{i \in F} f_i \left(t_i^{E_p} - t_i^1 \right) \tag{1}$$

General Constraints

Aircraft can use any link connecting the node in the airport network, and an individual aircraft should move from the origin to the destination. These requirements are expressed as Constraints 2. Constraints 3 ensure that each aircraft moves once in each planning period. Aircraft that move to one node in one planning period should move to another from this node. Although the aircraft can stay in the same node, it cannot be allowed to turn back. Constraints 4 represent these requirements. The above constraints are observed in many other models (*16*).

$$R^j_{(i,n_1,n_2)} \le C_{(n_1,n_2)},\ R^p_{(i,DES_i,DES_i)} = 1$$

and

$$R^1_{(i,ORI_i,ORI_i)} = 1 \qquad \forall i \in F, j \in \{1, \ldots, p\}, n_1, n_2 \in N \tag{2}$$

$$\sum_{m \in N} \sum_{n \in N} R^j_{(i,m,n)} = 1 \qquad \forall j = \{1, \ldots, p\} \tag{3}$$

$$\sum_{n \in N} R^j_{(i,n,m)} = \sum_{n \in N} R^{j+1}_{(i,n,m)}$$

and

$$R^j_{(i,n_1,n_2)} + R^{j+1}_{(j,n_2,n_1)} \le 1 \qquad \forall j \in \{1, \ldots, p-1\} \tag{4}$$

To implement the control strategy, the variables DEP$_i$ are introduced to represent the maximum allowed pushback delay for each departure. The pushback time found by the model should be not less than the planned pushback time, and the pushback delay should not be longer than the maximum allowed delay. For arrivals, the situation is difficult. The airport usually has only the planned arrival time for each flight. However, the flight can arrive earlier or later than planned according to some uncertainty. Thus, the arrival times might be considered as random variables, resulting in a complex model. To simplify the procedure, the variables DEA$_i$ represent the possible time deviation from the planned arrival. Although one flight may not arrive at the time found by the model, the flight can still follow the taxi route calculated by the model as long as the time deviation is not too large. In addition, the first planning period is used to fix an aircraft at its origin. Constraints 5 express the above requirements.

$$t_i^1 = t_i^2$$

$$\begin{aligned} &\text{EPT}_i \le t_i^2 \le \text{EPT}_i + \text{DEP} \qquad \forall i \in D \\ &\text{EAT}_i - \text{DEA} \le t_i^2 \le \text{EAT}_i + \text{DEA} \qquad \forall i \in A \end{aligned} \tag{5}$$

Order constraints should be considered to ensure that aircraft i_1 and aircraft i_2 pass node n in order. In addition, the order variables are set to 0 for the same aircraft. Then, one has Constraints 6.

$$Z^n_{(i,i)} = 0$$

$$\begin{aligned} &Z^n_{(i_1,i_2)} + Z^n_{(i_2,i_1)} \le \frac{\left(\sum_{m \in N} \sum_{j \in P} R^j_{(i_1,m,n)} + \sum_{m \in N} \sum_{j \in P} R^j_{(i_2,m,n)} \right)}{2} \\ &Z^n_{(i_1,i_2)} + Z^n_{(i_2,i_1)} \ge \sum_{m \in N} \sum_{j \in P} R^j_{(i_1,m,n)} + \sum_{m \in N} \sum_{j \in P} R^j_{(i_2,m,n)} - 1 \end{aligned} \tag{6}$$

Safety Constraints

This study assumes that the taxiway is wide enough to allow only one aircraft to move. Furthermore, if one aircraft arrives at one node earlier than another on the same link, it should arrive at the next node earlier as well. Hence, one has Constraints 7. In addition, two aircraft have to avoid a head-to-head collision (i.e., moving toward each other). Then the constraints can be obtained by using $R^j_{(i_1,n_2,n_1)}$ in Constraints 7 instead of $R^j_{(i_1,n_1,n_2)}$.

$$Z^n_{(i_1,i_2)} + Z^n_{(i_2,i_1)} \le 2 - \left(\sum_{j \in P} R^j_{(i_2,n_1,n_2)} + \sum_{j \in P} R^j_{(i_1,n_1,n_2)} \right)$$

$$\forall i_1 \ne i_2 \in F, n_1 \ne n_2 \in N$$

$$Z^n_{(i_1,i_2)} + Z^n_{(i_2,i_1)} \ge \left(\sum_{j \in P} R^j_{(i_2,n_1,n_2)} + \sum_{j \in P} R^j_{(i_1,n_1,n_2)} \right) - 2 \tag{7}$$

Minimum Separation and Runway Crossing Constraints

For safety, taxiing aircraft must maintain a certain distance between one another. No uniform standard exists for the minimum separation, since different authors apply different standards in the literature (*11–14*). However, any standard needs supporting data, and this issue needs to be investigated further. This study uses a minimum separation time t_{sep} instead of a minimum separation distance to make the constraint simpler. Because of the uncertainty of taxiing speed in the trajectory, the minimum separation needs to be large enough to ensure safety. This principle is illustrated in Constraints 8, where M is a large constant.

$$t_{i_1}^{j_1+1} + t_{sep} \le t_{i_2}^{j_2+1} + M \left(3 - Z^n_{(i_1,i_2)} - \sum_{m \in N} \left(R^{j_1}_{(i_1,m,n)} + R^{j_2}_{(i_2,m,n)} \right) \right) \tag{8}$$

Although runway crossing is not allowed at IAH, it is a popular phenomenon at many major airports. A successful runway crossing has to account for factors such as runway occupancy time and crossing time. To complete the model, related constraints are presented here. It is assumed that aircraft i_2 wishes to cross an active runway from node n_{cb} to n_{ca} and aircraft i_1 at runway threshold n_r uses the runway. Let $Y_{(i_1,i_2)}$ be the total time needed to complete one crossing. Constraints 9 illustrate the above requirements for the case of one departing aircraft using the runway.

$$t_{i_1}^{j_1+1} + Y_{(i_1,i_2)} \le t_{i_2}^{j_2+1} + M\left(3 - C_{(i_1,i_2)}^{n_r} - \sum_{m\in N}\left(R_{(i_1,m,n_r)}^{j_1} + R_{(i_2,m,n_{cb})}^{j_2}\right)\right)$$

$$\forall i_1 \in D, j_1, j_2 \in \{1, \ldots, p\}$$

$$t_{i_1}^{j_1+1} \le t_{i_2}^{j_2+1} + M\left(2 + C_{(i_1,i_2)}^{n_r} - \sum_{m\in N}\left(R_{(i_1,m,n_{ca})}^{j_1} + R_{(i_2,m,n_r)}^{j_2}\right)\right) \quad (9)$$

For actual operations, arrival aircraft have priority over departure aircraft. Departure aircraft have priority over crossing aircraft.

Solution Method

If one is able to solve the proposed MIP model, the optimal solution can be obtained. However, the computation time for obtaining the optimal solution would be extremely long when the problem size becomes large. Furthermore, limited by the memory of the computer, only a medium-sized network can be solved by the commercial MIP solver. A method that exactly solves the general MIP model within a practical time has not been found. As similar models have been widely used to formulate the problem of airport surface operations, it is reasonable to apply some heuristic methods to obtain a suboptimal solution of the proposed MIP model within a reasonable time. This study adopts the heuristic rolling method, which has been used in solving many scheduling problems (*17*, *18*). Although it cannot guarantee the optimal solution, the result of such a method is always close to the optimal solution (*17*). In practice, this method can be used to obtain a suboptimal solution in a short time.

The basic idea of a rolling horizon is to divide a long planning period into several small nonoverlapping subperiods and to optimize the schedules within each subperiod. Although the original purpose of this method is to decide a schedule independently within each subperiod, for the proposed model the taxi time of some aircraft could cross two subperiods (here it is assumed that any two consecutive subperiods can cover the taxiing time of one aircraft). In this case, the method should take care of these aircraft in the next subperiod.

In this study, the length of each planning subperiod can vary in a way that the number of aircraft scheduled in each period remains relatively stable. The obtained feasible solution needs to be compared with some bound of the optimal planned taxi times to show how this solution reaches optimality. Such a bound can be achieved by some heuristic methods.

Results and Discussion

To test the case in which there are more interactions between departures and arrivals, the configuration of Runways 26R/08L, 26L/08R, and all gates at five terminals are coded into the model. This is because both runways are used in a mixed mode at IAH. In addition, because it would be too complex if every gate (total > 100) were modeled as a node, the gates are grouped into nine nodes in the model. Sampled from the pushback schedule of departures at IAH from 18:00 to 19:00 on June 1, 2010, 46 departures are used in the test, along with 18 arrivals. It is assumed that Runway 26R/08L is used for arrivals and Runway 26L/08R is used for departures. To test the model performance, one crossing point is allowed for Runway 26R/08L.

There are nine planning subperiods in the rolling horizon method and 64 aircraft. For each planning subperiod, six arrival aircraft and two departure aircraft are scheduled (including the flight over two planning periods). Here, the planning subperiod refers to the time during which the model is solved once. For a large number of flights, the model could be solved several times. The proposed model was solved using a generic MIP solver in ILOG CPLEX with Version 12.1 (*19*). The results are shown in Table 4, where the total taxi time represents the value of an objective function. The bound of total taxi

TABLE 4 Results of Proposed Model

No. of Planning Period	Objective Value/Total Taxi Time (min)		Ratio (Bound/Solution of Rolling Horizon Method)	Computational Time (s)	
	Bound	Rolling Horizon Method		Rolling Horizon Method	Bound
1	30.4	30.4	100%	26.36	26.36
2	35.1	39.4	88%	174.35	11.9
3	37.3	38.8	96%	24.93	11.06
4	37.0	40.3	91%	422.58	34.54
5	32.1	37.0	85%	208.54	20.65
6	38.2	39.4	97%	328.15	57.95
7	33.2	33.3	100%	80.93	22.43
8	34.3	38.8	87%	46.96	12.95
9	42.2	43.8	96%	57.83	23.53
Total	319.8	341.1	93%	1,370.63	221.37

NOTE: Average taxi time = 5.32 min.

time is obtained by estimation heuristically without the rolling horizon method. Because the schedules of some aircraft should be optimized within two planning periods, the solution time is increased in the related planning period. The high computational times in Planning Periods 4 to 6 are due to this reason. Although the bound of the solution can be computed quickly, there are some large gaps between the bound and the solution of the rolling horizon method. From Table 4, the average taxi time obtained is around 5 min, which is close to the real value in this runway configuration. However, it is clear that the solution time is relatively large for this small-scale test case. It indicates that the advanced solution method should be studied further.

The solution obtained by the proposed model might be too optimal in practice. Although the obtained schedules increase the capacity at the airport and reduce average taxi times, the results are feasible on the theoretical side only. This is simply because the model does not consider many other real issues, such as the uncertainty of the boarding time, the interaction between the pilots and the ground controller, and the uncertainty of arriving flights. All these issues would disrupt schedules and increase taxi times. Therefore, future studies should consider these practical issues.

CONCLUSIONS

The analysis shows that IAH is operating close to capacity most of the time. The taxi-out times at IAH fluctuate at different hours and are generally long, while the taxi-in times are relatively stable. Although the departing capacity of IAH is analyzed, its value may be unstable because of the uncertainty. The analysis indicates that an advanced statistical method is required to investigate the airport data.

The proposed model for planning surface operations can be helpful for ground controllers to find more efficient plans for aircraft to save taxi times as well as to reduce fuel consumption. However, it is difficult to handle a large-scale problem because of the complexity of this model. A more efficient algorithm to solve the model should be studied in the future.

ACKNOWLEDGMENTS

This research was supported by TRB ACRP through the Graduate Research Award Program on Public-Sector Aviation Issues. The authors thank Larry Goldstein for his assistance throughout the project. The authors also thank project advisers and mentors Greg Albjerg, Randy Berg, Steven Domino, Juliet Page, and Keith Mew for their beneficial comments, guidance, and feedback.

REFERENCES

1. *Bureau of Transportation Statistics Special Report.* SR-008. Research and Innovative Technology Administration, Bureau of Transportation Statistics, 2008.
2. *Operational Evolution Plan: Version 8.0.* FAA, 2006.
3. *Data and Statistics.* Research and Innovative Technology Administration, Bureau of Transportation Statistics. http://www.bts.gov/xml/ontimesummarystatistics/src/index.xml.
4. *George Bush Intercontinental Airport, Master Plan and Technical Reports.* Houston Airport Systems, City of Houston, Tex., 2006.
5. Idris, H., J. P. Clarke, R. Bhuva, and L. King. Queuing Model for Taxi-Out Estimation. *Air Traffic Control Quarterly,* Vol. 10, No. 1, 2002, pp. 1–22.
6. Clewlow, R., I. Simaiakis, and H. Balakrishnan. Impact of Arrivals on Departure Taxi Operations at Airports. *Proc. AIAA Guidance, Navigation, and Control Conference,* Toronto, Ontario, Canada, American Institute of Aeronautics and Astronautics, Reston, Va., 2010.
7. Simaiakis, I., and H. Balakrishnan. Impact of Congestion on Taxi Times, Fuel Burn, and Emissions at Major Airports. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2184,* Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 22–30.
8. Simaiakis, I., I. Khadilkar, H. Balakrishnan, T. G. Reynolds, R. J. Hansman, B. Reilly, and S. Urlass. *Demonstration of Reduced Airport Congestion Through Pushback Rate Control.* MIT ICAT Report ICAT-2011-2. Massachusetts Institute of Technology, Cambridge, 2011.
9. Atkin, J., E. Burke, and S. Ravizza. The Airport Ground Movement Problem: Past and Current Research and Future Directions. *Proc., 4th International Conference on Research in Air Transportation,* Budapest, Hungary, 2010.
10. Cheng, V. H. L. Airport Surface Operation Collaborative Automation Concept. *Proc. AIAA Guidance, Navigation and Control Conference and Exhibit,* Austin, Tex., American Institute of Aeronautics and Astronautics, Reston, Va., 2003.
11. Smeltink, J. W., M. J. Soomer, P. R. de Waal, and R. D. van der Mei. Optimization of Airport Taxi Planning. *Proc. INFORMS Annual Meeting,* Denver, Colo., Institute for Operations Research and Management Sciences, Hanover, Md., 2004.
12. Marin, A. Airport Management: Taxi Planning. *Annals of Operations Research,* Vol. 143, No. 1, 2006, pp. 191–202.
13. Roling, P. C., and H. G. Visser. Optimal Airport Surface Traffic Planning Using Mixed-Integer Linear Programming. *International Journal of Aerospace Engineering,* Vol. 2008, 2008.
14. Balk, H., H. Sherali, and A. A. Trani. Time-Dependent Network Assignment Strategy for Taxiway Routing at Airports. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1788,* Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 70–75.
15. Balakrishnan, H., and Y. Jung. A Framework for Coordinated Surface Operation Planning at Dallas–Fort Worth International Airport. *Proc., AIAA Guidance, Navigation and Control Conference,* Hilton Head, S.C., American Institute of Aeronautics and Astronautics, Reston, Va., 2007.
16. Keith, G., and A. Richards. Optimization of Taxiway Routing and Runway Scheduling. *Proc. AIAA Guidance, Navigation and Control Conference,* Honolulu, Hawaii, American Institute of Aeronautics and Astronautics, Reston, Va., 2008.
17. Araujo S. A., M. N. Aranales, and A. Clarck. Lot Sizing and Furnace Scheduling in Small Foundries. *Computers and Operations Research,* Vol. 35, No. 3, 2008, pp. 916–932.
18. Mohammadi, M., S. M. T. Fatemi Ghomi, B. Karimi, and S. A. Torabi. MIP-Based Heuristics for Lot Sizing in Capacitated Pure Flow Shop with Sequence-Dependent Setups. *International Journal of Production Research,* Vol. 48, No. 10, 2010, pp. 2957–2973.
19. *IBM ILOG CPLEX V.12.1. User's Manual for CPLEX.* IBM, Armonk, N.Y., 2009.

The ACRP Project Panel for the Graduate Research Award Program on Public-Sector Aviation Issues peer-reviewed this paper.