Surface Performance of End-around Taxiways

Nicoletta Fala, Payuna Uday, Tiffany T. Le, and Karen Marais

Optimizing usage of end-around taxiways is a near-term operational change to reduce aviation emissions and increase efficiency at airports. An end-around taxiway is a path for an aircraft to taxi around an active runway. End-around taxiways provide benefits such as increased throughput and safety, reduced surface congestion, thus also yielding environmental benefits. This study analyzes end-around taxiway use at three airports: Atlanta (ATL), Dallas (DFW), and Detroit (DTW) using ASDE-X data over a six-month period. We developed three types of decision rules to maximize fuel savings. The most promising (environmentally beneficial) decision rule at each airport is based on multiple factors, including terminal destination and arrival time. Depending on the airport, the multi-factor rules resulted in an average aircraft taxi-in fuel savings of 8.9% to 25.4%. This research provides decision-makers at the operational level with a practical guidance tool to use end-around taxiways effectively. This research focuses on reducing taxi-in fuel burn; we do not directly consider the impact of the decision rules on departure parameters (such as throughput and taxi-out fuel burn). Future work will expand the model to optimize fuel burn benefits across integrated arrival and departure surface operations.

INTRODUCTION

Many airports operate at or near capacity, resulting in surface congestion and delays. Studies have also shown that airport operations have significant impacts on local air quality (Yim et al., 2013;

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Carslaw et al., 2006; and Yu et al., 2004). Airport capacity can be increased in two main ways: (1) add runways or (2) increase efficiency. While adding a runway can improve the capacity at a particular airport, doing so is difficult. Several research efforts are underway to improve surface operations efficiency (e.g., Sandberg et al., 2014; Khadilkar and Balakrishnan, 2014; Sölveling et al., 2011; Balakrishnan and Jung, 2007; Brinton et al., 2002; Carr et al., 2002; and Idris et al., 2002). For example, Sandberg et al. (2014) developed a decision support tool to reduce airport surface congestion by controlling the pushback rate of departure aircraft from their respective gates, while Khadilkar and Balakrishnan (2014) proposed a control algorithm that allows airport operators to maintain a steady traffic level on the airport surface.

Here, we focus on the use of end-around taxiways (EATs), which are paths for aircraft to taxi to or from the terminal without crossing active runways. By eliminating the need for aircraft to stop at active runways and wait for clearance to cross, these taxiways increase surface throughput (by reducing aircraft stops and starts) and safety (by eliminating active runway crossings). EATs can *reduce* surface fuel burn because they allow aircraft to taxi continuously without stopping and accelerating. Or, they can *increase* fuel burn because of the longer taxi path on these taxiways. Here, we investigate the conditions under which EATs can provide fuel savingswithout unduly reducing safety and efficiency benefits.

Previous work analyzed a 4-week period of EAT use at Dallas/Fort-Worth International Airport (DFW) (Uday et al., 2011). The analysis showed that taxi-in fuel burn was affected by several factors including traffic conditions on adjacent runways, traffic flow direction, arrival time of aircraft, and aircraft type. Simple decision rules based on these factors and observations showed the potential for significant taxi-in fuel burn reduction using EATs.

END-AROUND TAXIWAYS – A BRIEF DESCRIPTION

Many airports have dual or even triple parallel runways. Usually the in-board runway (closest to the terminal) is used for departures and the out-board runway is used for arrivals. Therefore, arriving aircraft must cross the in-board runway to reach the terminal gate. End-around taxiways are paths for aircraft to taxi around active runways without runway crossings, as shown in Figure 1. This taxiway permits arriving aircraft to taxi to the end of the arrival runway, roll on to the EAT, and move around the departure runway, thereby eliminating the need to stop and cross the active departure runway at one of the conventional taxiways. As stated by the FAA (2012), EATs “improve efficiency and provide a safe means of movement from one side of a runway to the other.”

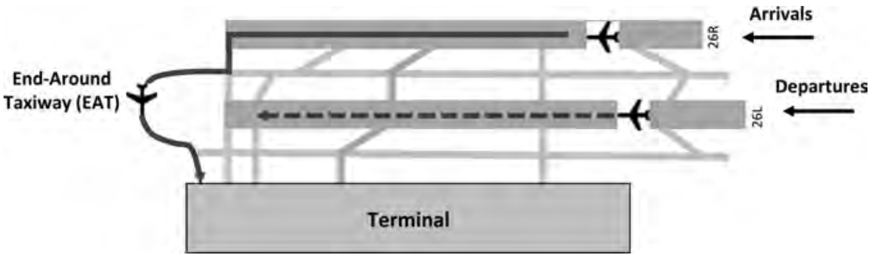

Figure 1. Illustrative end-around taxiway (path of arrival aircraft – solid line; path of departure aircraft – dashed line).

Note here that we use the term *conventional taxiway* to indicate explicitly taxiways that are not EATs (cf. Engelland and Ruszkowski, 2010). We use the term *route* to indicate the complete journey from leaving the runway to reaching the terminal. EATs were initially designed to improve safety by reducing the risk of runway incursions (Massidda and Mattingly, 2013; Engelland and Ruszkowski, 2010; and Satyamurti and Mattingly, 2007). Arrivals using the EAT do not need to be coordinated with departures on the crossing runway, which allows higher departure throughput and can reduce air traffic controller workload. The EAT shown in Figure 1 can be used in both west- and east-flow configurations. In the west-flow case, departures fly over the arriving aircraft on the EAT, while in the east-flow configuration, aircraft make a U-turn after landing and then use the end-around taxiway.

End-around operations can even be achieved without actually building end-around taxiways. For example, at Chicago O'Hare International Airport unimpeded arrival taxiways are used when the runways

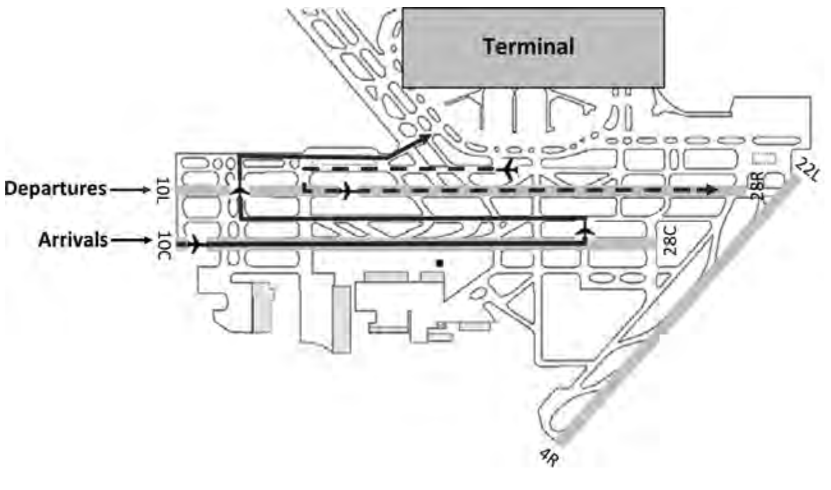

Figure 2. Unimpeded taxiway at Chicago O'Hare Airport (path of arrival aircraft - solid line; path of departure aircraft – dashed line).

are in east-flow configuration (as shown in Figure 2). Aircraft arriving on runway 10C taxi around departure runway 10L; thus, departures can operate independently from arrivals. In contrast to the end-around taxiway in Figure 1, the taxiway at O'Hare can be used only in east-flow configuration.

Currently, four operational EATs are used in the US: Hartsfield-Jackson International Airport (ATL), Dallas/Fort-Worth International Airport (DFW), Detroit Metro Airport (DTW), and Miami International Airport (MIA). Similarly, at the international level, Frankfurt/Main and Amsterdam Schiphol have introduced EATs to enhance runway throughput. In the next section we analyze surface operations at ATL, DFW, and DTW to better understand current end-around taxiway usage trends and patterns.

CURRENT USAGE TRENDS OF EATS

In this section we study surface operations at ATL, DFW, ad DTW to understand how the EATs at these facilities currently are being used. We begin with a description of the data used and the analysis performed for all the airports. The method consists of three broad steps:

1. *Data acquisition and pre-processing*: Raw airport surface data are obtained and filtered to obtain fields of interest (such as position, velocity, and aircraft type) for each flight.
2. *Aircraft-level analysis*: The data extracted in the previous step is used to calculate surface performance metrics, such as taxi time and fuel burn, for each flight.
3. *Airport-level analysis*: Flight-level metrics are aggregated and analyzed to study taxiway use, average taxi times, and average surface fuel burn at each airport.

Data Acquisition and Pre-processing

We used Airport Surface Detection Equipment Model X (ASDE-X) data for the three airports. ASDE-X data provide aircraft surface information such as flight position, speed, and time. These data take the form of text files containing a wide range of variables. For the analysis we first extracted (for each flight) the time, aircraft position, latitude, longitude, speed, fix (destination airport), aircraft type, callsign, and track number (pseudo-unique identifier for aircraft). Next, for each aircraft we determined: (1) the track it followed on the airport surface, (2) the taxiways it used, and (3) the runway configuration in operation at the airport. For each of the three airports the data extraction was carried out for approximately six months from 10 September 2012 to 28 February 2013. The ASDE-X system records times in terms of UTC; hence, all the observed times were adjusted to local time (for each airport). Additionally, an adjustment was made to record time in Eastern Daylight Time (or Central Daylight Time) during the months of daylight savings.

Aircraft-level Analysis: Surface Performance Metrics

We focus on two key surface performance metrics for each flight: taxi time and the corresponding fuel burn.

Taxi Time. Taxi time is a useful performance metric,because it shows the fastest taxi route. The variability in taxi time also dictates the predictability for on-time performance and taxi routing efficiency. Khadilkar and Balakrishnan (2011) presented an approach to estimate fuel burn using flight data recorder (FDR) data and a linear regression model. The authors concluded that the total taxi time is the main component to determine fuel burn, although the number of acceleration events was also a significant factor (see next section).

The taxi time is defined as the time from when an aircraft exits the arrival runway to the time it reaches the edge of the terminal area:

$$t_{taxi} = \min(t_{term}) - \max(t_{runway}) \tag{1}$$

The Airport System Performance Metric (ASPM) defines the average taxi-in time as the average difference between actual gate-in time and actual wheels-on time (FAA, 2014). The FAA defines “wheels-on time” as the time at which the landing gear touches down on the runway. Investigation of our ASDE-X data, however, revealed high variability in taxi time using this definition (for example, ATL terminal taxi time variability is 2.54 minutes). Thus, our definition excludes two taxi portions. First, we exclude the time from wheels-on to the time the aircraft exits the arrival runway. For a given runway this time varies depending on aircraft type and pilot. Second, we exclude the time the aircraft spends taxiing from the edge of the terminal area to its gate. This period can vary significantly, for example. because arriving aircraft may have to wait for departing aircraft to vacate a gate.

Fuel Burn. Two main publicly available aircraft performance databases provide fuel-flow and emission indices as a function of engine thrust: (1) the Aircraft Engine Emissions Databank, developed and maintained by the International Civil Aviation Organization (ICAO), and (2) the Base of Aircraft Data (BADA), developed and maintained by the EUROCONTROL Experimental Centre. BADA estimates fuel consumption as a function of thrust and airspeed primarily for the airborne phase of flight. As a result, using values from this database to evaluate ground fuel consumption may not be appropriate. Instead, our work estimated taxi fuel burn using the ICAO Aircraft Engine Emissions Databank, which is based on engine performance and emissions data obtained from full-scale engine tests at sea-level. The values of fuel flow (kg/s) and emission indices (grams of pollutant emitted per kilogram of fuel burnt) taken at 7%, 30%, 85%, and 100% output rates are provided in the databank for the majority of jet and turbofan commercial engines.

The ICAO Aircraft Engine Emissions Databank defines taxi/ground idle as 7% of full rated power, but it does not distinguish between the different phases of taxiing. A case study at DFW showed the stops and resulting accelerating events constitute approximately 18% of fuel spent in surface operations (Nikoleris et al., 2011). In this study we account for the potential increase in fuel burn from accelerations by decomposing each aircraft surface trajectory into three taxi phases: stops and starts (accelerating after a stop), perpendicular turns, and taxi at constant speed or braking.

Table 1 shows the baseline model assumptions for time and thrust levels at different taxi operation phases. Here, $t_{p,i}$ is the time aircraft i spent on taxi phase p, T is the total taxi time, n_s is the number of stops, and n_t is the number of turns. The assumptions used in Table 1 were adapted from Nikoleris's fuel burn estimate model based on inputs from commercial airline pilots and analysis of true idle estimates in a Transportation Research Board report (Wood et al., 2008).

The first taxi phase accounts for aircraft stops and starts. Aircraft using the conventional taxiways must stop and wait for clearance before crossing an active runway. Breakaway thrust or accelerating from stop have been found to be as high as 9% of full rated power in a study by British Airways (Morris, 2005). Our fuel burn estimate analysis models the effect of this acceleration using Nikoleris's assumption that an average of 8 seconds is needed for acceleration after a stop, consisting of 4 seconds to overcome inertia and 4 seconds to reach taxi speed. The second phase accounts for perpendicular turns at 7% of full-rated power for a 6-second turn. The third taxi phase is taxiing at a constant speed, which is estimated as 5% of full-rated power.

Table 1. Baseline Assumptions for Time and Thrust Levels of Taxi Operations Phases

Taxi phase, p	Time (s)	Thrust %
1. Stop and start ("breakaway thrust")	$t_{1,i} = 8 \cdot n_s$	9%
2. Perpendicular turn	$t_{2,\mathrm{i}} = 6 \cdot n_t$	7%
3. Constant speed	$t_{3,\mathrm{i}} = T - t_{1,i} - t_{2,i}$	5%

The total fuel consumed, TF_i, from exiting the runway to reaching the edge of the terminal area is given by:

$$TF_i = \sum_{p=1}^{3} t_{p,i} \cdot f_{p,i} \cdot n_i \tag{2}$$

where $t_{p,i}$ is the time (s) aircraft i spent on taxi phase p, $f_{p,i}$ is fuel flow (kg/s) while aircraft i is on taxi phase p, and n_i is the number of engines aircraft i used.

In addition to the time and thrust level assumptions presented above some other fuel burn assumptions were made in the study. We assumed that aircraft using the EATs do not stop during taxi-in. This assumption is based on Engelland and Ruszkowski's (2010) analysis for 16 months of taxiway operations at DFW. They found that the EAT taxi time is long-tailed with a standard deviation of 45 seconds, which suggests that most aircraft have similar taxi times (i.e., they all stop similarly, or they stop infrequently or for short times), while a few aircraft either taxi very slowly or stop often for a long time. We also excluded small turboprop aircraft, because they account for less than 1% of traffic during the study period.

Airport-level Analysis

Using the aircraft-level metrics of taxi time and surface fuel burn during taxi, in this section we summarize prior work on taxiway use and the impact of taxi routes on taxi time and fuel burn. See Le and Marais (2013) for a detailed discussion of the results presented here. For each airport we begin with a brief description of its layout, configuration, and taxiway use. Next, we highlight key observations about taxiway operations that were obtained using the analysis method outlined previously.

Atlanta/Hartsfield-Jackson International Airport (ATL). ATL was the world's busiest airport in 2012 by passenger traffic (92 million passengers annually) and total movements (ACI, 2013). ATL has made several improvements over the years to increase capacity, including the end-around taxiway, known as taxiway Victor (V), located on the north airfield. Approximately 700 aircraft per day arrive on the airport's northern- most runway, runway 8L/26R. Before the construction of Taxiway Victor, aircraft waited in line for clearance to cross the active departure runway, runway 8R/26L, to get to the terminal. Now, arriving aircraft can use the EAT to taxi continuously to the terminal area without stops and starts.

ATL West-flow Configuration (Table 2)

During the 6-month span, the north arrival runway was used in west-flow configuration 46% of the time and the south arrival runway 34% of the time. Figure 3 shows the most common routes to reach the

Table 2. Summary of Surface Performance Metrics at ATL (west-flow)

	To Terminal from Arrival runway 26R (in north airfield)		To Terminal from Arrival runway 27L (in south airfield)
Metric	EAT	Conventional taxiways	Conventional taxiways
Taxiway Use	62%	38%	100%
Avg. Taxi Time (min)	4.57	3.21	4.36
Median Fuel Burn (min)	4.23	2.82	3.80
Avg. Fuel burn (kg)	45.54	34.02	45.83
Median Fuel burn (kg)	41.13	29.68	36.41

terminal in west-flow configuration: (a) indicates the route taken to reach the terminal using taxiway Victor, the end-around taxiway; while (b) shows the routes using conventional taxiways, which involve crossing the in-board runway to reach the terminal. In west-flow configuration, the south airfield does not have an end-around taxiway.

Key observations for ATL in west-flow configuration:

- For aircraft arriving on runway 26R (north-airfield) the EAT is used the most often with an average of 140 aircraft per day.
- The EAT is the preferred taxi route throughout the day even during low departure hours, which suggests over-reliance on the EAT, which would increase fuel burn (peak departure is in the morning between 10 am and 11 am local time).
- There is less variability in taxi time for both the EAT ($\sigma = 1.81$ min) and the north conventional taxiways ($\sigma = 1.62$ min) than the conventional taxiways in the south ($\sigma = 2.39$ min).

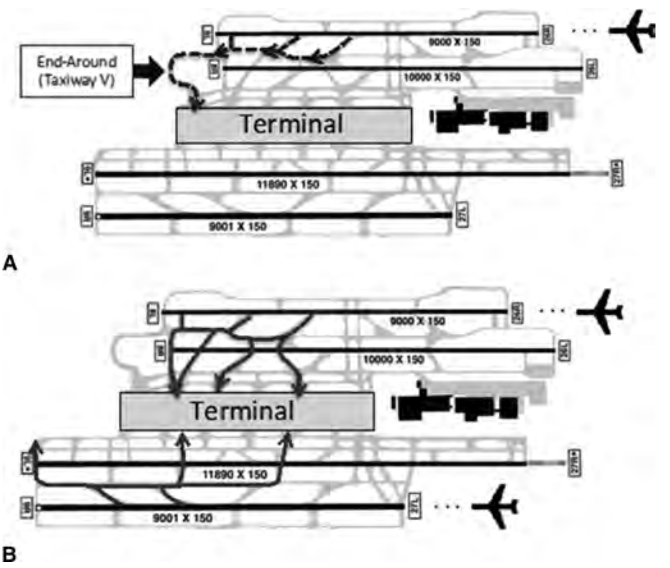

Figure 3. Taxi routes at ATL in west-flow configuration: (a) EAT and (b) conventional taxiways.

Table 3. Summary of Surface Performance Metrics at ATL (east-flow)

Metric	To Terminal from Arrival runway 8L (in north airfield) EAT	Conventional taxiways	To Terminal from Arrival runway 9R (in south airfield) EAT	Conventional taxiways
Taxiway Use	51%	49%	24%	76%
Avg. Taxi Time (min)	7.08	4.58	6.71	3.76
Median Taxi Time (min)	6.73	4.35	6.42	3.48
Avg. Fuel burn (kg)	73.14	49.41	66.63	41.40
Median Fuel burn (kg)	69.73	49.49	64.59	39.17

ATL East-flow Configuration (Table 3)

During the 6-month span, 53% of aircraft arrived in the east-flow direction at ATL. Figure 4(a) shows the airport diagram in east-flow configuration with the end-around taxiway in the north airfield and the end-around taxiway in the south airfield. On the north airfield, aircraft land on runway 8L and make a U-turn to use the EAT. Similarly, on the south airfield, aircraft arriving on runway 9R make a U-turn to use the end-around taxi route through taxiway P. Figure 4(b) indicates the conventional taxiways. Smaller aircraft like the CRJ7 can make the sharp right turn to exit the runway (for example, at taxiway D) and go straight to the terminal. Larger aircraft that need more runway length to slow down use the high-speed turn-offs and make a small U-turn to reach the terminal.

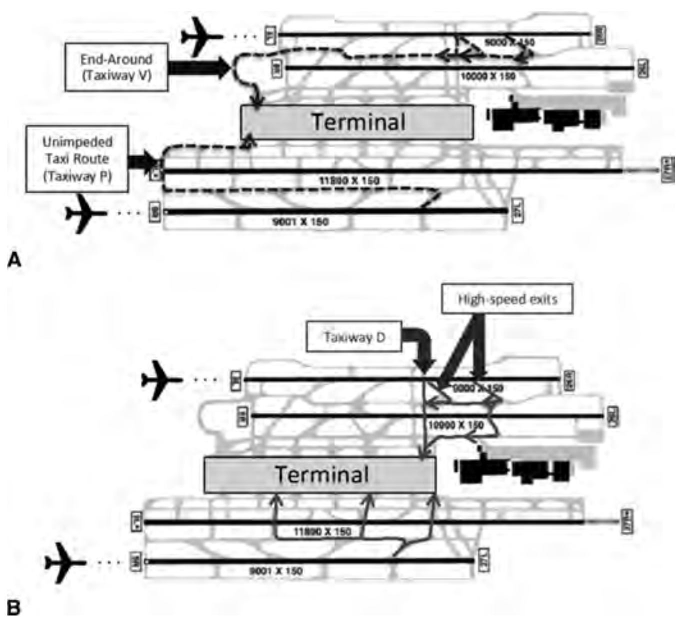

Figure 4. Taxi routes at ATL in east-flow configuration: (a) EAT and (b) conventional taxiways.

Key observations for ATL in east-flow configuration:

- The EAT is the most used taxiway with an average of 81 aircraft per day. Aircraft must make a U-turn to use the EAT, however, and, hence, depending on the destination gate, the taxi distance can be twice as long as when conventional taxiways are used.
- The south taxiway P is similar to the EAT because it is an unimpeded route to the terminal with comparable taxi time (7.04 min) and fuel burn (97kg) to the EAT taxi time (7.08 min) and fuel burn (101 kg).

Dallas/Fort-Worth International Airport. In 1997 DFW airport authorities released a 20-year development plan that recommended the construction of four EATs, one in each quadrant of the airport (DFW, 1997). The first EAT, which is located in the southeast section of DFW, entered service on 22 December 2008. None of the other planned EATs has been constructed to date. The EAT provides a path for aircraft to taxi around the in-board runways 17C and 17R (see Figure 5[a]). Prior to the construction of the EAT, 17L arrivals would typically taxi via taxiway ER and cross 17C and 17R (the primary eastside departure runway). During times of high traffic conditions, this wait time contributed significantly to taxi-in delay. The EAT allows traffic to flow freely around the end of both runways. The EAT is also used by runway 17C arrivals, although less frequently. Since only departing (and not arriving) aircraft may overfly an operational

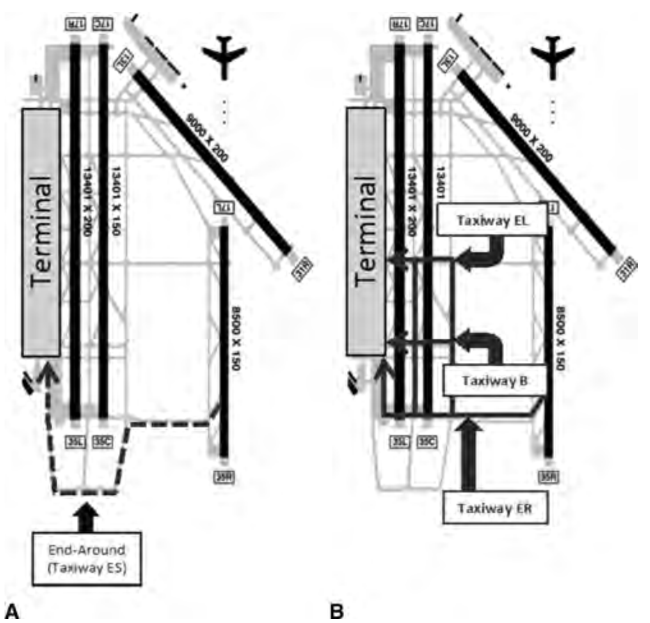

Figure 5. Taxi routes from runway 17L at DFW in south-flow configuration: (a) EAT and (b) conventional taxiways.

Table 4. Summary of Surface Performance Metrics at DFW (south-flow)

	To Terminal from Arrival runway 17L	
Metric	EAT	Conventional taxiways
Taxiway Use	55%	45%
Avg. Taxi Time (min)	10.49	8.34
Median Taxi Time (min)	10.02	7.97
Avg. Fuel burn (kg)	99.63	81.61
Median Fuel burn (kg)	102.18	85.09

perimeter taxiway, the EAT at DFW can be used only when the airport is in the south-flow configuration (AOSC, 2006).

DFW South-flow Configuration (Table 4)

Runway 17L is used in south-flow configuration for 70% of arrivals. Figure 5 shows the most common taxi routes when aircraft land on runway 17L in south-flow configuration. Aircraft exit the high-speed turn-off and take either the end-around taxiway (as shown in Figure 5 [a]) or one of the conventional taxiways (as shown in Figure 5[b]). If the arrival runway 17C is clear, arriving aircraft from 17L will cross 17C at taxiway ER and stop short of runway 17R and wait for clearance from departing aircraft. If the arrival runway 17C is not clear, aircraft must either wait for clearance or taxi north crossing 17C using taxiway B or taxiway EL.

Aircraft arriving on runway 17C used the end-around taxiway less than 0.1% of the time. Therefore, we focus our analysis on runway 17L arrivals.

Key observations for DFW in south-flow configuration:

- Runway 17L is used to accommodate a large number of arrivals between 9am to 2pm; use tapers off the rest of the day.
- Peak arrival time for runway 17L is from 9am to 11am with 12 arrivals per hour, and the EAT is the primary taxiway used with 8 aircraft per hour.
- The average EAT taxi time for arrivals from runway 17L is 10.49 minutes, and the average conventional taxi time is 8.35 minutes.

Detroit Metropolitan Wayne County Airport (DTW). In 2004 EAT Quebec (Q) was constructed at DTW (see Figure 6). This EAT allows aircraft arriving on runway 4L/22R to taxi end-around to the terminal without crossing the departure runway 4R/22L. The crosswind runways (27R/9L and 27L/9R) do not add capacity because they cannot be used simultaneously with the north-south runways; therefore, they are mostly used as additional taxiways. The DTW analysis is focused on the west airfield where the EAT is located. There are two distinct terminal areas: north terminal and south terminal.

DTW Runway 22R South-flow Configuration (Table 5)

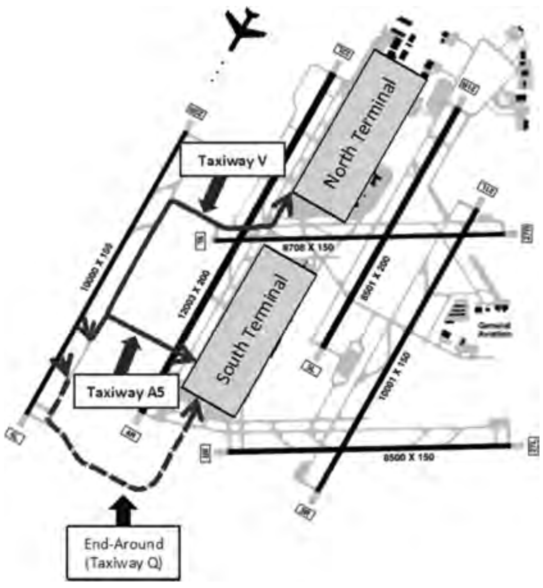

Figure 6. Taxi routes from runway 22R at DTW in south-flow configuration (dashed line indicates the end-around taxiway route and solid lines represent conventional taxiways).

Runway 22R is used in south-flow configuration for 90% of arrivals. Figure 6 shows the most common taxi routes when aircraft land on runway 22R in south-flow configuration. Aircraft exit the runway typically using one of the high-speed turn-offs and then take either the EAT or a conventional taxiway. The EAT circumvents the in-board departure runway 22L to reach the terminal. Taxiway A5 (see Figure 6) is the conventional taxi route closest to the EAT and taxiway V is the northern conventional taxi route. Taxiway V is used most often when the destination gate is at the north terminal.

Key observations for DTW in south-flow configuration include:

- 85% of south arrivals on runway 22R have destination gates in the South Terminal (126 gates) and 15% in the North Terminal (26 gates).

Table 5. Summary of Surface Performance Metrics at DTW (south-flow)

	To South Terminal from Arrival runway 22R			To North Terminal from Arrival runway 22R		
Metric	EAT	Taxiway A5	Taxiway V	EAT	Taxiway A5	Taxiway V
Taxiway Use	77%	17%	6%	1%	3%	96%
Avg. Taxi Time (min)	5.95	5.18	6.71	10.28	6.67	6.16
Median Taxi Time (min)	5.40	4.75	6.28	9.80	6.45	5.88
Avg. Fuel burn (kg)	42.04	27.40	54.20	68.85	55.43	50.03
Median Fuel burn (kg)	33.10	21.85	50.00	49.72	52.11	48.36

- Taxiway V is shortest and most fuel efficient path for aircraft with a North Terminal gate destination.
- The EAT is used 77% of the time to the South Terminal and has an average taxi time of 5.95 minutes. Mean taxi time to the South Terminal using Taxiway A5 is 5.18 minutes and using Taxiway V is 6.71 minutes.
- The EAT ($\sigma = 2.28$ min) has a smaller variability in taxi time than taxiway A5 ($\sigma = 2.36$ min) and taxiway V ($\sigma = 2.47$ min) because the taxi time is independent of the traffic on the departure runway.

DTW Runway 4L North-flow Configuration (Table 6)

Runway 4L is used in north-flow configuration 10% of the time. Figure 7 shows the most common taxi routes when aircraft land on

Table 6. Summary of Surface Performance Metrics at DTW (north-flow)

Metric	To South Terminal from Arrival runway 4L EAT	To South Terminal from Arrival runway 4L Taxiway A5	To South Terminal from Arrival runway 4L Taxiway V	To North Terminal from Arrival runway 4L EAT	To North Terminal from Arrival runway 4L Taxiway A5	To North Terminal from Arrival runway 4L Taxiway V
Taxiway Use	67%	7%	26%	0.4%	0.1%	99.4%
Avg. Taxi Time (min)	8.55	5.96	5.57	9.75	10.88	4.69
Median Taxi Time (min)	7.63	5.40	5.03	10.12	10.88	4.34
Avg. Fuel burn (kg)	57.88	30.15	39.07	60.28	95.58	37.58
Median Fuel burn (kg)	42.95	25.97	27.08	39.67	95.58	34.83

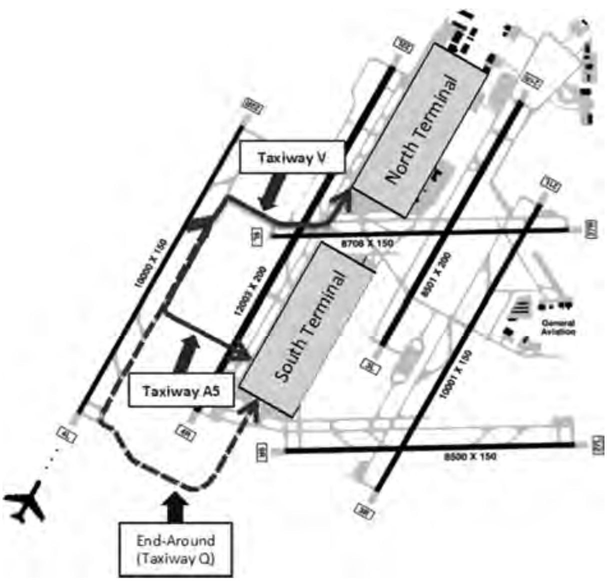

Figure 7. Taxi routes from runway 4L at DTW in north-flow configuration. (dashed line indicates the end-around taxiway route and solid lines represent conventional taxiways).

runway 4L in north-flow configuration. Aircraft taking the EAT must make a U-turn and head south on the parallel taxiway A to reach the EAT. Taxiway V is the shortest taxi distance to the north terminal. Taxiway A5 is about half the distance of the EAT route to the south terminal.

Key observations for DTW in north-flow configuration:

- 83% of north arrivals on runway 4L go to the South Terminal.
- The EAT is the most used taxiway with an average of 63 aircraft per day followed by taxiway V with 42 aircraft per day. Taxiway A5 is used only 6% of the time.
- The EAT is used 67% of the time in this configuration and has an average taxi time of 8.55 minutes. Mean taxi time on taxiway A5 is 5.96 minutes; on taxiway V taxi time is 5.57 minutes.
- EAT taxi distance (20,789 feet) is more than twice the distance of conventional taxiways, because aircraft must make a U-turn to use the EAT in north-flow configuration.
- Taxiway V is the shortest and most fuel efficient path for aircraft with a gate destination in the North Terminal for all configurations.

DECISION RULE DEVELOPMENT AND APPLICATION

While EATs can decrease fuel burn by requiring fewer and shorter stops, they often increase the total taxi time, leading to higher fuel burn. Here, we use the trends identified in the previous section to develop decision rules that could allow air traffic controllers to improve surface fuel burn.

Figure 8 shows the framework used to develop appropriate decision rules and to evaluate the potential environmental benefits (fuel savings relative to current fuel burn) they can yield. The process employs four main stages:

1. ***Obtain and process ASDE-X data***: This first step in this framework is to obtain and process the raw ASDE-X data (see section titled, Data Acquisition and Pre-processing).
2. ***Estimate fuel burn***: The next step is to estimate the surface fuel burn (for each aircraft) (see section titled, Fuel Burn).

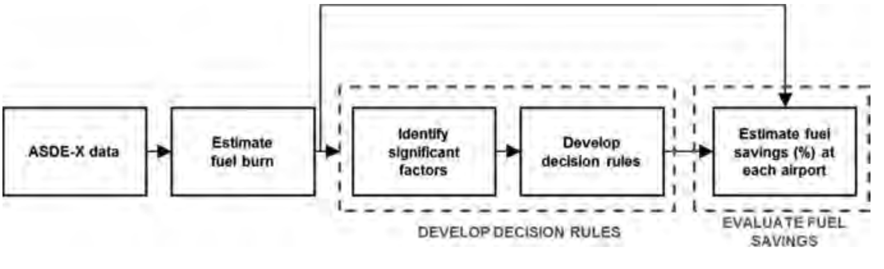

Figure 8. Development and Application of Decision Rules.

3. ***Develop decision rules***: We determined the key factors that impact the surface fuel burn consumption of arrival aircraft. Based on these contributors, we developed a set of decision rules that allow environmentally efficient taxiway use. (See section titled, Development of decision rules)
4. ***Evaluate fuel savings***: We used the fuel burn estimates (from step 2) and the decision rules (from step 3) to estimate potential fuel savings for each decision rule relative to the baseline case. (See section titled, Evaluating fuel savings at each airport)

Development of decision rules

Taxi fuel burn depends primarily on the taxi distance and the fuel burn rate of each particular aircraft. Taxi fuel burn is also affected by the number (and duration) of stops and starts and the number of turns, as discussed in the section titled, Fuel Burn. We estimated each of these effects using the ASDE-X data as shown in Table 7.

We argue that decision rules based on these two primary factors (choice of taxiway, and taxi distance) to minimize taxi-in fuel burn are useful as they will be relatively easy to implement from an ATC perspective. A set of five decision rules to guide taxiway use while maximizing environmental benefits (minimizing fuel burn) was developed:

1. **Always** rule: All aircraft use the EAT.
2. **Never** rule: None of the aircraft uses the EAT.

The next two rules are based on minimizing the fuel burn while limiting the effect on departures and maintaining simplicity.

3. **Arrival Time** rule: This rule is based on the factor ”arrival time.” All aircraft that arrive during peak traffic hours use the EAT, while aircraft arriving during low traffic hours use the conventional taxiways.
4. **Terminal** rule: This rule is based on “taxi distance.” Aircraft are directed to the shortest taxi route based on proximity to their terminal gates.

Note that ***always*** and ***never*** using the EAT are not realistic decision rules to implement. Always using the EAT would increase total

Table 7. Parameters Affecting Fuel Burn

Fuel Burn Factor	ASDE-X Data	Note
Taxi distance	Taxi Distance	See section, Fuel Burn
Fuel burn rate	Aircraft Type	See section, Fuel Burn
Stops and starts	Arrival Time Taxiway	Each taxiway has a given number of stops and starts. The duration of each stop depends on the traffic. We use arrival time as a proxy for traffic.
Number of turns	Taxiway	Each taxiway has a given number of turns.

taxi time and fuel burn because of the long taxi distance. Never using the EAT would reduce departures by increasing the number of runway crossings. These rules provide the bounds of the analysis and give insight into current and future operating practice.

The next two rules (***arrival time*** and ***terminal***) were selected on the basis of ease of execution for air traffic controllers. Arrival time and terminal destination are factors that might be incorporated relatively easily by tower and ground controllers, because they involve only a single factor.

More sophisticated rules built on a variety of factors could result in higher fuel savings (discussed in Conclusions). Here, we focused on the two primary fuel burn drivers (arrival time and terminal) and developed a relatively simple ***multi-factor*** decision rule specific to each airport that is based on a combination of the two factors. This rule assigns aircraft to the shortest route to their destination terminal, provided that the total number of aircraft crossing the departure runway remains below some threshold.

5. **Multi-factor** rule: This decision rule expands on the terminal rule to minimize fuel burn, while also limiting the number of aircraft that cross the departure runways during peak departure hours. Each runway configuration is assigned a maximum number of arrivals per hour that can use the conventional taxiways during peak departure hours. If there are more arrivals scheduled than the departure runway can accommodate, prioritized arrivals cross the runway based on their order of arrival. Arrivals are prioritized based on terminal destination.

In the next subsection we describe the details of each decision rule in the context of the three airports and evaluate their impact on surface fuel burn.

Evaluating fuel savings at each airport

For each aircraft at the three airports, depending on the decision rule being studied, we generated an appropriate fuel burn estimate from the corresponding fuel burn distribution. We calculated the average aircraft fuel burn for the 6-month period using a Monte Carlo simulation with 10,000 iterations for each decision rule. Finally, we compared the decision-rule average with the average computed from the original data set (***Baseline*** scenario) to determine the relative fuel savings (%) as shown in equation (3). Next, we discuss the results of applying this framework to the three airports.

$$Fuel\ savings = \frac{Average\ fuel\ burn_{New} - Average\ fuel\ burn_{Baseline}}{Average\ fuel\ burn_{Baseline}} \times 100 \tag{3}$$

Table 8. Decision Rules for ATL

Decision Rules	Aircraft using end-around taxiways	Aircraft using conventional taxiways
Always	All arriving aircraft	None
Never	None	All arriving aircraft
Arrival Time	During peak hours as follows: • 26R (west-flow): 8am to 11am, 3pm to 4pm, and 7pm to 9pm • 8L (east-flow): 8am to 11am, 12pm to 1pm, and 7pm to 9pm • 9R (east-flow): 8am to 11am, and 7pm to 8pm	All other times
Terminal	• Ramp 1 • Half of all arrivals to Ramps 2, 3, and 4	• Ramp 5 • Ramp 6 • Half of all arrivals to Ramps 2, 3, and 4

ATL Results. We performed the decision scenario analysis for aircraft arriving in the north airfield in both east and west-flow configurations, and to the south airfield in east-flow configuration, because it uses taxiway P as an unimpeded taxiway similar to the EAT (see Figure 4[a]). Table 8 gives the details of each decision rule.

Table 9 shows the resulting ATL average fuel burn savings estimates for the five decision rule scenarios. As expected, ***always*** using the EAT increased the fuel burn significantly in all cases. ***Never*** using the EAT (or unimpeded taxiway for 9R) decreased the fuel burn the most in all cases. The ***arrival time*** rule decreased fuel burn on all three runways (26R, 8L, and 9R). These results are expected because routes that use EATs are faster and burn less fuel per unit distance than using the conventional taxiway that must stop to cross adjacent runways during high traffic times.

The ***terminal*** decision rule decreases average fuel burn for two out of the three runways (26R, and 8L). The terminal ramp locations at ATL are spread out enough that different taxiways have a significant difference in taxi distance. The EAT is a convenient path to take when arrivals' gate destinations are in terminal ramp 1. In contrast

Table 9. ATL Average Fuel Burn Estimates from Decision Rule Simulations

Airport Configuration	Decision Rules				
	Always EAT	Never EAT	Arrival Time	Terminal	Multi factor
West-flow Runway 26R north airfield	10.5↑	−21.3% ↓	−6.0% ↓	−5.5% ↓	−18.8% ↓
East-flow Runway 8L north airfield	19.1% ↑	−13.8% ↓	−4.2% ↓	−4.3% ↓	−8.9% ↓
East-flow Runway 9R south airfield	17.0% ↑	−23.7% ↓	−3.7% ↓	1.8% ↑	−19.2% ↓

Table 10. Decision Rules for DFW

Decision Rules	Aircraft using end-around taxiways	Aircraft using conventional taxiways
Always	All arriving aircraft	None
Never	None	All arriving aircraft
Arrival Time	During peak hours as follows: • 17L (south-flow): 9am to 10am	All other times
Terminal	Depending on location of destination gate as follows: • Terminals C, D, E	Depending on location of destination gate as follows: • Terminals A, B

it is least beneficial to take the EAT, if the gate destination is in terminal ramp 6. In this case the conventional taxiway is the best taxiway to take to reach terminal ramp 6, especially in east-flow configuration.

Although the ***never*** decision rule yields the most fuel burn reduction, the departure rate on the adjacent runways would have to decrease to accommodate arrival runway crossings. Using the *never* decision rule, airport throughput suffers. The runway departure rate cannot be met without increasing surface congestion, fuel burn, emissions, and wait time for arrivals and, therefore, is infeasible.

The ***multi-factor*** decision rule has the largest fuel savings compared to the *arrival time* and *terminal* decision rules.

DFW Results. We analyzed the decision rules for runway 17L in south-flow configuration, because it is the primary user of the EAT (see section titled, Dallas/Fort Worth International Airport). Table 10 shows the details of the decision rules.

Table 11 shows the DFW average fuel burn savings estimates for the five decision rule scenarios. At DFW taxi fuel burn is significantly affected by traffic levels, since runway 17L is used for overflow arrivals during peak traffic hours. These aircraft then use the EAT to go around primary arrival runway 17C, as discussed in the section titled, Dallas/Fort Worth International Airport.

As with ATL, ***always*** using the EAT increased the fuel burn, in this case by 3.5% compared to the baseline. ***Never*** using the EAT decreases the fuel burn by 16.6% compared to the baseline, but has a negative impact on the adjacent departing runway traffic. The arrival rate on in-board runway 17C and the departure rate on runway 17R

Table 11. DFW Average Fuel Burn Estimates from Decision Rule Simulations

	Decision Rules				
Airport Configuration	Always	Never	Arrival Time	Terminal	Multi-factor
South-flow Runway 17L	3.5%↑	−16.6% ↓	−7.2% ↓	−10.2% ↓	−13.4% ↓

must decrease to accommodate runway crossings from arrivals on 17L. If the never scenario is used, arrival aircraft must take the conventional taxiway, which requires waiting for a gap in both arrivals and departures before air traffic control can instruct them to cross the two active runways.

The ***arrival time*** rule decreased the average fuel burn by 7.2%. The ***terminal*** rule increased fuel burn by 10.2%. Even though the EAT is closest to terminal E, the EAT taxi distance is significantly longer than the conventional taxiways. Having more aircraft use the EAT increased the fuel burn.

The ***multi-factor*** decision rule yields the largest fuel savings of 13.4%.

DTW Results. We performed the decision scenario analysis for aircraft arriving on runway 4L/22R in north and south-flow configuration. Table 12 shows the details of the decision rules. The ***terminal*** decision rule directs arrivals to the shortest taxi route (EAT, taxiway A5, or taxiway V) based on their terminal gate destination. The terminal is an important factor at DTW because the taxi distance greatly varies between the North and South terminal.

Table 13 shows the DTW average fuel burn savings estimates for the five decision rule scenarios. As expected, ***always*** using the EAT increased the fuel burn, more significantly for runway 4L.

Never using the EAT decreased the fuel burn, in the case of runway 4L by a large amount (25.5%). This large decrease may be due in part to the current practice of having the majority of arriving aircraft from 7 am to 10 pm use the EAT. As with ATL and DFW, however, never using the EAT negatively affects the departure rate and would likely increase total surface fuel burn because departing aircraft must wait for arriving aircraft to cross, and vice versa.

The ***arrival time*** rule decreased fuel burn on runways 22R and 4L by 0.9% and 10.9%, respectively. As noted above, the EAT is currently the primary taxi route for aircraft arriving on runway 4L between

Table 12. Decision Rules for DTW

Decision Rules	Aircraft using end-around taxiways	Aircraft using conventional taxiways
Always	All arriving aircraft	None
Never	None	All arriving aircraft
Arrival Time	During peak hours as follows: • 22R (south-flow): 2pm to 3pm, 4pm to 5pm, and 6pm to 7pm • 4L (north-flow): 2pm to 3pm, 4pm to 5pm, and 6pm to 7pm	All other times
Terminal	Half of all arrivals to Terminal 1	Half of all arrivals to Terminal 1 • All arrivals to Terminal 2

Table 13. DTW Average Fuel Burn Estimates from Decision Rule Simulations

Airport Configuration	Always	Never	Arrival Time	Terminal	Multi-factor
	Decision Rules				
South-flow Runway 22R	0.5% ↑	−10.3% ↓	−0.9% ↓	−4.9% ↓	−9.4% ↓
North-flow Runway 4L	16.4% ↑	−25.5% ↓	−10.9% ↓	−6.2% ↓	−25.4% ↓

7am and 10pm in north-flow configuration; thus, large savings compared to the baseline are possible by limiting EAT use. In north-flow configuration the EAT is twice the distance to the south terminal and three times the distance to the north terminal, so using the conventional taxiway saves more fuel in this case.

The ***terminal*** decision rule decreased fuel burn on runways 22R and 4L by 4.9% and 6.2%, respectively. This proposal is similar to what air traffic controllers are doing today and, therefore, could be fairly transparent to the operation. The primary difference is to have all aircraft with a gate destination in the North Terminal use Taxi 2, because it is the shortest route and saves fuel.

The ***multi-factor*** decision rule has the largest fuel savings compared to the *arrival time* and *terminal* decision rule. The average fuel savings for south-flow runway 22R is 9.4% and north-flow runway 4L is 25.9%. Again, the large fuel savings for the north-flow is because of the longer EAT taxi distance, so limited EAT use can bring substantial fuel reduction.

IMPACT OF DECISION RULES ON DEPARTURES

Arrivals and departures are closely related even at airports that assign runways exclusively to landings and takeoffs, because (usually arriving) aircraft must cross active (usually departure) runways, and because gates and the apron must be shared between arriving and departing aircraft. Therefore, a full optimization of taxi operations should consider both arrivals and departures. Since the focus of our paper is on showing the potential fuel use benefits of EATs, we present here a simplified first-order analysis of runway occupancy time. By analogy with the "runway occupancy time" (how long an aircraft spends on the runway when landing or taking off), we define the "average runway occupancy" as the total time that aircraft use a particular active departure runway during a given time period:

$$\textit{Average departure runway occupancy} = t_d.n_d + t_{rc}.n_{rc} \tag{4}$$

where t_d is the runway occupancy time (ROT) for departures (time between the start of the takeoff roll of the aircraft and wheels-up); t_{rc} is the time taken by aircraft arriving on adjacent runways to cross the departure runway; n_d is the average departures per unit time; and n_{rc} is the average runway crossings per unit time.

Figure 9 shows the daily average runway occupancy over the six-month period for the ***Baseline***, ***Arrival Time***, ***Terminal***, and ***Multi-factor*** rules. To achieve a worst case estimate, we use the worst case values from (Balakrishnan and Jung, 2007); thus, t_d is 110 sec and t_{rc} is 40 sec for each aircraft.

For clarity and since their impact is obvious, we do not show the always and never rules. For most of the day all curves track close to the baseline case. All the rules result in total average runway occupancy of less than an hour, suggesting that additional capacity remains. During certain periods in the day, the ***Terminal*** rule results in lower average runway occupancy. These results and the

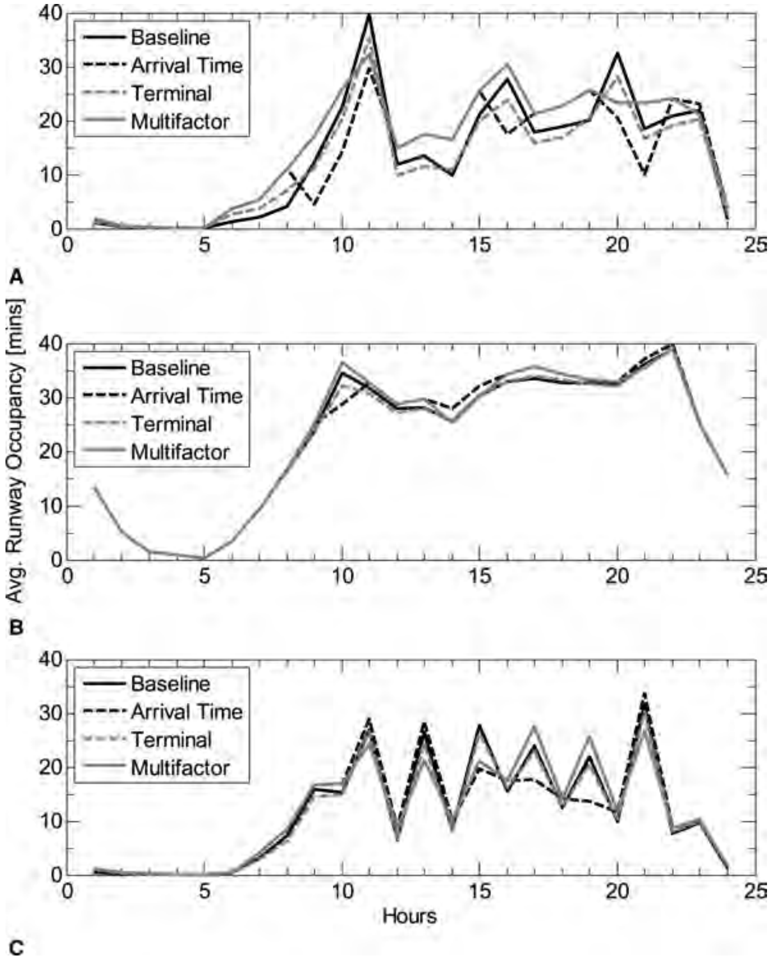

Figure 9. Average active runway occupancy on (a) runway 26L at ATL (west-flow configuration); (b) runway 17R at DFW (south-flow configuration); and (c) runway 22L at DTW (south-flow configuration).

fuel burn savings seen in Table 9 suggest that appropriate use of the EAT at ATL can bring about surface fuel burn benefits of arriving aircraft without unduly impacting throughput of the adjacent departure runway 26L.

Figure 9 (b) shows the average runway occupancy for DFW using the arrival, terminal, and multi-factor rules. Similar to ATL, all curves track very close to baseline. Figure 9 (c) shows the average runway occupancy for DTW using the arrival, terminal, and multi-factor rules. The multi-factor rule brings about most fuel savings but has somewhat higher runway occupancy times. All other curves track very close to the baseline case.

In all three cases our first-order metric of departure impact suggests that using the decision rules to allocate aircraft to the EAT and conventional taxiways can reduce fuel burn without affecting departures more than the current somewhat *ad hoc* approaches.

CONCLUSION

In this paper we showed how appropriate decision making about which taxiways to assign to arriving aircraft can decrease fuel burn while considering safety and congestion benefits. We developed a set of decision rules for ATL, DFW, and DTW, and estimated the potential fuel savings. At all three airports a multi-factor rule, based on terminal destination, departure order, and arrival time yielded the largest practical benefit, ranging from 8.9% average fuel burn reduction at ATL (west-flow runway 26R north airfield) to 25.4% at DFW (south-flow runway 17L).

Ideally, sophisticated multi-factor rules, based on the optimization of multiple factors, could increase fuel savings. Apart from the factors described in this paper, multi-factor rules should include departure queue length, departure queue sequence (a light aircraft following a heavy one would provide more time for runway crossings than if a heavy followed another heavy), and arrival delays (is the arriving flight late? Does it need to be turned around quickly?). The true benefits of implementing such rules, however, would be observed primarily only when they are calculated in real-time, thus raising the issue of trade-offs. How large should the optimization window be (e.g., 15 min, 30 min, or 1 hour) to yield significant fuel savings without increasing controller workload? Also, adopting such optimization rules will necessitate updates to technology in control towers, and perhaps require additional training for controllers to use these rules.

The focus of this paper is on taxi-in fuel burn reduction; however, arrival and departure surface operations are usually closely coupled. While this research does not explicitly model these effects, we performed a first-order analysis by creating a simple total runway occupancy metric to estimate the effect of the rules on departure throughput. In each case the rules did not unduly increase the total runway occupancy above the baseline case. Detailed simulation and modeling are needed to more accurately quantify the impacts of the decision rules on related departure parameters (throughput and taxi-out fuel burn). Future work will also expand the model to assess the environmental implications of integrated arrival and departure operations.

The decision rules necessarily require a change in air traffic controller procedures that must be evaluated carefully for safety and workload implications. Experiments with different forms of decision aids, followed by a pilot implementation at one or more airports, could yield valuable data.

The same analysis approach presented here can be applied to other congested airports to estimate the potential benefits of EATs. Since the ASDE-X data system is collected at 35 major airports across the US, extending taxi operation improvement analysis within this network of airports would be relatively easy.

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ACRONYMS

ASDE-X	Airport Surface Detection Equipment Model-X
ASPM	Airport System Performance Metric
ATL	Atlanta Hartsfield-Jackson International Airport
BADA	Base of Aircraft Data
DFW	Dallas/Fort-Worth International Airport
DTW	Detroit Metropolitan Wayne County Airport
EAT	end-around taxiway
FAA	Federal Aviation Administration
FDR	flight data recorder
ICAO	International Civil Aviation Organization
MIA	Miami International Airport
ROT	runway occupancy time

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