Impact of Congestion on Taxi Times, Fuel Burn, and Emissions at Major Airports

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Taxiing aircraft contribute significantly to fuel burn and emissions at airports. This paper provides a comprehensive assessment of the impact of surface congestion on taxi times, fuel burn, and emissions through analysis of the departing traffic data from four major U.S. airports. Several metrics based on airport throughput and taxi-out times are introduced and studied, including one that considers the number of flights that encounter a congested airport, a second metric that compares the observed taxi-out times with the unimpeded ones, and a third that evaluates them in conjunction with the airport throughput.

The "taxi-out time" of a flight is defined as the time that elapses between its pushback from the gate and the takeoff and is representative of the amount of time a departing aircraft spends on the airport surface with engines on. As a result, fuel burn surface emissions from departures are closely linked to the taxi-out times.

Taxi-out delays are frequently caused by congestion, which occurs when departure demand exceeds the capacity (*1*). While this imbalance often occurs during bad weather conditions, most major airports have periods of severe congestion even in good weather (*2*). As a result, at several of the busiest airports, taxi-out times are long and tend to be much greater than the unimpeded taxi times. This paper attempts to analyze departure data from four major airports to estimate the magnitude of congestion and to evaluate its effect on delay, fuel burn, and emissions.

The remainder of this paper is organized as follows: First, the data sources used in this work are introduced. Then departure data from four major airports [John F. Kennedy International Airport, New York (JFK); Newark Liberty International Airport, New Jersey (EWR); Philadelphia International Airport, Pennsylvania (PHL), and Boston Logan International Airport, Massachusetts (BOS)] are analyzed, and these airports are shown to have surface congestion in both good and bad weather conditions. The levels of congestion are quantified, and the impact of congestion on taxi-out times and the corresponding emissions are calculated.

The Aviation System Performance Metrics (ASPM) database offers a wealth of data that enable the study of airport performance in the United States (*3*). The following pieces of information from the ASPM database are used:

1. Actual pushback time of each flight,
2. Actual takeoff time of each flight,
3. Actual taxi-out time of each flight,
4. Flight code (airline and flight number) of each flight,
5. Runway configuration in use, and
6. Reported meteorological conditions.

ANALYSIS OF SURFACE CONGESTION

Flow Analysis of Departure Process

Operations on the airport surface include those at the gates, the ramp areas adjoining the gates, the taxiways, and the runway system. Each component could be subject to queuing delays and is also influenced by downstream factors such as the terminal airspace. On the basis of observations by Idris (*4*), four regions were identified on the surface where queues primarily form during the departure process: gates (before pushback), ramp, taxiways, and runways.

Conceptually, the departure process can be described as follows: First, aircraft request pushback from their gates. They wait to be cleared for pushback; this waiting time is modeled by the pushback queue. After pushback, they enter the ramp and then the taxiway system; then they taxi to the departure queues that form at the runway(s) to wait for takeoff. While taxiing out, different aircraft may interact with each other. For example, aircraft queue up to cross an active runway (runway-crossing queue) or to enter a taxiway segment where another aircraft is taxiing.

The different queues that form on the surface have different characteristics and costs associated with them. This paper primarily focuses on taxiing delays, fuel burn, and the aircraft emissions during taxi-out. As a result, the queues of particular interest are the ramp queue, the taxi queue, the runway-crossing queue, and the departure queue. Delays incurred at these queues are a direct consequence of congestion and contribute to excess fuel burn and emissions. Therefore, to estimate the total impact of congestion on taxiing aircraft, the waiting times in all four queues are added.

Key variables that affect the taxi time of a departing flight include runway configuration, weather conditions, downstream restrictions, gate location, and queuing delays (*5*). The concept of a segment, which is defined as a particular combination of runway configuration and weather conditions, is adopted here (*6*). The reported meteorological conditions [denoted either visual meteorological conditions (VMC) or instrument meteorological conditions (IMC)] are used as the indicator of weather conditions. The runway configuration is characterized by both the runways used for arrivals and those used for departures. A segment is denoted as (weather conditions; arrival runways | departure runways).

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Congestion Metric Based on Throughput Saturation

Prior work (*7, 8*) used the total number of departing aircraft on the ground as a measure of the congestion. However, the total number of aircraft on the ground does not, by itself, provide much insight into the level of congestion, as it does not say how many of the aircraft on the ground are "moving" and how many are being queued.

A better approach is to consider the relationship between the number of aircraft on the ground at the beginning of a time period t, denoted $N(t)$, and the takeoff rate during a later time period (*8*). One would expect that during times when $N(t)$ is small, few takeoffs take place. As $N(t)$ increases, the takeoff rate (or throughput) increases until the departure capacity is reached. This relationship is illustrated in Figure 1, where the average takeoff rate is shown as a function of the number of departing aircraft on the ground for a segment at PHL in 2007. The error bars show 1 standard deviation of the takeoff rate at a particular value of $N(t)$.

As expected, the takeoff rate increases at first and then it saturates close to airport capacity. For this segment, the surface saturates when there are 20 departing aircraft on the ground. The number of departures at which saturation occurs is defined as the saturation point, denoted by N^*. By definition, at N^* the airport works at its full capacity: increasing the number of departures further will only lead to further congestion. Therefore, the congestion regime is defined by $N(t) > N^*$. In the congestion regime, the takeoff rate remains stable, with small fluctuations about the departure capacity.

While an individual aircraft may experience some queuing for values of N less than N^*, the congestion area is representative of the amount of queuing at the airport on average. The total amount of time during which the airport operates in the congestion regime ($N(t) > N^*$) is therefore an insightful measure of congestion.

Sustained Departure Throughput

In addition to providing a congestion metric, the method described in the introduction also provides a way to measure the departure throughput. Although defining and measuring the capacity of an airport is an open research question (*1*) and outside the scope of this work, Figure 1 provides an estimate of the maximum throughput seen during a segment. For values of $N(t) > 20$, the takeoff rate is around 47 aircraft per hour (i.e., it is the observed average takeoff rate during busy periods). Although Figure 1 does not convey the length of time during which this capacity can be sustained, the fact that over the course of a year the takeoff rate is about 47 aircraft per hour when the airport operates in the congestion regime suggests that it is the maximum takeoff rate that this segment can achieve on average.

In the context of this paper, the word "capacity" is used to denote the departure throughput that a segment can sustain—that is, the average observed takeoff rate of a segment for $N(t)$ greater than or equal to N^*.

Although it was stated previously that the number of aircraft on the ground is well correlated with the takeoff rate of the following time interval, the choice of the length and the starting point of the time interval were not discussed. Following the approach introduced by Shumsky (*7*), $T_n(t + dt)$ is defined as the takeoff rate over the time period $(t + dt - n, t + dt - n + 1, \dots, t + dt, \dots, t + dt + n)$—that is, the number of aircraft that took off during that time period divided by its length $(2n + 1)$. For each segment, the values of n and dt are calculated that yield the highest correlation coefficient between $N(t)$ and $T_n(t + dt)$ over the times when this segment was in use.

Figure 1 displays the relationship between takeoff rate and $N(t)$ over a year of observations. The y-axis denotes the takeoff rate, $T_9(t + 9)$; that is, $n = 9$ and $dt = 9$. These parameters were chosen because they give on average the highest correlation coefficient at PHL for the time intervals in the year 2007 when this segment was in use.

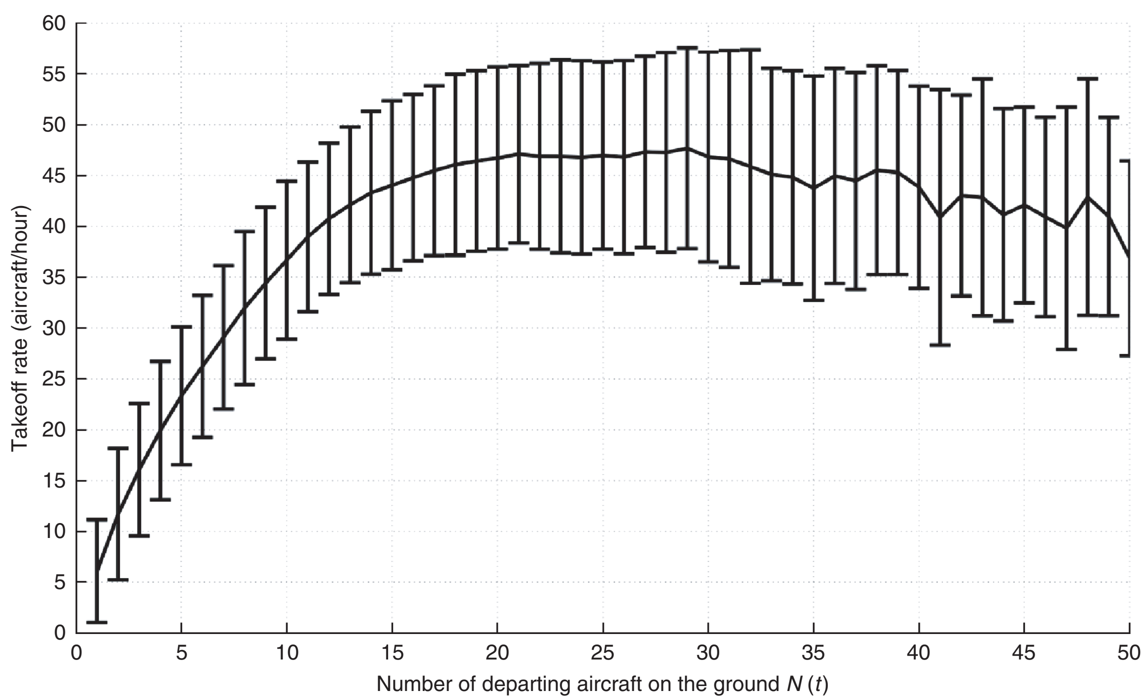

FIGURE 1 Departure throughput of PHL segment as function of number of departures postpushback (vertical bars denote one standard deviation).

TABLE 1 Reported Weather Conditions at Four Major Airports in 2007

Airport	Weather Conditions	Total Hours in Use	% of Time in Use	Number of Takeoffs
JFK	VMC	7,549	86.18	180,171
JFK	IMC	1,179	14.46	24,412
EWR	VMC	6,995.5	79.86	171,280
EWR	IMC	1,381.5	15.77	31,181
PHL	VMC	7,559	86.29	204,002
PHL	IMC	1,200.75	13.71	25,976
BOS	VMC	7,305.5	83.4	155,060
BOS	IMC	1,417.75	16.18	24,893

Congestion Analysis for Major Airports in 2007

Following the steps prescribed previously, congestion is analyzed at four airports in 2007: JFK, EWR, PHL, and BOS. Table 1 shows the weather conditions, Table 2 shows runway use, and Table 3 shows the congestion analysis results for the four airports.

John F. Kennedy International Airport

Table 1 shows the reported meteorological conditions at JFK for 2007. The percentages do not add up to 100% because there are occasional time intervals for which the weather is not reported. The first observation is that since reported weather conditions are favorable more than 85% of the time, the congestion problems at JFK may not be entirely weather related.

The total number of runway configurations that were reported used under VMC was 41. The six most frequently used runway configurations under VMC at JFK are shown in Table 2, as well as the amount of time they were in use, and the number of aircraft they served (the total number of aircraft that took off when each configuration was in use). This paper focuses on the congestion analysis for these six runway configurations, as the others are rarely used.

Table 3 reveals the magnitude of the congestion problem at JFK. The airport is congested 17.9% of the time that it operates in one of the six configurations. 31.2% of takeoffs take place while the airport is saturated, which means that 31.2% of departures spend more time taxiing than is needed to ensure that the airport operates at capacity. Runway Configurations 4 and 6, which utilize two runways for departures (22R, 31L and 4L, 31L, respectively) have the highest throughput, as one would expect. Finally, the estimates are reasonably

TABLE 2 Runway Configuration Use at Four Major Airports in 2007

Airport	WC	RC	RC Number	Total Hours in Use	% of Time in Use	Number of Takeoffs
JFK	VMC	31R | 31L	1	1,500.25	19.87	29,633
JFK	VMC	31L, 31R | 31L	2	1,497.25	19.83	35,833
JFK	VMC	13L, 22L | 13R	3	1,435.25	19.01	32,409
JFK	VMC	22L | 22R, 31L	4	772	10.02	24,136
JFK	VMC	13L | 13R	5	598.25	7.92	13,726
JFK	VMC	4R | 4L, 31L	6	426.5	5.65	13,092
JFK	VMC		[1–6]	6,229.5	82.52	148,829
EWR	VMC	22L | 22R	1	2,559.75	36.59	59,324
EWR	VMC	4R | 4L	2	1,464.25	20.93	36,690
EWR	VMC	11, 22L | 22R	3	1,355.5	19.38	33,757
EWR	VMC	4R, 11 | 4L	4	757.5	10.83	18,253
EWR	VMC	4R, 29 | 4L	5	406.25	5.81	9,354
EWR	VMC	22L | 22R, 29	6	240.25	3.43	7,966
EWR	VMC		[1–6]	6,783.5	96.97	165,344
EWR	IMC	22L | 22R	1	536	38.79	11,918
EWR	IMC	4R | 4L	2	567.25	41.06	13,722
EWR	IMC		[1–2]	1,103.25	82.12	25,640
PHL	VMC	26, 27R, 35 | 27L, 35	1	5,877	77.75	160,357
PHL	VMC	9R, 17 | 8, 9L, 17	2	377	4.99	9,652
PHL	VMC	9R, 35 | 8, 9L, 35	3	368.5	4.87	10,818
PHL	VMC	26, 27R | 27L	4	356.75	4.72	8,419
PHL	VMC		[1–4]	6,979.25	92.33	189,045
PHL	IMC	9R, 17 | 8, 9L, 17	2	282	23.49	7,243
PHL	IMC	9R | 8, 9L	5	302.75	25.20	7,219
PHL	IMC		[2,5]	584.75	48.70	14,228
BOS	VMC	22L, 27 | 22L, 22R	1	2261	30.95	45,783
BOS	VMC	4L, 4R | 4L, 4R, 9	2	1,280.5	17.53	30,437
BOS	VMC	27, 32 | 33L	3	1,026.5	14.05	23,490
BOS	VMC	33L, 33R | 27, 33L	4	398.75	5.46	9,157
BOS	VMC	Other	[5,6, . . . ,20]	1,920	26.28	36,550
BOS	VMC		[1–20]	6,886.5	94.26	145,417
BOS	IMC	4R | 4L, 4R, 9	10			
BOS	IMC	4R | 9	12			
BOS	IMC	4R | 4R, 9	13	709.75	50.06	15,152

NOTE: WC = weather conditions, RC = runway configuration.

TABLE 3 Congestion Analysis at Four Major Airports in 2007

Airport	WC	RC Number	Optimal (*n*,*dt*)	Capacity (AC/hour)	*N**	No. of Hours in Congestion	% of Time in Congestion	No. of Takeoffs in Congestion	% of Takeoffs in Congestion
JFK	VMC	1	(15,15)	40.46	28	220.12	14.67	8,847	29.86
JFK	VMC	2	(19,19)	41.35	25	313.5	20.94	12,397	34.6
JFK	VMC	3	(15,15)	41.24	32	234.13	16.31	9,553	24.98
JFK	VMC	4	(18,18)	46.09	29	127.05	16.46	6,016	24.93
JFK	VMC	5	(15,15)	43.09	28	109.58	18.32	4,725	34.42
JFK	VMC	6	(16,16)	43.71	26	107.63	25.24	4,827	36.87
JFK	VMC	[1–6]		42	28	1,112.02	17.85	46,365	31.15
JFK	IMC	All	(20,20)	35.65	27	283.92	24.09	9,926	40.94
EWR	VMC	1	(11,11)	39.82	24	247.33	9.66	9,784	16.49
EWR	VMC	2	(15,15)	41.06	28	174.25	11.90	7,139	19.46
EWR	VMC	3	(12,12)	39.71	28	119.87	8.84	4,760	14.1
EWR	VMC	4	(16,16)	36.23	23	156.02	20.60	5,635	30.87
EWR	VMC	5	(12,12)	36.92	23	66.17	16.29	2,454	23.23
EWR	VMC	6	(13,13)	45.89	22	86.25	35.90	3,944	49.51
EWR	VMC	[1–6]		39.7	25	849.8	12.53	33,716	20.39
EWR	IMC	1	(17,17)	35.92	18	124.52	23.23	4,442	37.27
EWR	IMC	2	(19,19)	38.36	36	42.9	7.56	1,604	11.69
EWR	IMC	[1–2]		37		267.42	15.17	6,046	23.58
PHL	VMC	1	(9,9)	46.97	20	836.47	14.23	39,390	24.57
PHL	VMC	2	(9,9)	38.2	19	142.43	37.78	5,379	56.08
PHL	VMC	3	(10,10)	42.71	23	80.77	21.92	3,492	32.35
PHL	VMC	4	(8,8)	41.85	17	78.28	21.94	3,194	38.39
PHL	VMC	[1–4]		46.01	20	1,137.95	16.30	51,455	27.22
PHL	IMC	2	(10,10)	38.61	18	83.97	29.77	3,245	45.7
PHL	IMC	5	(10,10)	35.48	14	102.53	33.87	3,666	51.43
PHL	IMC	[2,5]		37		186.5	31.90	6,911	48.75
BOS	VMC	1	(9,9)	41.53	16	255.31	11.29	10,582	23.11
BOS	VMC	2	(9,9)	43.89	17	81.38	6.36	3,609	11.86
BOS	VMC	3	(9,9)	43.36	21	35.92	3.50	1,567	6.67
BOS	VMC	4	(9,9)	49	21	6.7	1.68	323	3.35
BOS	VMC	[5–20]	(8,8)	40.61	18	88.95	4.63	3,555	9.73
BOS	VMC	[1–20]		42.42	18	468.27	6.80	19,636	13.5
BOS	IMC	[10,12,13]	(10,10)	35.84	15	97.67	13.76	3,424	22.6

NOTE: AC = aircraft.

close to the FAA benchmark report values: according to the report, Configurations 1 and 2 have a benchmark capacity rate of 75 to 87 aircraft per hour (*9*). Assuming a 50% mix of arrivals and departures, the benchmark rate corresponds to 37.5 to 43.5 aircraft per hour departure capacity.

Figure 2 shows the congestion for different hours of the day. Solid bars depict the average values of $N(t)$ during a particular hour of the day in 2007. Error bars illustrate 1 standard deviation. This figure suggests that, on average, the number of departing aircraft on the ground is greater than the average $N^* = 28$ for 3 h of the day. This number shows that significant congestion is expected at JFK on a daily basis even in good weather as a result of the high departure demand. This systematic imbalance between demand and capacity for a significant fraction of the day implies that an airport would benefit from some strategy to control excessive taxi times on a regular basis.

Table 1 suggests that weather conditions at JFK are classified as IMC quite infrequently. Controllers tend to use a rich mix of runway configurations under IMC; therefore, all runway configurations that are used under IMC are treated as one segment, as shown in Table 3. The analysis shows that the capacity under IMC is lower than that under VMC as expected and that 40.94% of departures take off while the airport is saturated.

Newark Liberty International Airport

The weather conditions at EWR are visual most of the time, as shown in Table 1. EWR has fewer runways and a simpler layout than JFK, which is reflected in the number of recorded runway configurations: only 17 in 2007. The most frequently used runway configurations at EWR in 2007 under VMC are shown in Table 2. Configurations 1 to 6 were used 97% of the time under VMC. The congestion for these six main runway configurations is analyzed.

Table 3 shows that the departure capacity of the two most frequently used runway configurations 22L|22R and 4R|4L is around 40 aircraft per hour. Comparing the capacity of Configurations 4 and 5 with that of Configuration 2 shows that adding an arrival runway reduces the departure capacity. This decrease occurs because the runway (11–29) intersects the runway (4L–22R). Adding a runway for departures increases the departure capacity, as can be observed from the capacity of Configuration 6 (around 46 aircraft per hour). These results agree with the FAA benchmark report, which gives an average optimum rate under VMC of 42 departures and 42 arrivals per hour (*9*). Table 3 shows that EWR is less congested than JFK. Nonetheless, it has severe congestion as well, as it is congested 12.5% of the time and 20.4% of the flights take off in the saturation area.

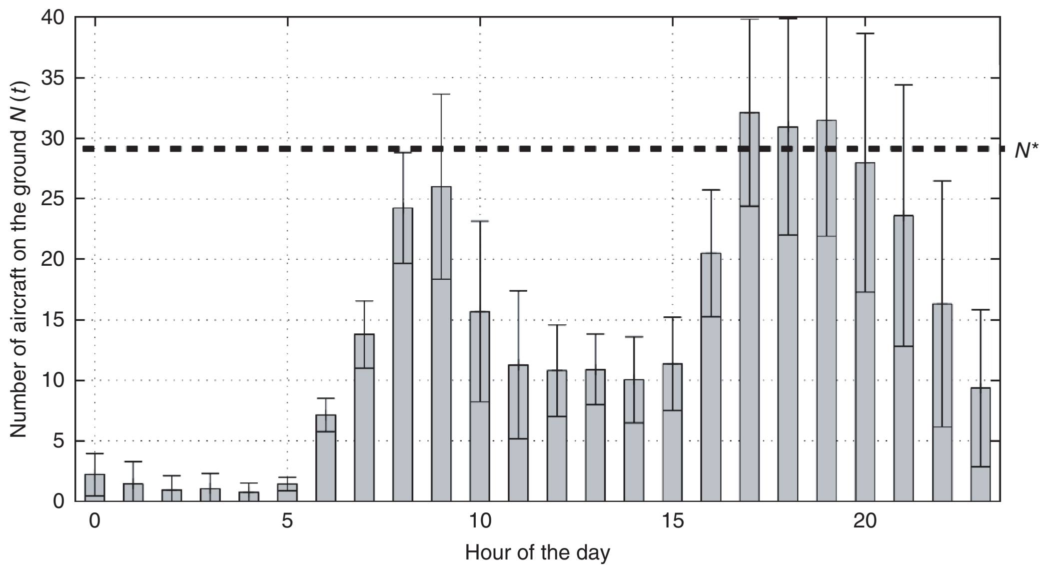

FIGURE 2 Congestion at JFK under VMC during different hours of day.

Under IMC in EWR, the most frequently used configurations are 22L|22R and 4R|4L (used 82% of the time). They are also the most frequently used runway configurations under VMC (Table 2). As shown in Table 3, Configuration 2 has a higher capacity than Configuration 1 under IMC, as was the case under VMC. One can also observe that the capacity of both Configurations 1 and 2 decrease under IMC compared with VMC, as expected.

There is a noticeable difference between the N^* values of the two configurations: 18 and 36. The takeoff rate of Configuration 1 saturates at around 36 aircraft per hour when $N = 18$. In contrast, Configuration 2 appears to stabilize around 34.8 aircraft per hour for N taking values between 19 and 26 and then increases again to stabilize at 38.4 aircraft per hour for $N \geq 36$. A possible reason for this behavior may be that controllers give priority to arrivals for low values of N and attempt to increase the departure service rate when the congestion due to departing aircraft worsens. The high value of N^* (i.e., 36) is also responsible for the near absence of congestion in Configuration 2: almost all the operations are classified as non-congested. The data for Configuration 1, on the other hand, clearly show the effect of weather: the airport is congested 23.2% of the time, and 37.3% of departures take off in the congestion regime under IMC. These numbers are twice as large as those of Configuration 1 under VMC.

Philadelphia International Airport

At PHL, as in the case of JFK and EWR, the airport predominantly operates under VMC, as shown in Table 1. The most frequently used runway configurations at PHL in 2007 during VMC are shown in Table 2. The total number of the runway configurations reported under VMC in 2007 was 38. However, configuration 26, 27R, 35|27L, 35 was used 77.8% of the time that the airport was under VMC.

Table 3 illustrates the magnitude of congestion at PHL. On average, it is congested 16.3% of the time and 27.2% of the departures take off in the congestion regime. Comparing these numbers with the corresponding ones for JFK and EWR shows that PHL is more congested than EWR and almost as congested as JFK. This result motivates the need for a congestion metric: EWR has higher average taxi-out times than PHL, but it is not necessarily more congested than PHL. Taxi times may be longer simply because the aircraft need more time to reach the runway threshold (because of size or layout).

Weather conditions at PHL are rarely classified as IMC, and controllers tend to use a rich mix of runway configurations under poor weather conditions. Therefore, the analysis is confined to two configurations, 2 and 5, which are used almost 50% of the time. Table 3 reveals that PHL has the greatest congestion when it operates in Configurations 2 and 5 under IMC. However, weather appears to be only indirectly responsible for this phenomenon: the departure capacity of the runway Configuration 2 does not decrease because of the weather, nor does the saturation point shift significantly, which suggests that IMC results in increased congestion at PHL not because the capacity decreases but because the airport cannot use the most efficient runway configuration as much as it does under VMC.

Boston Logan International Airport

Table 1 shows that BOS experiences visual conditions most of the time. BOS has a complicated runway complex consisting of five runways, four of which intersect with at least one other runway. This situation creates opportunities for numerous runway configurations—in 2007, 61 different runway configurations were reported at BOS. The most frequently used runway configurations under VMC were 22L, 27|22L, 22R; 4L, 4R|4L, 4R, 9; 27, 32|33L; and 33L, 33R|27, 33L (Table 2). However, these four configurations account for less than 70% of the VMC times. Therefore, congestion is analyzed for the mix of 16 other configurations (denoted as 5, 6, . . . , 20), which were used between 60 and 250 h each at BOS in 2007 (26.28% of the time).

Table 2 shows that Configurations 1, 2, and 3 have similar capacities. This may appear counterintuitive, as they have two, three, and one assigned departure runway(s), respectively. However, at BOS, controllers tend to use one runway primarily for departures regardless of the particular configuration. Prior studies of BOS found that configuration 4L, 4R|4L, 4R, 9 has a higher capacity than 22L, 27|22L, 22R, which is consistent with these findings (*1*).

The three runway configurations differ in the values of the saturation point, N^*. While Configurations 1 and 2 use runways whose thresholds are located close to the gates, Configuration 3 uses the more remotely located runway 33L for departures, which results in a higher value of N^*, because aircraft can be spread out on the ramps and the taxiways. More aircraft are therefore needed (compared with Configurations 1 and 2) to maintain pressure on the runway in the subsequent time period. Finally, Configuration 4 appears to have a higher capacity than the other configurations, but it is rarely used, resulting in small sample sizes in the observations.

BOS has less congestion than the other three airports examined. Configuration 1 is congested 11.4% of the time and 23.1% of the flights in this configuration take off when the airport is saturated. IMC conditions are relatively rare in BOS, as shown in Table 1. Controllers tend to use a rich mix of 42 different runway configurations under IMC. In contrast to JFK, different runway configurations have different capacity and saturation values, so they cannot all be grouped. However, congestion is analyzed for a set of three configurations, which are used 50% of the time under IMC (Table 2).

Table 2 shows that instrumental meteorological conditions result in decreased capacity compared with visual meteorological conditions. The time the airport experiences congestion under IMC is twice as much as the time it experiences congestion under VMC, and 22.6% of the departing flights take off when the airport is saturated. This value is a significant increase from the VMC case, in which only 13.5% of the takeoffs took place when the airport was saturated. It is concluded that, although BOS is a relatively noncongested airport, IMCs decrease its capacity and result in a significant increase in congestion.

EFFECT OF SURFACE CONGESTION ON TAXI-OUT TIMES

This section proposes metrics to evaluate the effects of congestion on taxi times by introducing two baseline metrics for comparison: the unimpeded taxi-out time and the saturation taxi-out time. The subsections on unimpeded taxi-out time metric and saturation taxi-out time metric describe these baseline metrics, while the subsections on analysis of taxi-out times and fuel burn and emissions analysis describe how they can be used to calculate the impact of surface congestion on taxi-out times, fuel burn, and emissions.

Unimpeded Taxi-Out Time Metric

The unimpeded taxi-out time is the nominal, free-flow taxi-out time. The FAA defines the unimpeded taxi-out time as "the taxi-out time under optimal operating conditions, when neither congestion, weather nor other factors delay the aircraft during its movement from gate to takeoff" (*10*, pp. 10–11). In other words, the unimpeded taxi-out time is the time spent on the surface if it does not experience any queuing delays during taxiing. By this definition, the unimpeded taxi-out time is not the minimum time that an aircraft would need to taxi-out and take off, but rather it is the average time that an aircraft needs to complete the departure process when it spends no time waiting in queues. The service time for each of the steps of the departure process may vary among flights for several reasons, including differences in dispatch processes, taxiway routes, taxi speeds, and runway assignments; variability in the duration of pushback and engine start; and differences in pilot–controller communications. Some of these factors, such as dispatch process or communication delays, contribute to the variability of the unimpeded taxi times (*11*). This paper follows the method outlined by Simaiakis and Balakrishnan (*2*) to estimate the unimpeded taxi-out times.

Unimpeded Taxi-Out Time as a Baseline

The unimpeded taxi-out time provides a measure of the "ideal" taxi-out time of an aircraft, in the absence of any queuing. The unimpeded taxi-out time therefore provides a useful baseline to evaluate surface congestion: by comparing the observed taxi-out time with the unimpeded taxi-out time, the queuing delay experienced by an aircraft is estimated. The mean unimpeded taxi-out time of a segment can also be estimated as the average of the unimpeded taxi-out times of the flights in that segment.

For each segment at an airport, the unimpeded taxi-out time, $\tau_{unimped}$, is calculated for the flights of each airline. Then, flights that have a taxi time higher than the unimpeded taxi time of their airline are identified. These flights are defined as "impeded flights" because they do not take off within their unimpeded taxi time. The impeded taxi-out time, $\tau_{impeded}$, is the difference between the actual taxi-out time of an impeded flight and its unimpeded taxi-out time.

Saturation Taxi-Out Time Metric

Definition of Saturation Taxi Time

While the comparison of the observed taxi-out times with the unimpeded ones is a good measure of the impact of queuing on taxi time, it may not be possible to achieve unimpeded taxi-out times in practice. Under current operational procedures, the unimpeded taxi times are achievable only when the demand for resources (air traffic control communications, gates, ramp areas, taxiways, and runways) is close to zero—that is, only when the number of taxiing aircraft is very small.

To account for the presence of other aircraft on the ground, the saturation point (N^*) denotes the point at which the airport reaches its sustained departure capacity. The takeoff queue of an aircraft i, $NQ(i)$ is considered, which is defined as the number of takeoffs between its pushback and takeoff time (*5*). In other words, the takeoff queue of an aircraft is the number of aircraft ahead of it in the departure process. These quantities motivate the second proposed baseline of acceptable taxi-out time, the saturation taxi-out time, which is defined as the mean taxi-out time of all flights having ($N^* - 1$) aircraft in their takeoff queue. Flights in congestion are also defined to be those flights that have at least N^* aircraft in their takeoff queues.

In theory, flights in congestion could be held at the gate until their takeoff queue reaches ($N^* - 1$) without adversely affecting either their delay or the airport throughput. However, this approach is difficult in practice, because the takeoff queue of a flight is not known at pushback. An easier approach is to control according to the number of departures on the ground at pushback, which is a simpler but less efficient policy.

Estimation of the Saturation Taxi-Out Time

For each segment at an airport, the saturation taxi time, τ_{sat}, is calculated as the mean taxi time of all aircraft having ($N^* - 1$) aircraft in their takeoff queue.

Mean Taxi-Out Time of Flights in Congestion

A flight in congestion does not contribute toward increasing airport throughput but contributes to surface congestion. The mean taxi-out time of all flights in congestion is denoted as T in congestion. Because the taxi time of an aircraft scales with its takeoff queue (*2, 5*), the difference between T in congestion and τ_{sat} provides an estimate of how deep in the congestion area the airport tends to operate. This metric complements the flights in congestion metric, as the latter does not provide information about the prevalence of congestion. For example, two different airports could have 10,000 flights in congestion. However, if the difference between T in congestion and τ_{sat} is 30 min in the first case and 2 min in the second, the first airport faces a more severe congestion problem.

Analysis of Taxi-Out Times

The excessive taxi-out time baselines and metrics for the most frequently used segments of JFK, EWR, PHL, and BOS are now evaluated. For each segment, the following metrics are determined:

- Mean taxi-out time, τ;
- Mean unimpeded taxi time, $\tau_{unimped}$;
- Number of impeded flights and their mean impeded taxi-out time, $\tau_{impeded}$;
- Saturation taxi-out time of the segment, τ_{sat}; and
- Number of flights in congestion, and their taxi-out time, T in congestion.

The analysis results are summarized in Table 4.

JFK Taxi-Out Times

The results from JFK reinforce the earlier conclusion that the airport is very congested: 139,713 flights of the 148,829 served in the segments [1–6] had taxi-out times longer than their unimpeded times. It is also worth noting the extent to which flights are delayed: the mean taxi-out time in congestion can be as much as 18 min longer than the saturation taxi-out time. 33,743 flights operate in congestion and on average taxi out for 15 min longer than the saturation taxi time, thereby contributing to congestion, fuel burn, and emissions. The results also show that runway Configurations 4 and 6, which use two departure runways, have lower unimpeded taxi times.

The analysis shows that the congestion problem worsens under IMC: 7,866 of the 24,412 flights push back under congestion. These flights have an average taxi-out time of 69 min, which is 20 min more than the saturation taxi-out time. Unimpeded taxi times are higher under IMC than under VMC, as is expected as nearly all departure processes, including taxi speeds, are slower under IMC.

TABLE 4 Taxi-Out Time Analysis at Four Major Airports in 2007

Airport	WC	RC Number	τ	$\tau_{unimped}$	No. of Impeded Flights	τ of Impeded Flights	$\tau_{Impeded}$	τ_{sat}	No. of Flights in Congestion	T in Congestion
JFK	VMC	1	36.08	16.49	27,517	39.25	22.92	42.66	6,891	60.02
JFK	VMC	2	34.54	16.28	33,923	37.04	21.22	40.05	8,114	56.38
JFK	VMC	3	37.46	17	30,717	40.23	23.43	47.6	7,194	61.59
JFK	VMC	4	31.16	15.15	22,871	34.55	19.48	38.18	4,239	48.85
JFK	VMC	5	36.32	17.14	12,301	39.09	21.89	39.54	3,794	54.97
JFK	VMC	6	33.27	15.27	12,384	36.67	21.87	34.36	3,511	49.32
JFK	VMC	[1–6]	34.99	16.37	139,713	37.92	21.87	41.31	33,743	56.4
JFK	IMC	All	45.23	19	23,273	51.81	32.95	47.46	7,866	68.83
EWR	VMC	1	25.55	13.25	56,089	29.28	16.08	36.19	8,177	50.09
EWR	VMC	2	29.55	13.77	35,890	32.42	18.69	41.23	6,476	54.23
EWR	VMC	3	27.81	13.48	31,494	29.31	15.85	43.35	3,707	54.46
EWR	VMC	4	32.7	14.37	16,737	34.61	20.18	38.32	4,591	56.08
EWR	VMC	5	30.43	14.32	8,697	31.8	17.49	37.73	2,111	52.19
EWR	VMC	6	28.95	11.97	8,246	31.49	19.66	28.39	2,719	41.05
EWR	VMC	[1–6]	28.13	13.54	157,153	30.83	17.33	38.02	27,781	51.9
EWR	IMC	1	29.01	14.03	11,813	32.87	18.83	29.58	3,587	45.26
EWR	IMC	2	32.7	13.68	13,544	34.96	21.27	57.16	914	70.19
EWR	IMC	[1–2]	30.99	13.84	25,357	33.99	20.14	35.18	4,501	50.32
PHL	VMC	1	21.45	11.39	140,992	23.63	12.28	25.47	39,098	35.78
PHL	VMC	2	33.91	12.72	9,354	39.27	26.61	28.7	3,925	48.65
PHL	VMC	3	27.59	11.37	10,127	29.43	18.08	32.35	2,930	46.16
PHL	VMC	4	23.11	12.24	7,278	30.35	18.36	25.13	2,184	37.39
PHL	VMC	[1–4]	22.51	11.5	167,751	25.15	13.7	26.13	48,137	37.53
PHL	IMC	2	27.81	12.4	6,769	33.08	20.77	27.45	2,458	41.52
PHL	IMC	5	26.66	12.32	6,606	29.93	17.67	23.17	2,976	38.83
PHL	IMC	[2, 5]	27.22	12.36	13,375	31.52	19.24	25.1	5,434	40.05
BOS	VMC	1	20.25	12.84	40,016	21.81	8.96	23.58	8,540	32.1
BOS	VMC	2	18.59	11.52	27,469	19.75	8.24	23.83	3,250	34.16
BOS	VMC	3	21.4	13.15	21,561	22.59	9.51	30.27	1,594	39.77
BOS	VMC	4	19.6	13.23	8,111	20.6	7.59	28.63	329	36.16
BOS	VMC	[5–20]	19.5	12.65	31,536	21.63	9.04	27.04	2,904	38.56
BOS	VMC	[1–20]	19.87	12.59	128,693	21.38	8.83	24.98	16,617	34.45
BOS	IMC	[10, 12, 13]	21.61	12.58	12,923	24.03	11.57	25.54	2,876	37.22

EWR Taxi-Out Times

Taxi-out times for the most frequently used VMC segments at EWR tend to be lower than those at JFK. Nevertheless, 157,153 of the 165,344 flights in 2007 recorded taxi-out times higher than their unimpeded ones. Although in every segment a large number of flights encountered a congested takeoff queue, the total number of flights in congestion was smaller than at JFK.

Taxi-out times in congestion at EWR exceed the saturation taxi-out time by 14 min on average. Unimpeded taxi times tend to be higher at JFK than at EWR, possibly because of the more complicated layout of JFK and the longer distances between the gates and the runways. As a consequence, the mean impeded taxi-out time at JFK is only about 5 min longer than at EWR, even though the mean taxi-out time for the major VMC configurations is 7 min longer at JFK than at EWR.

Because of the high value of N^* for Configuration 2 under IMC (see Table 3), there are insufficient samples of flights in congestion for a statistically meaningful comparison of configurations. However, weather appears to affect the taxi times only marginally. The mean impeded taxi-out time increases by only 3 min from VMC to IMC at EWR, whereas the difference was 11 min at JFK.

PHL Taxi-Out Times

An analysis of taxi-out times at PHL in 2007 shows significant congestion. 48,137 of the 189,045 flights (25.5%) faced a congested takeoff queue, as opposed to 22.7% of flights at JFK. However, the net effect of congestion appears to be similar. The average impeded taxi-out time is less than 14 min, and the taxi-out time of the congested flights is 11 min longer than the saturation taxi-out time. Although many flights face congestion, they are affected in a more moderate way, and the mean taxi-out time is much smaller at PHL than at JFK and EWR. In addition, the unimpeded taxi-out time is almost 5 min shorter at PHL than at JFK.

Comparing the taxi-out times of VMC segments at PHL and at EWR, both the total and the impeded taxi-out times are higher at EWR than at PHL. On the other hand, the product of the total number of congested flights and their taxi-out times is higher at PHL than at EWR. This finding suggests that a strategy aimed at reducing the taxi-out times during congested periods would be more effective at PHL than at EWR.

Runway Configuration 2 has very similar performance characteristics under VMC and IMC (unimpeded taxi-out time and saturation taxi-out time), and it is more congested under VMC (higher impeded taxi-out time, higher taxi-out time in congestion, and more flights in congestion). Configuration 5 has the shortest saturation taxi-out time. A large proportion of its flights face a congested takeoff queue, but their taxi times are similar to those of congested flights in other segments. In summary, instrumental weather conditions do not appear to affect congestion and taxi-out times at PHL.

BOS Taxi-Out Times

Table 4 shows the analysis results for the most frequently used VMC segments at BOS. BOS is the least congested airport among those considered in this analysis. The impeded taxi-out times are less than 10 min, and they are less than the unimpeded taxi-out times at the other airports. Taxi-out times in congestion are less than 10 min longer than the saturation taxi-out times.

The analysis of the most frequently used IMC segments at BOS shows that configurations using runways 4R, 4L, and 9 [10, 12, 13] are more congested than the corresponding VMC segment [1], which uses the same runways. The taxi-out time in congestion is almost 12 min longer than the saturation taxi-out time, and the impeded flights have higher taxi-out times than the impeded ones under VMC. These results suggest that a strategy to mitigate congestion at BOS would be more effective under IMC than under VMC.

Fuel Burn and Emissions Analysis

Table 5 shows the baseline fuel burn and emissions for the flights taking off from the airports and configurations considered. It also shows the estimated fuel burn and emissions if the flights experienced their unimpeded taxi-out times. At JFK, EWR, and PHL, the actual fuel burn and emissions are more than double those from unimpeded operations. These results suggest that there is significant potential to decrease the environmental footprint of these airports.

The fuel burn and emissions calculations were conducted assuming that each flight taxis at 7% throttle setting and using fuel burn and emissions indices from the International Civil Aviation Organization (*12, 13*). In practice, some taxiing aircraft, especially those delayed because of downstream restrictions, are diverted to holding pads, where they typically have their engines off. To obtain realistic estimates, the fuel burn and emissions from flights having a taxi-out time longer than 90 min are truncated to correspond to a 90-min taxi-out time.

As mentioned earlier, it is difficult to achieve unimpeded taxi-out times for all flights under current operations. Therefore, the fuel burn and the emissions of all congested flights were calculated and compared with the fuel burn and emissions that would result if their

TABLE 5 Fuel Burn and Emissions in JFK, EWR, PHL, and BOS

Airport	Fuel (10^3 gal)	HC (kg)	CO (kg)	NO_x (kg)
Reported Taxi Times				
JFK	27,665	157,773	1,798,774	360,341
EWR	20,778	124,752	1,550,600	268,279
PHL	21,521	163,736	1,593,594	275,793
BOS	13,656	89,007	945,291	172,563
Unimpeded Taxi Times				
JFK	12,483	71,917	808,654	162,514
EWR	10,213	59,192	749,569	131,918
PHL	9,914	75,820	732,084	126,725
BOS	8,444	54,781	584,203	106,901
Taxi Times of Flights in Congestion				
JFK	10,804	59,032	687,460	141,388
EWR	5,648	35,915	434,560	73,139
PHL	9,144	69,418	673,457	117,323
BOS	3,079	20,750	217,956	38,765
Saturation Taxi Times				
JFK	8,327	45,508	530,845	108,998
EWR	4,291	27,185	329,536	55,538
PHL	6,232	47,573	460,954	79,946
BOS	2,188	14,554	154,162	27,572

NOTE: HC = hydrocarbons, CO = carbon monoxide, NO_x = nitrogen oxides.

taxi-out time were the saturation taxi-out time of their segment. The results are shown in the lower part of Table 5. Significant reductions in fuel burn and emissions could be achieved if the congested flights experienced just the saturation taxi time of their segment. PHL appears to have the greatest potential for reductions in fuel burn and emissions despite having a lower average taxi-out time than JFK and EWR. There appears to be a significant pool of benefits from controlling the pushback of aircraft so as to avoid unnecessary accumulation of active aircraft on the surface.

CONCLUSIONS

Congestion analysis showed that the departure processes at JFK, EWR, and PHL experienced surface congestion 10% to 20% of the time in 2007. The major reason for the observed levels of congestion appeared to be the very high departure demand. The analysis also showed that BOS has moderate congestion compared with the other three airports. However, at BOS, IMC decrease its capacity and double the time the airport spends in congestion.

The taxi-out time analysis showed that taxi-out times tend to be two to three times the unimpeded times at JFK, EWR, and PHL. Fuel burn and emissions could be reduced by nearly 50% if the unimpeded taxi-out times could be achieved. The analysis also showed that the unimpeded taxi-out times differ from airport to airport and that taxi-out times alone do not completely reflect the time aircraft spend queuing on the surface.

A new metric for measuring the effect of congestion on taxi-out times was introduced. This method classified as congested all flights that faced a takeoff queue longer than the one necessary to achieve the departure capacity. According to this metric, PHL was found to be more congested than EWR and as congested as JFK.

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