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Using ASDE-X Surveillance for Taxi-Out Time Benchmarking and Delay Estimation

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Surface performance indicators for taxi-out delay depend on reference ideal unimpeded (nominal) times to identify areas in need of improvement. Current FAA practice derives unimpeded taxi-out times through a statistical analysis of ASPM-provided Out-Off-On-In (OOOI) sensor timestamps. This statistical technique uses a regression of taxi-times against the number of aircraft active on the surface to determine times of low congestion and presumably under conditions when times would be "unimpeded." These OOOI timestamps are rounded to the nearest minute and reported by a subset of carriers, leading to data concerns. Furthermore, the current unimpeded taxi-out method is only based on departure airport, operating carrier, season, and calendar year, which fails to include both start taxi-out location (gate/terminal) and wheels-off location (runway). Given these shortcomings, opportunities exist to estimate surface performance indicators through the use of surveillance data. Surveillance systems, such as the Airport Surface Detection Equipment-Model X (ASDE-X) system, provide aircraft temporal and spatial information by the second, enabling terminal area and runway information to be incorporated. The purpose of this paper is to utilize these new capabilities when identifying taxi-out routings that contribute the most to delay and inefficiency. The paper first assesses the current statistically derived unimpeded time against alternatives based on upper percentile benchmark methods. It then evaluates alternatives to current methodology by developing both an ASDE-X and hybrid ASDE-X/ASPM Key Surface Event Database. Techniques using the ASPM, ASDE-X, and hybrid surface databases are compared for five top U.S. airports during Fiscal Year 2014. Results show that ASDE-X provides better and more consistent data coverage when compared to the current ASPM process. An ASDE-X source also allows the taxi-start location to be identified, unlike ASPM. However, given existing data limitations, it is recommended that ASDE-X be supplemented with ASPM messages in order for an analysis to capture a more complete understanding of surface performance, specifically in the masked, non-movement area.

I. Introduction

SURFACE movement efficiency is important to airports, airlines, and passengers due its impact on costs. Its effect on costs is significant, as even small improvements in surface movement efficiency can lead to large returns. For example, implementing a single congestion technique at JFK airport resulted in "total annualized taxi time reductions of 14,800 hours which translated into annual savings of 5.0 million US gallons of fuel and 48,000 metric tons of carbon dioxide."[1] Due to its impact, several aviation performance measures are in place to assess

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efficiency on the airport surface and identify improvement opportunities in operations. These measures include 1) Gate departure/arrival punctuality, 2) Compliance with assigned departure times, 3) Runway occupancy times and 4) Surface delay.

Surface delay, specifically, is calculated as the actual taxi-out travel time against an estimated ideal unimpeded (nominal) benchmark time. There are several options for estimating an unimpeded time including 1) statistical processing of actual travel times, 2) subtracting all hold times recorded by ground surveillance data, or 3) modeling times in which an assumed taxi speed is used for different aircraft and the airport layout has been digitized as an input into a surface model. For statistical techniques, there is often a process that attempts to filter for low congestion periods. Typically this is calculated using percentiles, such as the 20th percentile or the average of the 5th-to-15th percentile taxi-out times.[2] The quality of the statistics also depend on the ability to group flights by common characteristics such as the start/end points of the ground taxi (gate area/runway) as well as the aircraft type and season.

In current FAA practice, the unimpeded benchmark time is statistically derived from "optimal operating conditions (when congestion, weather, or other delay factors are not significant)."[3] Using this method, flights are first grouped by airport, operating carrier, departure season, and departure calendar.[4] Then, for each flight grouping, a regression analysis estimates unimpeded travel times during uncongested periods using Gate-Out, Wheels-Off, Wheels-On and Gate-In times (otherwise known as OOOI times) as inputs. These unimpeded times, as well as the OOOI times, are then published by the FAA's Aviation System Performance Metrics (ASPM) for surface delay benchmarking.

This taxi-out benchmarking time estimation has several opportunities for improvement. In ASPM, the OOOI times are rounded to the nearest minute and reported by a subset of carriers. These select carriers represent approximately 70% of the traffic across key airports in the US. For non-reporting carriers, OOOI times are estimated based on the first available RADAR position point on departure or last available RADAR point on arrival.[5,6] The list of reporting carriers changes year to year and can lead to confounding factors where performance trends can change due to data coverage rather than to FAA investment or other operational reasons.

In addition to the data inconsistencies, the benchmarking estimation method itself can also be improved. Specifically, the flight grouping dimensions do not incorporate the taxi-out distance in the benchmark time estimation. That is, operating carrier is used as a proxy for the departing terminal (start taxi location) since terminal is not reported in ASPM. This is problematic as an airline can span several terminals at an airport where each has a noticeably different distance from the runways. And although runway information (end taxi location) is available in ASPM, it is not incorporated into the unimpeded taxi-out estimation. Ideally, a single source with consistent reporting would be used that has all key event times as well as surface area locations for the start-taxi and end-taxi events.

Overall, the main goal of this paper is to explore unimpeded taxi-out estimations using both non-surveillance data and surveillance data. The data sources are evaluated based on data coverage and the robustness of estimated surface delay metrics. The results of this comparison are then used to recommend improvements to the system and method. Also, after combining the non-surveillance and surveillance datasets, surface movement times are analyzed for each phase of the taxi-out process.

II. Data Summary

Surface performance metrics developed by the FAA are based largely on OOOI times collected through the Aircraft Communications Addressing and Reporting System (ACARS). The complete set of OOOI times, both airline-reported and RADAR-estimated, are compiled in the ASPM database which is largely available to the public and outlined in Figure 1. For the wheels-off event, ASPM records both the time and location. However, only the time is reported for the gate-out event. To incorporate the gate-out location into this study, the ASPM dataset was supplemented with gate/terminal information that was obtained through FlightStats.

Alternatively, surface event information can be obtained through Airport Surface Detection Equipment Model X (ASDE-X) surveillance data contained in Advanced Surface Movement Guidance and Control Systems (A-SMGCS). In contrast to ASPM, ASDE-X provides second-by-second coverage of aircraft location information from the time the aircraft enters the movement area (i.e. taxiway area) to wheels-off, as shown in Figure 1. Within the FAA's ATO Performance Analysis Group, ASDE-X data is processed by the Performance Data Analysis and Reporting System (PDARS) to parse out the time and location of the enter movement area (taxi-start), enter runway

(taxi-stop), and wheels-off events. The ASDE-X[§] data's taxi-start time occurs when the aircraft enters the movement area and is not a true gate-out time. Surface measures that look at gate time or ground holding near the gate, therefore, would benefit from a true gate-out time as provided by ASPM data. Additional background information on the three data sources used to complete this research can be found in Table 1.

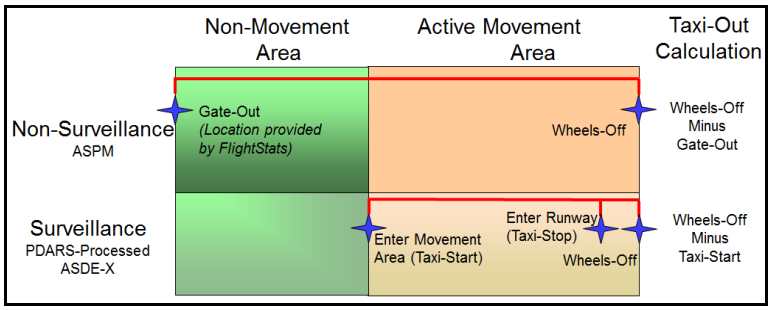

Figure 1 Time and location taxi-out data points collected by ASPM and PDARS-Processed ASDE-X[2]

Table 1 Summary of Data Sources

Date Source	Description/Key Data Elements
ASPM	Non-surveillance information containing airline-reported and RADAR-derived gate-out time, wheels-off time, and RADAR-derived departure runway
ASDE-X	Surveillance information obtained through PDARS-processed ASDE-X data containing enter movement area time, enter movement area location, enter runway time, enter runway location, and wheels off time
FlightStats	Supplemental data for ASPM containing gate/terminal information

It is important to note that even though both ASDE-X (surveillance) and FlightStats-supplemented ASPM (non-surveillance) contain the start-taxiing location, these two datasets group flights differently based on this point. Non-surveillance groups flights on origin terminal. For example in Figure 2, flights from Terminal F (both the East and West sides) would be grouped together as having similar taxi-start locations. In contrast to this method, surveillance groups based on the gaps between the terminals. That is, the real driver in grouping flights is a common entry point when exiting the apron area and entering the movement area of the airport. For example, flights from the East side of Terminal F and West side of Terminal G have common entrances into the movement area and would be grouped together. This method of identifying the taxi-start location removes the issue of grouping flights that share the same terminal, but have significantly different taxi-out paths due to departing from different sides of the terminal. For example, non-surveillance data would group all flights from Terminal E together, but many flights from the West side of Terminal E have a longer taxi-out path than the East side due to taxiing around the airport. Surveillance would group these separately. In this example, if the 5th-to-15th percentile is used for the definition of unimpeded, the unimpeded taxi-out time for Terminal E would be 14.04 minutes. However, if done by terminal gaps, the West side of E would have an unimpeded time of 15.01 minutes and the time for flights departing between the E and F terminals would be 12.22 minutes.

[§] PDARS-processed and quality-controlled ASDE-X. PDARS detects both the time and location of the enter movement area, enter runway, and wheels-off events using ASDE-X data.

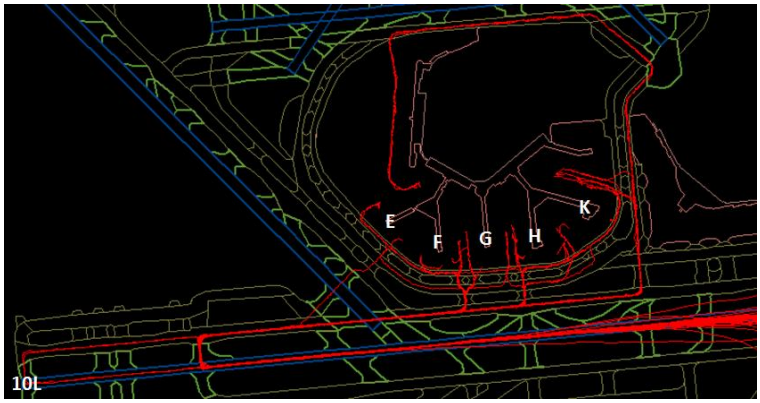

Figure 2 ORD Flights to Runway 10L

Not only do the datasets differ based on content and grouping method, but ASPM and ASDE-X also differ based on coverage. ASPM reports flight event information for 77 airports. Figure 3 illustrates the ASPM data coverage for the Core 30 airports excluding Honolulu using data for Fiscal Year (FY) 2014, which contains departures from October 1, 2013 to September 30, 2014. The figure shows data coverage for key times and key data parameters which are believed to be necessary for effective surface performance reporting. The OOOI coverage for reporting carriers is highly variable, ranging from 88.4% for Atlanta down to 19.2% for Memphis with an overall average coverage of 69.4% for these airports. Without Memphis, this overall average increases to 70.2%. Due to the low OOOI coverage at some of the airports, it is expected that unimpeded taxi-out time estimations based on ASPM data could be subject to biases as they are based on a small subset of the overall population.

Data coverage becomes even more of an issue when ASPM is supplemented with FlightStats. The lower half of Figure 3 shows the gate/terminal coverage post-merge for both OOOI and non-OOOI observations. Gate/terminal information is more prevalent than OOOI times with an overall average of 82.5%. It is important to note that the low value for MEM in the FlightStats data is due to missing cargo terminal information. The remainder of this study focuses on the ATL, JFK, LGA, ORD, and PHL airports, which are differentiated in Figure 3.

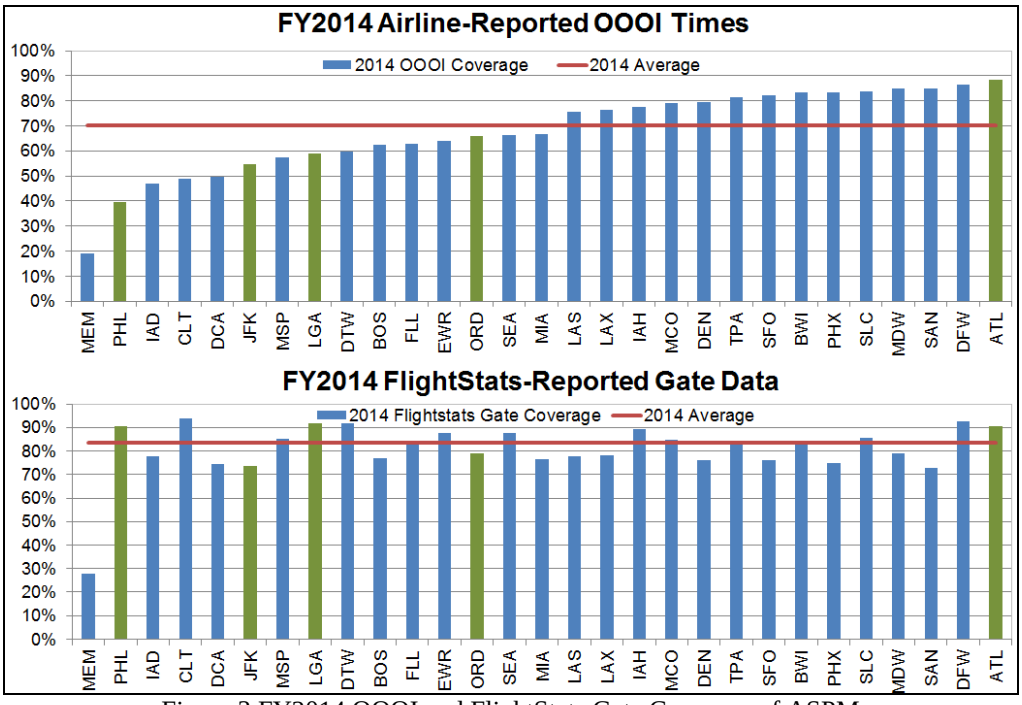

Figure 3 FY2014 OOOI and FlightStats Gate Coverage of ASPM

III. Creating a Hybrid Surface Performance Database

Given the instability of reported ASPM data and the need to supplement it with gate/runway information, ground surveillance systems were investigated to determine the degree to which performance measures could be used directly or whether key events and ground locations from surveillance data could be merged into a the main ASPM system. This produced a hybrid database containing merged ASPM, FlightStats, and ASDE-X datasets, which resulted in linking the non-surveillance, terminal and surveillance information for each flight, respectively. The datasets were merged in a multi-stage process where residual, unmerged data from the previous step was merged using different constraints. Figure 4 illustrates the timestamps and locations for key taxi-out events of a single flight.

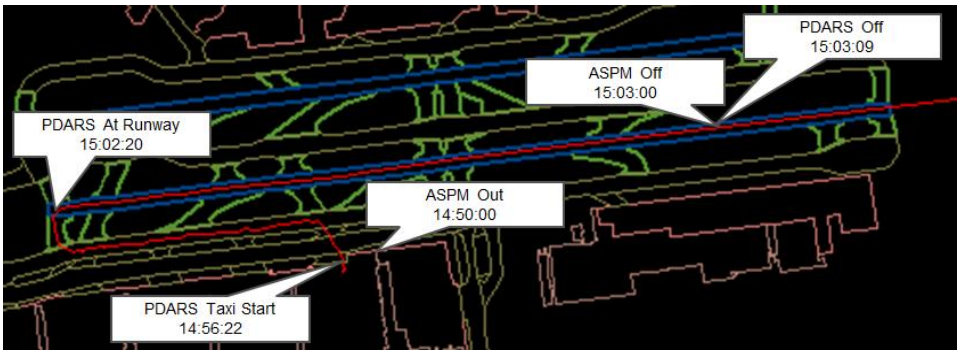

Figure 4 Taxi-out path for a flight at ATL airport

Figure 5 shows relative coverage of ASDE-X when compared to ASPM and a merged ASPM/FlightStats data source. The percent ASDE-X coverage shows the number of ASDE-X samples divided by ASPM samples. At a high level, ASDE-X and ASPM report near identical numbers of departures for FY2014. For example, the ASDE-X data for PHL has 99.3% of the number of flights as ASPM. This means that ASDE-X systems working independently from ASPM would be referencing nearly the same number of flights. The potential advantage of ASDE-X is shown in comparing the bars percent match to ASDE-X to percent match to FlightStats. Using PHL for example, 94.2% of ASPM's samples could be matched with ASDE-X. Of the ASPM samples, 90.4% were able to be matched with terminal information in FlightStats. That is, 9.6% of ASPM did not have terminal information where either the observation was not in FlightStats or was present but missing the terminal field.

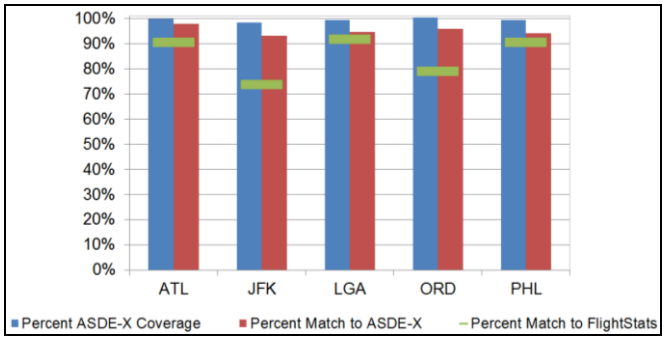

Figure 5 FY2014 Comparison of ASPM and ASDE-X Coverage

After merging the three datasets, flights were then clustered into common terminal gaps using a K-Means clustering algorithm on the latitude/longitude information for the taxi-start event provided in ASDE-X. The K-means is a non-deterministic algorithm that groups each point with a centroid, where the number of centroids is specified by the user.[7] This task was performed using the statistical programming software R and its supplemental add-on packages.[8-11] Figure 6 illustrates the algorithm's output using PHL airport with 12 cluster centroids. It shows that the K-means algorithm is not only effective in grouping by terminal gap area, but also determining valid taxi-start locations. That is, if a taxi-start point is located further from the centroid than a set threshold it can be identified as a poor taxi-start point and should be excluded from future taxi-out time estimations. The K-means algorithm was not used to determine the take-off runway as this was identified through the PDARS processing.

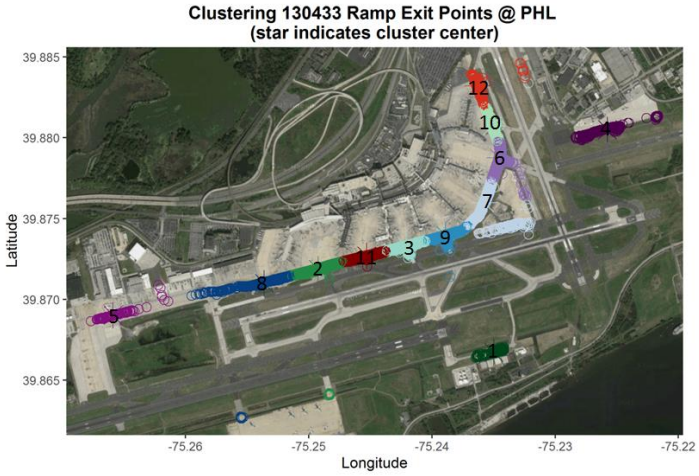

Figure 6 K-means clustering results on PHL terminal gaps

In addition to clustering taxi-start locations, the hybrid surface performance database enabled the comparison of timestamps. Specifically, both ASPM and ASDE-X provide wheels-off times, which are evaluated in Figure 7. The probability density functions for OOOI and non-OOOI flights show that on average the difference in ASPM and ASDE-X wheels-off times is less than one minute, the precision level of ASPM timestamps. The wheels-off time for ASDE-X is more closely aligned with non-OOOI samples from ASPM than with OOOI. That is, the difference in ASDE-X and non-OOOI times is centered on zero where this is not the case in the difference between ASDE-X and OOOI times. This is not surprising as both ASDE-X and non-OOOI times are derived from RADAR while the OOOI wheels-off time is airline-reported. However, it is expected that OOOI gate-out times are more accurate than non-OOOI because non-OOOI's is based off of the first available RADAR position point on departure (i.e. DZ point).

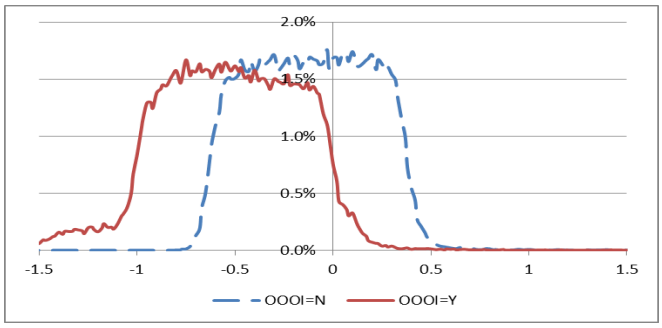

Figure 7 ASPM wheels-off minus ASDE-X wheels-off in minutes for PHL.

The overall coverage of the hybrid dataset containing the five airports of interest is shown in Figure 8. The total samples is from the raw data whereas the complete samples have the actual, not estimated, times and locations of all the key taxi-out events. While the ASPM and ASDE-X datasets have very similar total sample sizes, ASDE-X provides a better coverage of complete samples for all five airports. LGA is the only airport in which the number of complete samples from each dataset is negligible. This is due to 46% of LGA's samples missing the taxi-start location in ASDE-X. Specifically, there is a minimum distance from the gate that is masked and not recorded by surveillance, similar to the majority of the non-movement area. This in turn causes flights originating from gates near the taxi-way not to have a taxi-start time as they are too close to the gate when entering the taxi-way. Although all airports were affected in some way by this circumstance, LGA was the most impacted.

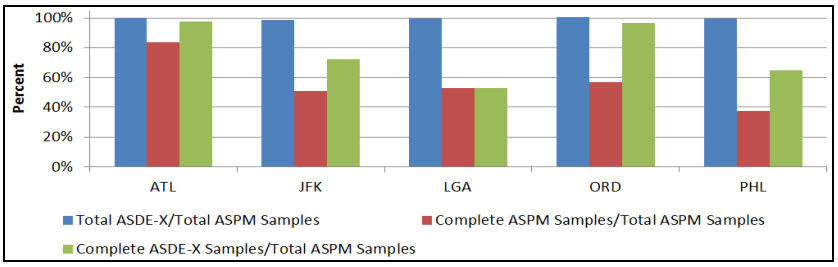

Figure 8 FY2014 Comparison of ASPM and ASDE-X Sample Size

IV. Unimpeded Times Estimation Methodology

Regardless of whether non-surveillance data or surveillance is used, the goal when estimating the unimpeded taxi-out time using a statistical method is to effectively balance the level of aggregation with the sample size. Although the data contains several variables that influence taxi-out times (e.g. airport, airline, runway, terminal, etc.), a significant sample size of flights must share all of these characteristics before calculating an unimpeded taxi-out time. Otherwise, the data must be aggregated for that group of flights where the grouping is performed on fewer characteristics.

Using percentiles, the unimpeded taxi-out times were calculated for flights sharing the departure airport, airline, runway, terminal, and season. The data was aggregated up to a point where the sample size met a threshold of 385 OOOI flights. For example, if fewer than 385 flights in FY2014 shared the same departure airport, season, runway, terminal, and airline, then the sample size without the airline constraint would be evaluated for meeting the threshold. This process is further outlined in the Appendix section, where each row is a group of flights and the unimpeded time in seconds with an acceptable sample size is boxed. The characteristics were ordered based on completeness of data. For example, carrier is the last category because all non-OOOI carriers would have a sample size of zero at that point and, therefore, the unimpeded time would only be based on categories prior in the list.

It is important to note that using this methodology might not always capture unimpeded times as some runways are mostly used during high-demand, congested periods. However, this methodology can be beneficial as it allows the taxi-out times to be benchmarked against a best achievable unimpeded taxi-out time as a percentile of recorded travel times. This in turn identifies problem areas that have large delay mitigation opportunities whereas the alternative (i.e. calculating the unimpeded time assuming no traffic) would most likely consistently point to these "high-demand" runways as the problem areas which have a reduced opportunity for delay mitigation.

V. Results

A. Taxi-Out Phase Distributions

This section analyzes the individual phases of the taxi-out process using the hybrid database. The timestamps received for each flight from combining non-surveillance and surveillance datasets enables us to examine the distribution and variability of times for individual taxi-out phases, as shown in Table 2. From this table, it is shown that the taxiway phase accounts for the largest portion of the taxi-out time for most airports and is the main source of unpredictability in the overall taxi-out process. ATL had the lowest average time for the overall taxi-out process (gate-out to wheels-off) and the New York City area airports (JFK and LGA) had longer taxi-out phases than the other three airports in this study.

Table 2 Average (standard deviation) of times for individual taxi-out phases in minutes

	ATL	JFK	LGA	ORD	PHL
Ramp Time**	8.43 (3.79)	10.61 (6.46)	9.58 (5.95)	9.60 (6.95)	7.83 (4.08)
Taxiway Time††	8.48 (6.25)	15.00 (11.82)	15.23 (11.46)	8.48 (8.34)	11.80 (11.31)
Runway Time‡‡	1.34 (0.58)	1.66 (1.25)	1.50 (0.89)	1.23 (2.35)	1.30 (0.94)

Figure 9 shows the probability mass function of each taxi-out phase time rounded to the nearest half minute.

** Time between the gate-out and taxi-start (enter movement area) phases
†† Time between the taxi-start (enter movement area) and taxi-stop (enter runway area) phases
‡‡ Time between the taxi-stop (enter runway area) and wheels-off phases

Consistent with previous research, the "ramp time" phase curves are Eurlang distributions[12] with the exception of the increased number of flights in the one to three minute range. This part of the curve can be attributed to cases where the aircraft is pushed back into the active movement area, allowing for the radar to pick up flight information quickly after leaving the gate. In these cases, part of the pushback is then attributed to the "taxiway" time instead of the "ramp time." This can happen when the gate is close to the active movement area, such as at the end of a terminal, near the taxi-way entrance. Alternatively, many flights have fairly long ramp times. While it is hard to diagnose the cause of these increased times due to the non-movement area being masked in the surveillance data, there are times when the increase is due to the flight re-entering the non-movement area during the taxi-out process.

The taxiway time distribution shown is from when the plane enters the movement area to when it enters the runway. Although the low taxiway times are mostly an indication that the terminal was located close to the runway, there are samples where the taxi-out path crosses a runway different from the departure runway causing the on-runway time to be reported prematurely. Therefore, it was decided to use the wheels-off time as the end of the taxi-out process instead of the enter runway time for benchmarking purposes. Also, as previously mentioned, if the flight is close to the movement area during pushback, this can cause an increase in taxiway time. Overall the airports located in the northeast (JFK, LGA, and PHL) had the largest standard deviation of taxiway time. Lastly, the on-runway phase is the shortest segment in the taxi-out process in terms of time. On average, flights spent less than 2 minutes on the runway, where the highest averages are attributed to the New York airports.

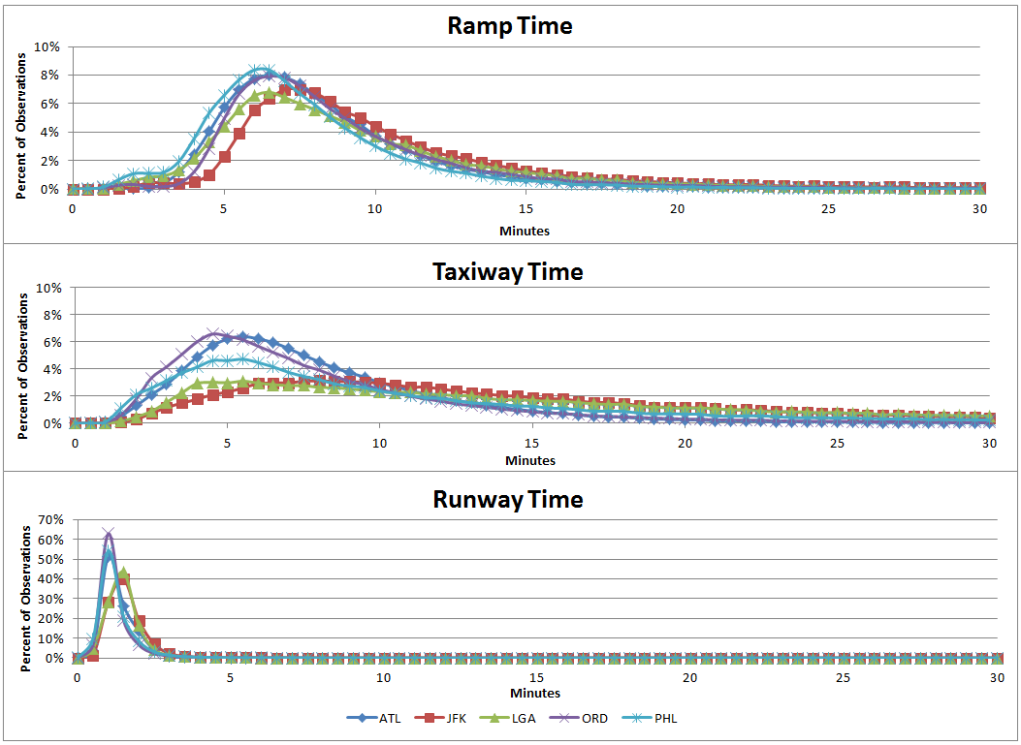

Figure 9 Taxi-Out Phase Times

B. ASPM-Only Unimpeded Times by Airport

Table 3 shows the estimated unimpeded taxi-out times and corresponding additional delay by data source. The first method (ASPM published) is the benchmark time currently in the ASPM data, which does not include terminal or runway information and is regression-based. The second (ASPM) uses the method described in the appendix on the same variables used to estimate the ASPM published times (i.e. missing terminal and runway). The third (merged ASPM) uses the method described in the appendix on the merged ASPM/Flightstats dataset and incorporates terminal and runway information. This shows the impact of including terminal and runway information by comparing ASPM with ASPM merged with FlightStats terminal data, both of which use the 5^{th} -to-15^{th} percentile unimpeded taxi-out time. Overall, JFK has the highest nominal times and ORD has the lowest. LGA has the largest taxi-out delay on average, while ATL has the lowest. When aggregated by departure airport, the addition of terminal and runway information seems to have minimal effects on unimpeded taxi-out times. No airport has an

average change greater than one minute between the two percentile methods, which is the level of precision for times reported in ASPM. However, when looking at flight groupings, it was found that individual taxi-out paths at these airports can benefit greatly from the terminal and runway information.

Table 3 ASPM Unimpeded taxi-out times and additional delay estimations in minutes

Airport	ASPM-Published Nom. Time[§§]	ASPM-Published Add. Delay	ASPM 5th-15th Nom. Time[***]	ASPM 5th-15th Add. Delay	Merged ASPM 5th-15th Nom. Time[†††]	Merged ASPM 5th-15th Add. Delay
ATL	12.84	4.72	11.16	6.39	11.28	6.28
JFK	17.55	7.76	14.71	10.59	15.08	10.22
LGA	13.49	11.25	13.25	11.49	13.83	10.91
ORD	11.48	6.06	10.72	6.82	11.15	6.39
PHL	12.95	5.93	11.19	7.69	11.25	7.63

Looking at a more disaggregate view in Table 4 (i.e. looking at groups of flights sharing specific characteristics) it can be said that terminal and runway information can make a significant impact on the benchmarking times. Then a separate set of unimpeded times are calculated by adding terminal information to find which taxi-out paths are over- or under-estimated the most when the terminal location is not incorporated. The terminal-runway combinations with the greatest difference between these two unimpeded taxi-out times are listed in Table 4. For example, the 5th-to-15th percentile unimpeded taxi-out time for all BTA flights departing from ORD using Runway 10L was 12.13 minutes. Of these flights, 422 flights came from Terminal E. This subgroup had a unimpeded taxi-out time of 17.61 minutes. Therefore, incorporating terminal information changed the unimpeded taxi-out time by over 5 minutes. As expected, a large portion of the groups listed in Table 4 are international terminals, which are can be located further away from the departure runway than other terminals and include larger equipment types.

Table 4 Impact of incorporating runway into unimpeded taxi-out times in minutes

Departure Airport	Operating Airline	Terminal	Runway	Count	W/out Terminal	W/ Terminal	Difference
ORD	BTA	E	10L	422	12.13	17.61	5.48
SLC	SKW	C	34L	730	9.80	14.19	4.39
SLC	SKW	B	34L	3,284	9.80	14.19	4.39
ATL	DAL	F	8R	761	10.17	14.46	4.29
DFW	AAL	D	17C	735	9.63	13.64	4.01
EWR	BTA	C	4L	518	11.19	15.14	3.95
MSP	DAL	C	30L	609	9.58	13.20	3.62
PHL	AWE	A	27L	9,382	11.15	14.76	3.61
MSP	DAL	G	30R	854	9.58	13.14	3.56

The group of flights with the largest unimpeded taxi-out difference is compared in Figure 10. The unimpeded taxi-out time for Terminal E is greatly underestimated, by an average of 5.48 minutes per flight, as the flights head north and taxi around the airport, resulting in additional distance traveled. When terminal information is not incorporated, the unimpeded taxi-out time is mostly a reflection of taxi-out times from Terminal F, where most of the BTA flights heading to Runway 10L originate. This path does not include the excess distance that is present in the Terminal E taxi-out path. Therefore, current benchmarking practices might flag unimpeded flights from Terminal E as impeded due to interpreting the additional taxi-out time as delay, when in reality the additional time is

[§§] Average of the unimpeded-taxi out times reported in ASPM. Calculation method consistent with the EU/US Benchmarking Report.[13]

[***] Average of 5th-to-15th percentile using (ASPM Off-ASPM Out). Incorporates airport, season, and airline using ASPM. These are the same variables the current ASPM unimpeded taxi-out times are estimated from.

[†††] Average of 5th-to-15th percentile using (ASPM Off-ASPM Out). Incorporates airport, season, runway, terminal, and airline using ASPM and FlightStats datasets.

due to excess distance traveled. This serves as a prime example of why airline is not always a sufficient proxy for terminal, which is the current estimation method for the published ASPM unimpeded times.

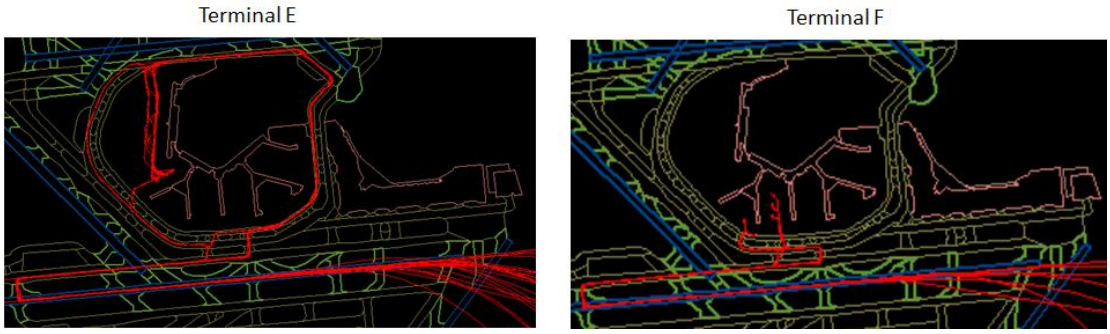

Figure 10 BTA flights at ORD using Runway 10L

The second and third greatest differences between unimpeded times are compared in Figure 11. SKW flights originating from both Terminal B and C departing from Runway 34L are underestimated on average by more than 4 minutes per flight if terminal information is not incorporated. When all SKW flights going to Runway 34L are grouped together, the unimpeded taxi-out time is heavily weighted by flights originating at Terminal E, which is conveniently located close to the departing runway. This results in a similar situation to the first example, where unimpeded flights with additional taxi-out distance may be flagged as impeded. Therefore, ASPM may only consider flights originating from Terminal E to be unimpeded for this group of flights.

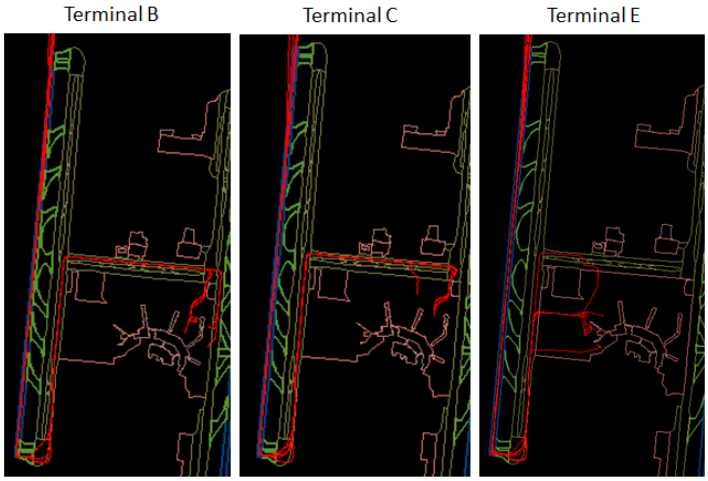

Figure 11 SKW flights at SLC using Runway 34L

C. ASDE-X-Only Unimpeded Times by Airport

Next, unimpeded taxi-out times were calculated only using the ASDE-X surveillance data. When comparing ASDE-X estimations for unimpeded time with Merged ASPM, it is apparent that ASDE-X underestimates both unimpeded and additional taxi-out time. For example, ASDE-X underestimates ATL's unimpeded time and delay by about 6 minutes and 2 minutes, respectively. This underestimation is due to surveillance's inability to fully capture operations in the non-movement area. Therefore, it is recommended when using ASDE-X for taxi-out time estimation to supplement it with ASPM data. This would incorporate a true gate-out time instead of an enter taxiway time.

Table 5 ASPM Unimpeded taxi-out times and additional delay estimations in minutes

Airport	Merged ASPM 5^{th}-15^{th} Nom. Time	Merged ASPM 5^{th}-15^{th} Add. Delay	ASDE-X 5^{th}-15^{th} Nom. Time[‡‡‡]	ASDE-X 5^{th}-15^{th} Add. Delay
ATL	11.28	6.28	5.19	4.65
JFK	15.08	10.22	6.88	9.60
LGA	13.83	10.91	6.71	11.54
ORD	11.15	6.39	4.86	4.73
PHL	11.25	7.63	5.00	8.09

D. Hybrid Database Unimpeded Times by Airport

Lastly, unimpeded times based on an ASPM and ASDE-X "hybrid" database were analyzed. This hybrid method used the gate-out time provided by ASPM and the wheels-off time from ASDE-X. If ASDE-X was missing a wheels-off time, the ASPM time was used instead. Also, the gate clusters were utilized for grouping purposes. Unfortunately, since the hybrid method depended on both ASPM and ASDE-X, the sample size for estimating unimpeded taxi-out times was limited to samples with both OOOI information from a reporting carrier as well as ASDE-X surveillance information. Table 6 shows the first method, which used merged ASPM and FlightStats data, had similar nominal and delay outputs as the hybrid method when aggregated to the airport-level. However, as shown in the Figure 2 example, there are cases where clustering by terminal gap as opposed to terminal can have significant effects on the unimpeded taxi-out time. It is expected that the over- and under-estimated taxi-out times cancelled each other out.

Table 6 Comparison of ASPM and ASDE-X Unimpeded taxi-out times and additional delay estimations in minutes

Airport	Merged ASPM 5^{th}-15^{th} Nom. Time	Merged ASPM 5^{th}-15^{th} Add. Delay	Hybrid 5^{th}-15^{th} Nom. Time[§§§]	Hybrid 5^{th}-15^{th} Add. Delay
ATL	11.28	6.28	11.36	6.20
JFK	15.08	10.22	15.09	10.22
LGA	13.83	10.91	13.74	11.00
ORD	11.15	6.39	11.37	6.17
PHL	11.25	7.63	11.40	7.48

VI. Limitations and Direction for Future Research

Both non-surveillance and surveillance data sources suffered from key limitations and, if overcome in the future, would improve unimpeded taxi-out time delay estimations. Non-surveillance had both precision and coverage issues. With the gate-out times and wheels-off times being rounded to the nearest minute, a single flight's taxi-out time could be incorrectly estimated by as much as a minute (about 30 seconds per timestamp). On top of that, only the ever-changing group of OOOI carriers have to report these times, leaving a significant portion of flights' timestamps to be estimated from the DZ point. On the other hand, while surveillance overcame these precision and coverage issues, its inability to capture the gate-out time in the non-movement area made it necessary to be supplemented with other data as well.

In addition to the data, there are opportunities for future improvement of the benchmark estimation method. Although this analysis used the average of the 5th-to-15th percentile samples, it is possible that each airport will need its own specific percentile due to differing levels of congestion. An alternative to this is to use one of the other methods described such as using a regression, subtracting holds, or digitizing the taxi-out path and assuming an unimpeded constant speed.

[‡‡‡] Average of 5^{th}-to-15^{th} percentile using (Enter Movement Area-Wheels Off). Incorporates airport, season, runway, terminal, and airline using ASDE-X data.

[§§§] Average of 5^{th}-to-15^{th} percentile using (Gate Out-Wheels Off). Incorporates airport, season, runway, terminal, and airline using ASDE-X data.

VII. Conclusion

In this study, it was found that ASPM has limitations in terms of data coverage, missing gate/terminal location and timestamp precision. Although ASDE-X was able to overcome these limitations for each of the five airports, its inability to fully capture the events in the non-movement area means it cannot account for taxi-time and delay that occurs at the gate. This leads to underestimation of the time to complete the overall taxi-out process. Therefore, surveillance currently should not be the sole source for unimpeded taxi-out time estimations. However, it is advantageous to supplement ASPM with surveillance data in order to group the taxi-start locations using the clustering method and to analyze a more precise wheels-off time (rounded to the nearest second instead of minute).

This study also analyzed the impact of including both the terminal and runway in benchmarking estimations. The average unimpeded time by airport is not influenced heavily by including these two parameters. However, including this information can change the unimpeded time for individual flights by several minutes. It was found this is especially true for many flights originating from international terminals and when a single airline spans several terminals at an airport.

Appendix

Characteristic					Unimpeded Time					Sample Size					Overall
1. Airport	2. Season	3. Rwy	4. Terminal	5. Carrier	1	2	3	4	5	1	2	3	4	5	Unimpeded Time
ATL	1	8R	1	SKW	11.20	11.30	10.00	9.75	9.75	385,170	86,043	13,670	3,039	11	9.75
ATL	1	8R	1	SWA	11.20	11.30	10.00	9.75	9.75	385,170	86,043	13,670	3,039	590	9.75
ATL	1	8R	1	TCF	11.20	11.30	10.00	9.75	0	385,170	86,043	13,670	3,039	0	9.75
ATL	1	8R	1	TRS	11.20	11.30	10.00	9.75	9.75	385,170	86,043	13,670	3,039	215	9.75
ATL	1	8R	2	AAL	11.20	11.30	10.00	10.53	10.53	385,170	86,043	13,670	2,353	214	10.53
ATL	1	8R	2	ASH	11.20	11.30	10.00	10.53	10.53	385,170	86,043	13,670	2,353	23	10.53

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