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Benefits of Virtual Queuing at Congested Airports Using ASDE-X:

A Case Study of JFK Airport

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Abstract— ASDE-X, a runway safety system data, may also be used to manage arrival and departure delay at congested airports. This paper demonstrates the potential for delay management by using departure data recorded by the ASDE-X system at JFK Airport before runway reconstruction in 2010 began. The paper lays out concepts, data, metrics, and a framework to estimate benefits from virtual queuing, a departure management system that allows the aircraft to maintain their rolling spots in the queue without physically joining the queue. While virtual queuing is relatively more common in Europe, its use in the US is limited. This analysis demonstrates that there may be significant benefit, even with most conservative assumptions, of using virtual queuing for departure management at congested airports. Environmental benefits of virtual queuing at JFK Airport are significant as well.

Keywords: Departure performance; Virtual queuing.

I. INTRODUCTION

Airport Surface Detection Equipment, Model X (i.e., ASDE-X) is a runway-safety system that enables air traffic controllers to detect potential runway conflicts by providing detailed and accurate coverage of movement on runways and taxiways. The ASDE-X system collects data from numerous sources: surface movement radar located on the air traffic control tower or remote tower, multilateration sensors, ADS-B (Automatic Dependent Surveillance-Broadcast, where available) sensors, terminal radars, the terminal automation system, and from aircraft transponders. Fusing these data together, the ASDE-X system tracks vehicles and aircraft on airport surfaces and obtains identification information from aircraft transponders. The ASDE-X systems, as deployed at most major US airports (36 airports), are mostly known for improvements in safety via alerts and improved air traffic control situational awareness. This is accomplished by providing tools to supplement tasks of the tower controllers [1]. For a representative departure, the ASDE-X system provides detailed data from entry to taxiway through wheels-off and runway clearance; for an arrival, detailed tracking from final approach to wheels-on, through taxiway until taxiway exit to ramp data are available as well.

In addition to markedly improve safety, ASDE-X data can be used to support management of delay. ASDE-X data can be used to trace where delays are occurring and to calculate unimpeded taxi times from gates, ramp areas, or a hold spot on the movement area to runways. These calculations can support use of virtual queues, which keep aircraft back at their gates and maintain priorities of physical queues. While reducing delays, this procedure may also reduce fuel burn during congested departure periods. Virtual queues, when accompanied with some collaborative decision-making between stakeholders, can have other benefits for airlines in prioritization and sequencing of flights as well. The challenge of virtual queues lies in the feasibility of leaving aircraft idle in a waiting area, either at gates or in ramps. This study uses ASDE-X data to (a) identify time spent on different spots during the departure and quantify the magnitude of the time that may be redistributed via improved traffic flow management; and (b) understand the feasibility of virtual queues at one of the World's busiest airports to explore air traffic management (ATM) implications.

The organization of the paper is: Section 2 provides a brief background of the available research, their findings, and lays out the state of ATM advances across both sides of the Atlantic; Section 3 uses a single day at JFK Airport for introducing concepts, data, preparations and key metrics generation. Building on the preceding section, Section 4 explores key relationships, and provides findings on a detailed data analysis for 236 days at JFK Airport. This section also quantifies the benefit pool that are likely available to implement virtual queue-based aircraft departure clearance. Finally, Section 5 explores policy choices and challenges facing the stakeholders in internalizing the benefits from implementing virtual-queue based departure clearance. This section also provides some concluding thoughts including future research. Although the paper uses JFK Airport as a case study, similar results are anticipated in any airports where congestion is measurable with ASDE-X data.

II. BACKGROUND

Previous studies [2] estimated taxi delays but have not used detailed surface data to identify and assess the recoverable delay achievable by keeping aircraft back at the gate. Keeping aircraft at the gate as opposed to having them wait in the movement area, assuming gates are not needed by arriving aircraft, saves airlines time and fuel burn. Comparative US and European ATM performance analysis [2], using top 34 airports in the US and Europe, found that the US has experienced 40% more taxi delay than in Europe, on average. In particular, the three NY-area airports had average delay of nearly 15 minutes. Taxi delay was estimated to be responsible for 25 percent of excess fuel burn in the US. Delay (excess) in the study was defined as excess time above "unimpeded" taxi times.

Taxi delays represent an opportunity to reduce airline fuel costs and improve the environment. In order to minimize this, information is shared between stakeholders via Airport Collaborative Decision Making (A-CDM). Under A-CDM, real-time arrival/departure data is shared between the airport operator, airlines, and other service providers including baggage handling, catering, and aircraft cleaning services. Zurich Airport (ZRH), for example, implemented an early form of A-CDM focusing on movement areas and airport operator ensuring virtual queuing at ZRH. Munich Airport (MUC), on the other hand, was the first airport to implement the European version of A-CDM. The robust sharing of airport, airline, and ATM data led to improvements including better management of airport and airline resources reducing turn-times and overall delays. Taxi queue benefits were estimated to have been reduced by one minute per flight [2]. In addition, the A-CDM system provides data to the Eurocontrol Central Flow Management (CFMU) on aircraft departure times for improved estimates of en-route sector loading. Integration of improved surface management to traffic flow management (TFM) can significantly improve en-route performance as well.

In the US, however, coordinated surface flow management is at an early stage. Although there has been a recent focus on the taxi problem, efforts to fix the problem have come primarily from regulatory authority (DOT) (e.g., regulations like the "3 hour rule" - a passenger rights' law requiring airlines to compensate passengers when held on taxi ways for more than 3 hours – went into effect on April 29, 2010). Absent using data in a coordinated fashion to address the taxi delays within the terminal ATM environment, one of the other challenges facing the US is gate utilization and limited common-use gates. This can significantly impact the ability to keep flights at gates during busy periods despite what may be needed from an efficient ATM using virtual queuing. Nevertheless, holding in ramp or taxi areas with engines idled may be explored where gate availability could be an issue with implementing virtual queues.

One reason for lower taxi-out delay in Europe is related to the pre-coordinated airport slot allocations. While only the three New York City area airports have had slots, all of the top 34 airports in Europe have pre-coordinated slot management. Despite having used slot management, however, NYC-area airports still continue having the highest taxi delays in the US. Notably, even though the magnitude of the taxi delay problem is less than in the US, Europe is investing aggressively in implementing A-CDM.

As noted in [2], some coordinated surface management is presently underway at JFK Airport. The need for departure management was reinforced with the closure of the longest runway at JFK Airport due to the reconstruction of runway 31L in 2010[1]. JFK Airport is the one US airport currently managing the departure process via virtual queuing. The need for coordinated surface management originated during winter operations when long taxi-out queues caused some aircraft to routinely return for repeated de-icing prior to take-off. Returning for deicing generally meant incurring more expenses as well as losing the prior spot in the departure queue, which was expensive for airlines and cumbersome for ATC. Based on this experience, the Port Authority of New York and New Jersey (PANYNJ) and airline stakeholders decided to establish a temporary virtual taxi queue departure control system in early 2010 in preparation for the runway construction project. The overall objective was to reduce the total number of aircraft queuing on taxi-ways, thus reducing the overall taxi delay. Notice that overall delay has not been reduced directly as a consequence but was moved to an area where fuel is not burned. Anecdotal data indicates that virtual queues have impacted overall surface performance positively at JFK Airport. It is important to note, however, there is currently no formalized ATC or FAA coordination with departure management at JFK Airport, which is in contrast with European A-CDM (see [2] for more details).

Additional benefits of queue management may include facilitation of prioritizing high value flights (i.e., intra-airlines' and inter-airlines' swap), potential capacity increases by organizing aircraft wake categories (i.e., re-sequencing), maintaining departure fix loading and sequences, and improved predictability of departure times for en route sectors. The latter will require integration of the virtual departure queuing manager to TFM flow manager and will require further investigation. Additional benefits from A-CDM are fewer missed passenger connections, reduced taxiway and runway maintenance costs, reduced controller workload, and improved regulatory compliance (e.g., 3-hr rule).

In Europe, better surface management is ensured via controlled release, better gate utilization, and virtual queuing. In the US there is a potential ability, particularly now with available data for developing targeted metrics via ASDE-X for 36 airports, to improve overall delay and ATM performance. This can be facilitated by developing and fielding targeted

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[1] JFK runways 13L-31R were closed during March 15-July 15, 2010 for paving and expansion. Many procedures improving traffic management were put in place during that time. Our data and analysis (Section 4) refer to periods earlier and thus perhaps comparable to other large airports.

decision support tools, and institutionalizing collaborative processes involving stakeholders. With that in mind, the paper introduces in the next section basic data preparation, and key metrics generation that can be utilized for improved delay management.

III. DATA PREPARATION, METRICS GENERATION, AND TAXI DURATION

Under a surveillance data preparation task, relevant airport surface data (e.g., surveillance, airport map) are assembled to support metrics generation and analysis. Upon the selection of the airport for study and the desired date range for the analysis, the data analysis proceeds with the use of ASDE-X data and appropriate tools. This section describes the process by which the ASDE-X data are converted from surveillance recordings into flight object data and metrics. The computation of unimpeded taxi durations from ASDE-X data is also presented.

III.A. MAP INSPECTION AND PREPARATION

Before processing large amounts of surveillance data, an initial assessment of the airport surface map is undertaken. This is important because features of the map, such as taxiways and runways are used to determine events in the movement of the aircraft (e.g., on-time, off-time). A subset of surveillance data are processed and plotted against the airport surface map to inspect the map for completeness and accuracy; this inspection can also be done by comparison of the airport surface map against recent, publically available imagery. Airport surface maps can be obtained from the US FAA ASDE-X Program Office[2] or from commercial vendors (e.g., Jeppesen, GeoEye). The completeness of map occasionally requires more detailed consideration if the surveillance data spanning years of operations whereby airport surface features may have changed. If the map is found to be incomplete, some modest amount of work with existing tools is undertaken to amend the map to add, change, or remove features (e.g., inclusion of new taxiway).

III.B. SURVEILLANCE DATA PROCESSING

With the selected surveillance data files and the airport surface map, the surveillance track reports are processed in the following three steps: first, production of tracks (i.e., time-ordered position data) for aircraft and vehicles on the airport surface as well as for aircraft aloft in the vicinity of the airport is undertaken. This is important to any efficiency evaluation that depends on finding interactions in airport surface traffic between aircraft and other moving vehicles. The ASDE-X data contain positional reports for both non-cooperative surveillance systems (e.g., SMR) and cooperative surveillance systems (i.e., MLAT, ASR). Second, flight or vehicle track objects are created by joining surveillance track segments by using the fusion tracker id and aircraft/vehicle mode S code. The aircraft/vehicle trajectory (time-position-velocity-acceleration or, TPVA) data is reconstructed for each aircraft/vehicle track object which provides higher-quality estimates of position, velocity, and acceleration than are available in the original ASDE-X surveillance data files. Third, the flight event times are estimated for aircraft, the route taken by the taxiing aircraft is determined, and the time events are estimated. These events may include: movement area entry or exit, terminal airspace entry or exit, start or stop surveillance, wheels-off, wheels-down, runway entry or exit, gate entry or exit (at airports with gate-level surveillance). Aircraft and vehicle track objects are separated into movement objects: arrivals, departures, surface movements (tracks that have only observed on the airport surface, approaching arrivals, departures leaving the airport and reaching a maximum distance away from a departure runway, and flyover flights.

III.C. METRICS GENERATION

The final step in the data processing is the application of algorithms[3] to measure surface traffic efficiency. A list of these metrics (for departures) is given in Table 3.1.

TABLE 3.1: METRICS LIST FOR TAXIING DEPARTURES

Hold duration in ramp area at spot	Push-time in ramp area
Taxi-out duration in ramp area	Hold duration in ramp area at push
Unimpeded taxi-out duration in ramp area	Entry time to movement area
Unimpeded taxi-out duration in movement area	Hold duration in movement area
Hold duration in queue	Entry time to departure queue
Entry time to runway	Hold duration on runway before roll
Wheels-off time	Runway fanning/exit time

Figure 3.1 shows a selection of events detected in a departure at JFK Airport from Runway 31R and includes the measurements of ramp exit time, departure queue entry, runway entry time, runway exit time, and wheel-off-time, as well as holds that occurred while taxiing. The trace of the taxiing departure is shown in red, and holds are depicted as blue dots. Events such as gate-out and wheels-off are depicted with black dots. Given the time events for gate-out, entry to movement area, take-off, and hold delay duration, the taxi time for this departure is separated into taxi-time in the ramp, movement area, departure queue, and runway, as well as the holding delay.

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[2] Sensis Corporation, one of our co-authors' employer, fielded and maintained the ASDE-X systems for the FAA and archived the data. FAA is the owner of the ASDE-X data.

[3] Using proprietary algorithms, Sensis Corporation analyzed and operationalized raw data for additional metric value.

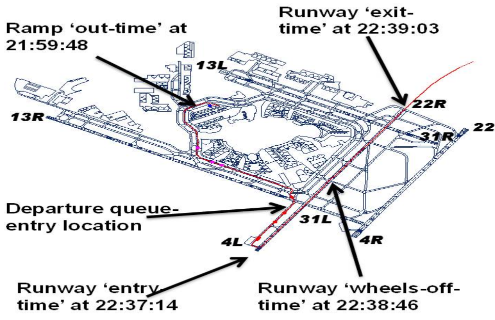

Figure 3.1 Depiction of Events in a Taxiing Departure

The total taxi-out time from push-back to wheels-off was 31.37 min, of which 14.8 min was holding delays during taxiing in the movement area and 3.98 minutes holding delay in the ramp area (Table 3.2).

TABLE 3.2: TAXI-OUT DURATION 'BUDGET' FOR A DEPARTURE

	taxi-out budget (minutes)		
region	**unimpeded**	**excess**	**total**
ramp area	**3.48**	**3.98**	**7.46**
movement area (pre-queue)	**5.95**	**4.88**	**10.83**
departure queue	**2.14**	**8.83**	**10.97**
runway	**1.02**	**1.09**	**2.11**
total taxi-out	**12.59**	**18.78**	**31.37**

III.D. COMPUTATION AND OBSERVATIONS ON UNIMPEDED TAXI DURATIONS

Taxi-in and taxi-out delays on the airport surface are metrics reported by the FAA's Office of Aviation Policy's aviation system performance metrics (ASPM) as well. The taxi delays are computed in the ASPM system as the difference between taxi-out (or taxi-in) duration and the unimpeded taxi time. For the ASPM system, the unimpeded taxi time is estimated by regression equations developed on selected quantiles of taxi time data [3]. In other words, the unimpeded taxi-time data in ASPM are not directly observed from the surveillance data; it is calculated. Furthermore, the ASPM data does not include flight-specific data on runway, gate, and taxi route which are important explanatory variables for understanding sources of variability in the taxi duration and unimpeded taxi time [4, 5]. Nevertheless, a comparison of ASPM and ASDE-X taxi-out reveals that they appear to align well for JFK Airport [6] as aggregate statistics.

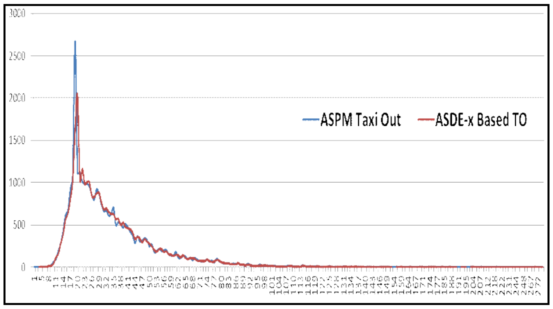

Figure 3.2 ASPM vs. ASDE-X Taxi Out Minutes

The availability of surveillance data for moving aircraft and vehicles on the airport surface allows the direct measurement of all aspects of movement history (e.g., taxi events for an aircraft). As noted earlier, total taxi duration is found from push-back to wheels-off time provided gate-level surveillance exists. Holds during taxiing out are directly observed in the surveillance data such that the hold duration, hold location, identity of impacted aircraft and the causes may be identified as well. Hold causes for departure, include gate holds, tail push-back hold, holding at the 'spot', holds for other surface traffic, holds to cross active runways, holds in the departure queue, and holds on the runway before 'roll out' [7].

ASDE-X data thus can be used to quantify the taxi-delays from the surface surveillance data. Using surveillance data to compute the taxi hold delays, the unimpeded taxi time is computed as the difference between the total taxi duration and the total holding delays. Total taxi-time duration is measured from the surveillance data. A benefit to the use of the surveillance data is the appropriate conditioning of taxi time data (total and unimpeded) on airport configuration, airline gate/ramp area, and taxi route. The result is a more accurate representation of the unimpeded taxi-time for all taxiing aircraft along the same route between the same gate and runway pair. At JFK Airport, the standard deviation of the unimpeded taxi time is about 5-6 minutes, and for some airports, it can be as low as 1 minute.

Another key influence on taxi time duration is the taxi path. At JFK Airport, because of its geometry, taxi paths for departures can vary greatly in distance, even between the same origin and destination location on the airport surface. Shown in Table 3.3 are the taxi statistics for the paths taken by 23 departures that taxied between Taxiway W and Runway 4L. Most of the 18 departures summarized in Table 3.3 take the same path (red text). Other taxi paths form minor variations on the dominant path and some are greatly different.

TABLE 3.2: FLIGHT-SPECIFIC MOVEMENT AREA TAXI-OUT DURATION STATISTICS SHOWING ROUTE IMPACT, DEPARTURE ON 8/8/09 FROM TAXIWAY W TO RUNWAY 4L AT JFK AIRPORT

route/ color code	sample size	taxi-out statistic	taxi-path length (m)	total taxi duration (min)	total hold duration (min)	unimpeded taxi duration (min)
A	1	singleton	4215	26.6	13.5	13.1
B	1	singleton	4115	33.9	17.3	16.6
C	1	singleton	6098	64.7	39.3	25.4
D	1	singleton	5923	54.7	31.0	23.7
E	1	singleton	6074	63.0	43.6	19.4
F	18	mean	4172	32.8	19.6	13.3
		stdev	251	17.6	14.9	3.9

Finally, the longer the taxi distances, the chances of having higher holds increases because of the higher likelihood of a taxiing aircraft having to negotiate intersections and other taxiing aircraft. Note that the total taxi-out duration and the unimpeded taxi-out time increase with distance. It can also be shown that the unimpeded taxi-time changes with time-of-day as speeds drop due to congestion during peak hours.

IV. JFK RUNWAYS DURING 2008-2009

This section reports analysis of almost a year's worth of departure data[4] from ASDE-X to understand the nature and general trends of the metrics discussed earlier for a larger sample. The purpose of this section is to (a) derive generalized relationships underlying the above metrics and uncover operational implications; and (b) identify and quantify the benefit from *slack*, if any, emanating from the practice of existing operational procedures. JFK data prior to construction began was chosen for the primary reason that, in many ways, JFK Airport emulates the existing ATC procedures of many large and congested airports; in fact, many of the NAS delays are originated in operations around NY-area airports, JFK Airport in particular [8]. Understanding JFK Airport departure delay is, therefore, critical in understanding fundamental operational characteristics at large and congested airports; and its impact on others in the NAS.

TABLE 4.1: BASIC STATISTICS OF 5 DEPARTURE PERFORMANCE METRICS FOR JFK AIRPORT RUNWAYS

	totalTaxiOutDuration					totalTimeInDepartureQueue				
runway name	Number of ıon missin values	Average value	Median	Maximun value	Standard deviation	Number of non missing values	Average value	Median	Maximum value	Standard deviation
13L	1405	18	14	88	14	1391	4	0	60	7
13R	18395	20	17	235	16	18357	3	0	71	5
22L	8	16	3	45	20	4	0	0	0	0
22R	30661	20	14	313	18	30658	3	0	170	5
31L	62093	17	13	272	14	62093	3	0	112	5
31R	113	5	2	25	7	61	0	0	0	0
4L	20875	19	15	244	15	20873	4	1	106	7
4R	53	27	13	110	34	33	0	0	0	0

	holdTimeDurationInMovementArea					holdTimeDurationInDepartureQueue				
runway name	Number of ıon missin values	Average value	Median	Maximun value	Standard deviation	Number of non missing values	Average value	Median	Maximum value	Standard deviation
13L	1405	7	4	79	10	1405	3	0	54	6
13R	18395	9	4	210	12	18395	2	0	58	4
22L	8	9	0	27	13	8	0	0	0	0
22R	30661	7	3	300	14	30661	2	0	164	4
31L	62093	6	3	258	9	62093	2	0	96	4
31R	113	1	0	14	2	113	0	0	0	0
4L	20875	6	3	206	9	20875	2	0	103	5
4R	53	13	2	68	20	53	0	0	0	0

	unimpededTaxiOutTime				
runway name	Number of ıon missin values	Average value	Median	Maximun value	Standard deviation
13L	1405	8	7	54	4
13R	18395	10	11	42	6
22L	8	6	3	17	8
22R	30661	11	10	52	5
31L	62093	9	8	48	5
31R	113	4	1	22	6
4L	20875	11	10	67	5
4R	53	14	9	110	19

Following the guidance of the metrics (Table 3.1), this section attempts to establish magnitude of taxi delays, and approximate benefit from redistribution of aircraft (i.e., redistribution of delays) for departure. Taxi delays that may be recovered via some form of redistribution (i.e., keeping aircraft in the gate as opposed to joining physical queue), alternate to what existed during the data sample period, and approximating the nominal value of those recovered times is the primary focus of this section.

The paper uses data for all eight runways at JFK Airport during August 8, 2008 - July 5, 2009. However, daily data were not available for most months during November, 2008 – January, 2009. In total, data for 236 days with 133,603 observations was available for this analysis, or on average 566 departures a day.

In aggregate, 31L and 22R accounted for most of the observations (46% and 23%, respectively) while 4L and 13R were fairly active as well (16% and 14%, respectively). 13L, 22L, 31R and 4R had very few observations: 1405, 8, 113, and 53 observations respectively (see Table 4.1). Given the paucity of data for 13L, 22L, 31R and 4R, the paper focuses primarily on13R, 22R, 31L, and 4L for analyzing key metrics later.

The primary focus of this section is on five metrics: total taxi out duration, total time in departure queue, hold time duration in movement areas, hold time in departure queue, and unimpeded taxi out time. The basic statistics for these five metrics are summarized in Table 4.1.

During the time period (August 2008 – July 2009), total taxi-out duration time averaged between 15-20 minutes with the exception of 31R that had value of around 5 minutes; which may have resulted due to paucity of observations (box 1 in Table 4.1). Furthermore, taxi-out duration time appears to have large variations as captured by standard deviations around the averages.

As indicated earlier, runway location and geometry affect the distance between gate and the final queuing for departure. Total time in taxi-out are divided into two phases of the departure as captured by hold time duration in movement area and hold time duration in departure queue (box 3 and 4, respectively)[5]. Categorizing hold times into two is to acknowledge the basic fact that times spent in those two areas are qualitatively different; i.e., hold time in movement areas may have relatively more maneuvering opportunities while those in departure queue have very little. Furthermore, longer hold in movement areas vis-à-vis departure queue, may also be construed as a proxy for congestion on the runways. Although both these times can be cumulatively accumulated in the originating gate for understanding benefit implications from

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[4] Given that departure performances are dependent on arrivals, a corresponding analysis involving arrival data was performed but results are not reported here in order to keep the paper to a manageable size.

[5] This paper focuses on departure delay resulting due to holds in the movement area which is further broken into time spent in movement area and departure queue. Data for delays due to holds in the ramp area is also available from ASDE-X but presently not part of the analysis. This is ignored because ramp areas are often owned and operated by airlines and departure performance is usually subject to operational procedures specific to airlines. Improving performance in ramp area will thus involve complex arrangement between airports, airlines, and the terminal ATC of the FAA, a focus far more complicated than the immediate focus of this paper. For this reason, only delays due to holds in the movement area are considered in this paper.

an alternative departure management, they may not add linearly due to aircraft's spatial location and importance of those two times in completing a departure event. Figure 4.1 summarizes the average distribution of these two hold times.

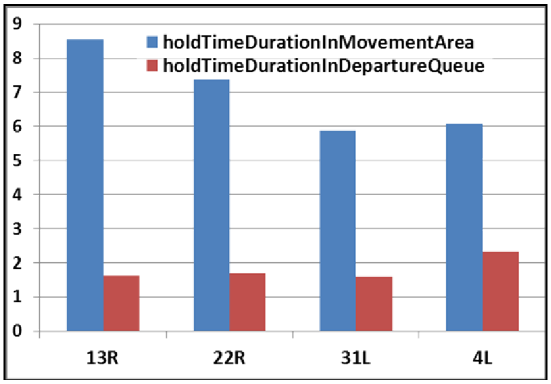

Figure 4.1 Average Hold Time (Minutes) in Movement Area and Departure Queue Distributions at 4 JFK Airport Runways

For reasons discussed earlier, hold time in departure queue is relatively shorter in comparison to hold time in movement areas. Thus, hold time in departure queue accounted for around a quarter of the total hold time. While 13R and 22R appear to have had similar hold time in movement areas (8.5 and 7.3 minutes, respectively), 4L and 31L experienced hold time in the range of 6.1 and 5.9 minutes, respectively. Interestingly, however, 4L have had relatively higher hold time in departure queue in comparison to the other three runways; consequently, it accounted for a larger portion of the total delays in movement areas (Figure 4.1).

Notice that the hold time in departure queue is also embodied, and thus, determinant of total time spent in departure queue as captured in the box 2 of Table 4.1. A departure queue is formed whereby departing aircraft is advanced according to its position in the queue and sequenced along to the waiting aircraft as one in the front of the queue takes off. A comparison of the box 2 and 4 reveals that, on average, aircraft in departure queue spends around 60% of its time on holding. Once the departure is in the physical queue, there is little that can be done to change the time through the queue due to safety stipulation (usually, 2 minutes depending upon the types of aircraft), wake limitations and consequently, opportunities for re-sequencing are very limited. As a result, the benefit pool for rearranging the aircraft in the physical departure queue is small. The larger benefit to departure management emanates from controlling the physical queue depth such that reductions in holding in the queue and sequence control are simultaneously attained.

Unimpeded taxi out time is the difference between total taxi out duration time and total hold time spent in movement areas and in departure queue. Unimpeded taxi out time contains taxi speeds that are influenced by ATC policy, weather, and congestion in two hold areas of the runways. Generally speaking, average unimpeded taxi out time and distance is captured by linear approximation as demonstrated by the figure below (Figure 4.2).

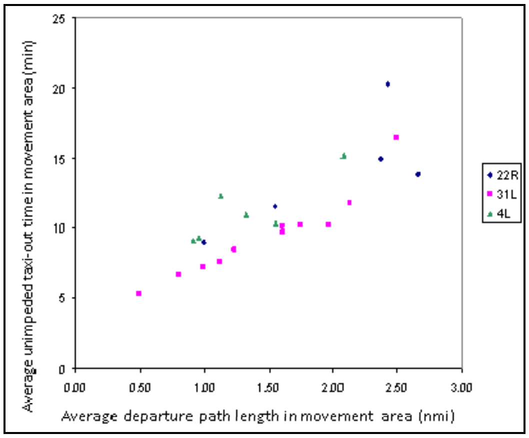

Figure 4.2 Impact of Departure Path Length on Unimpeded Taxi-Out Duration Based on Runway and Multiple Movement Area Entry Locations

As the result of appropriate conditioning (i.e., gate location and geometry of the runways), there is a clear relationship between the distance traveled between gate and runway and the associated unimpeded taxi time. Shown on Figure 4.2 are a set of average unimpeded taxi-out durations for departures at JFK Airport to Runways 4L, 31L, and 22R; the numerous points along the abscissa represent distances to each runway from entry locations to the movement area. It is evident that longer the departure path, higher the average unimpeded taxi-out time in movement area.

Given the paucity of data for 13L, 22L, 31R and 4R, basic statistics for unimpeded taxi out time are reported for remaining four runways, 13R, 22R, 31L, and 4L in the table below (Table 4.2).

Table 4.2: Basic Statistics of Unimpeded Taxi Out Time at 4 JFK Airport Runways

Unimpeded Taxi Out Time				
runway Name	**N Obs**	**Mean**	**Std Dev**	**Maximum**
13R	**18395**	10	6	42
22R	**30661**	11	5	52
31L	**62093**	9	5	48
4L	**20875**	11	5	67

On average, unimpeded taxi out time has been observed in the range of 9-11 minutes range for the four runways. Average unimpeded time captures variations in runway/ramp pairing and availability of different departure routes from the departure fixes. Within the four runways, 4L appears to have had the highest average unimpeded taxi out time together with standard deviations of a little over 5 minutes.

By and large, unimpeded taxi out time accounts for 50-56% of total taxi out duration (not including any taxi time or holding prior to the movement area). In particular, unimpeded taxi out time accounted for around 50% of total taxi out time in 13R while it was 54%, 55% and 56% for 22R, 31L and 4L, respectively. A threshold benefit pool can be easily calculated given these distributions, a topic that is addressed at the end of this section.

Movement areas precede departure queue. Aircraft are generally held in the movement areas as departure pressure mounts. Departure queue responds to this pressure by building an active queue depth. Thus, departure queue (i.e., number of lagging aircraft) is also a measure of congestion on the runways. On average, departure queue depth equal to or less than 10 accounted for over 98% of the data for these 4 runways; (i.e., out of a total of 132,024 observations, 129,548 departures accounted for 10 queue depth or less). Not all subsequent departure queues have the same properties; the larger the departure queue depth, the more complicated operational procedures are because any complications ahead in the queue ripples through the entire hold. So, it is anticipated that more deep the departure queue, higher the hold time in movement areas and in departure queue.

Figure 4.3 provides the relationship between hold time in movement areas (vertical axis) and the queue depth (limited to 10; reported along horizontal axis). Generally speaking, a positive relationship between the two is not observed; on the contrary, as the queue depth increases, hold time in movement areas appears to be going down with large variations observed on individual runways. Given this, we ran a fixed effects model where hold time in movement areas was regressed on discrete queue depth stratified by runways. Contrary to what the graphs indicate, queue depth indeed has had positive and statistically significant effects on time held in movement areas; however, models have large unexplained variations as casual examination of data would confirm as well.

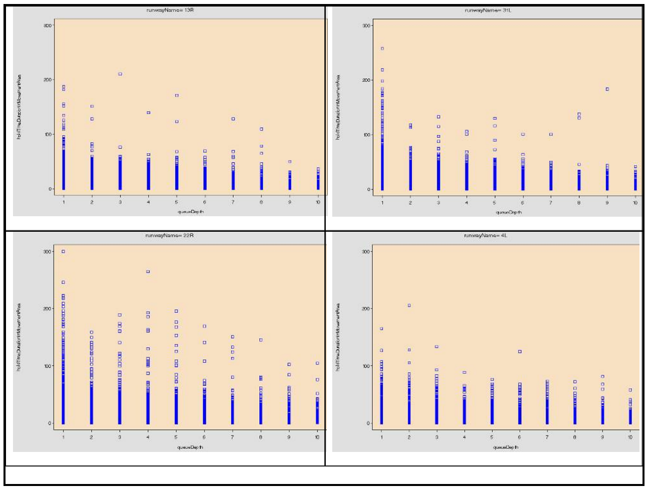

Figure 4.3 Hold Time Duration in Movement Areas and Queue Depth at 4 JFK Airport Runways

Reviewing these results along with the graphs indicate that time held in movement areas increases disproportionately around queue depth of 3-5, relatively more visible in case of 22R (lower left panel). This seems to imply that higher queue depth may have qualitatively different impact on the hold experienced in movement areas.

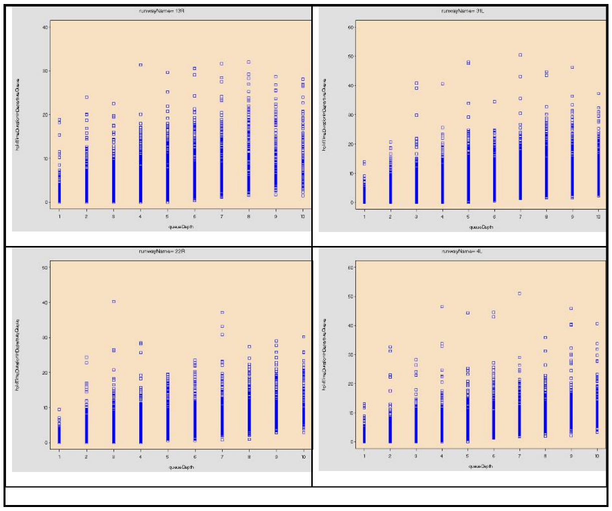

Figure 4.4: Hold Time in Departure Queue and Queue Depth at 4 JFK Airport Runways

The positive monotonicity is observed far stronger in case of hold time in departure queue and queue depth; i.e., the deeper the departure queue depth, more the hold time in departure queue (Figure 4.4). Furthermore, time in departure queue increases relatively more disproportionately on longer departure queue than at the smaller queue depth. Alternatively, as congestion on departure queue builds up (i.e., likely during morning and evening peak hours), hold time in departure queue increases disproportionately complicating the efficiencies in movement areas as well.

A fixed-effect model regressing hold time in departure queue on discrete queue depth at four runways was tried. Unlike the case above, however, this model explained over 60% of variations in hold time in departure queue and the relationship was estimated to be statistically significant.

IV.A. A FIRST-ORDER APPROXIMATION OF BENEFIT FOR VIRTUAL QUEUING IN DEPARTURE MANAGEMENT

As evident from the discussion above, the higher granularity of surface data via ASDE-X sensors provides a spatial distribution of inefficiencies emanating from the existing ATC procedures underlying aircraft departure sequencing during August 2008-July 2009. The higher the departure queue, hold time in departure queues get longer; and it is likely that some of those times are rippled onto hold time in movement areas. Eliminating these hold times via some new ordering and redistribution of aircraft may yield significant benefit. However, elimination of all queues are neither feasible; nor is it optimal for efficient runway management. Thus, some departure queue depth is necessary to appropriately manage the efficient flow. A queue depth of 5 is assumed to be required for efficient management of runway.

Eliminating times above and beyond a queue depth of five would be beneficial for those who are redirected to wait in the *virtual queue* without physically joining the queue. These virtual queues can be appropriately managed via holding aircraft in their gates. Instead of departing to a taxi queue, aircraft can be kept at the gate and metered to the runways when queues open up. Data is collected on the time needed to go from each gate to each runway via ASDE-X sensors and can be fine-tuned to calculate a refined benefit pool. Furthermore, this data can be used to build a virtual queue at the gate. While virtual queues may reduce overall delay, their primary purpose is to move delay back to the gate saving fuel and minimizing the environmental impacts. In addition to saving fuel burn, environmental benefits include savings in HC, CO, NO_x, and CO_2. Maintaining a smooth and ordered flow of aircraft may also be critical in eliminating exponential departure queues and/or diversion of aircraft once the departure queue exceeds a safety threshold.

Some aircraft may have to be moved to metering points from the gates in order to efficiently manage the departure flow. For calculation of benefit in this section, however, the focus is put on a conservative measure of time savings only. In below, time savings have been calculated that occur due to maintaining a certain departure queue depth and the time that are saved by moving the lagging aircraft, i.e., 6th place behind the lead aircraft, onto the gate.

In addition to queue depth, average time in departure queue, i.e. total time in departure queue divided by queue depth, is assumed to be independent of the depth of the departure queue[6]. That is, there are n-1 aircraft waiting on the queue with the lead aircraft without any queue ahead of it; thus, a *benefit quotient* can be calculated as the average time in departure queue multiplied with the number of aircraft lagging behind the lead aircraft.

Given the following notation,

TTOT: Total taxi out duration time
UTOT: Unimpeded taxi out time
ATDQ: Average time in departure queue
LagAC: Number of lagging aircraft in departure queue

total benefit for the pool can be calculated as:

$$\text{Benefit Pool} = [TTOD - [UTOT + (ATDQ)*LagAC]] \qquad (1)$$

The table below summarizes the results of the benefit calculation for 4 runways (for queue depth <= 5):

TABLE 4.3: BENEFIT POOL FOR OPERATING VIRTUAL QUEUES (<= 5) AT 4 JFK AIRPORT RUNWAYS

Runways	Mins saved	Benefit ($)
13R	66,830	$776,565
22R	122,307	$1,421,212
31L	210,047	$2,440,743
4L	107,813	$1,252,792

It is evident that all runways have some slacks or inefficiencies as captured by saved minutes. Using this as the basis for benefits, it is assumed: (a) saved times are treated equally, at the calculated average time without weighting them by the observed variations, i.e. no higher weight was given on larger values and vice versa; and (b) $5.64 (on fuel) and $5.98 per minute (on maintenance) for aircraft time for keeping aircraft in the gate [9]. Using these conservative parameters, 31L ranked highest in terms of benefit, followed by 22R, 4L and 13R. In total, benefit is calculated in the tune of approximately US $6 million for 236 days; or almost $25,000/day. Additional metrics, e.g., environmental impact from fuel burn, CO_2, HC, CO and NOx, can also be calculated. The table below provides an estimate of excess fuel saved assuming 15kg/min [4] for aircraft time corresponding to Table 4.3:

TABLE 4.4: EXCESS FUEL BURN ASSOCIATED WITH VIRTUAL QUEUES AT 4 JFK AIRPORT RUNWAYS

Runways	Excess fuel burn (kg)
13R	1,002,450
22R	1,834,611
31L	3,150,701
4L	1,617,201

Further benefit includes, fewer missed passenger connections, ability for airlines to prioritize high-value flights through flight swapping (i.e., collaborative decision making for traffic flow management), lower taxiway maintenance costs, reduced workload for controllers, greater airport capacity and compliance to DOT-imposed 3-hour rule.

It is evident that determining queue depth is critical in determining the total time saved using the proposed calculation. Airlines experience different taxi-out duration and queue depth depending upon their terminal locations. As with any airport, airlines at JFK Airport experience varying taxi-out time in departure. Figure 4.5 (source: [7]) demonstrates these variations in average taxi out time for five runways.

Clearly, Delta (both mainline (DAL) and Comair (COM)) experiences far higher taxi-out time than others, particularly in comparison with American (both mainline (AAL) and Eagle (EGF)) and JetBlue (JBU). Terminal location advantage and

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[6] In fact, this dependence, if it exists, is expected to be distributed non-linearly with those lagging in the queue experiencing relatively longer time in the queue. This relationship can be tested empirically and modeled, a task kept aside for future research.

distance to the departure runways make this possible. Given the location characteristics and subsequent taxi-out time, airlines may not agree on a common departure queue which, by all likelihood, may favor one airline over another.

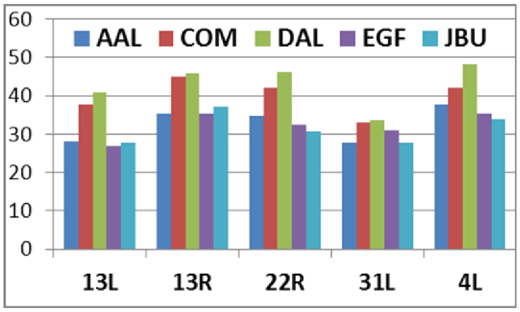

Figure 4.5: Average Taxi Out Time by Carrier

Given this observation, experimentation with different queue depths (3-11) and their impact on time savings was performed and they are reported in Figure 4.6.

Notice that higher the queue depth, less time is saved by pushing the aircraft onto the gate. This makes sense since very little time can be recovered from redistribution. It is also interesting to note that while 22R and 4L tend to demonstrate similar profile in time saving from lowering the queue depth, 31L accrues the highest time saving in the group. Finally, time requirements for runways tends to converge closer to each other as queue depth increases; in other words, as the pressure on runways increases and complexity intensifies, negative externalities are spread all around.

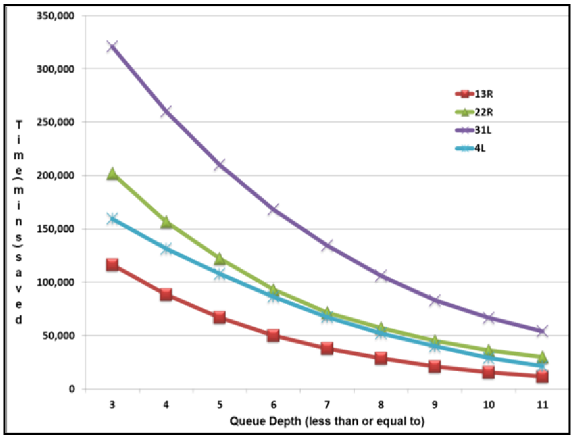

Figure 4.6: Impact of Queue Depth on Time Saved

Substituting time associated with departure queue back to gates is the essence of time savings and provides rationale for virtual queuing. Maintaining a virtual queue, therefore, will involve agreement between airlines (i.e., primarily an agreement of departure queue depth), airport, and terminal ATC. These arrangements are often complicated by ownership issues (e.g., gates and ramp areas), equity/fairness (e.g., ration by schedule vs. other flow techniques), and the present anti-trust regulations prohibiting direct contact between competing airlines. Thus, a decision support tool arranging traffic flow would involve anonymous participation by all parties. Such tools are already available in the traffic flow management involving all parties via collaborative decision making. Decision support tool formalizing collaborative decision making at the airport level is thus essential for extracting the observed benefit from introducing and operating virtual queue based departure flow. As noted earlier, some form of this management by airport operator is already in practice at some airports, including JFK.

Despite the fact that higher benefit would require institutionalizing traffic flow management regime, an envelope of lower-bound benefit can be calculated for pushing selective departures onto the gates. In calculating this by using equation (1), it is assumed that departure depth is 10 or less (i.e., capturing 98% of data) that may be considered as a norm at JFK Airport. Management of those departures that faced more than 10 departure queue depth, therefore, requires attention and can be handled separately. The following table summarizes the time saved (and subsequently, nominal benefit) provided the excess time for departure beyond queue depth more than 10 are eliminated (i.e., aircraft are held at the gates when queue depth is already 10 or higher):

TABLE 4.5: LOWER BOUND ENVELOPE FOR BENEFIT

Runways	Mins saved	Benefit ($)
13R	11,649	$135,366
22R	30,026	$348,901
31L	54,100	$628,648
4L	21,249	$246,915

Over 20% of benefit is accrued at this category, a significant amount still.

V. POLICY CHOICES, FUTURE RESEARCH AND CONCLUDING THOUGHTS

At US airports flights enter the physical queue for the runway on a first come first served basis. Under this allocation scheme, airlines have no incentive not to join the physical queue, lest they lose their priority in departure sequencing. Virtual queuing as proposed in this paper replaces this allocation in a limited way, i.e., rationing by schedule is still maintained up to 5 queue depth, as aircraft are held at the gate and ensured their queue position virtually. The primary policy trade-off, therefore, requires answering the fundamental question: Is the benefit large enough to replace the present departure management given the assurance of safety?

The paper estimated conservative benefit that amount to substantial gain. Even with the narrow consideration of time savings, the paper estimated the benefit in the tune of US$25,000/day associated with virtual queuing with a queue depth of five. A lower envelope of benefit that mirror present distribution of departure management but augments with some form of limited queuing (ten) garners benefit of US$6,000/day. Calculation of excess fuel indicates that environmental benefit corresponding to these virtual queuing, i.e., CO_2, HC, CO, NOx and local air quality could be substantial as well.

Examples of virtual queues have been implemented on a very limited basis in the US. More work and political will is needed before broader changes in departure management take place. To achieve the benefits using ASDE-X data, from its present usage in improving safety situational awareness, would require all stakeholders' participation managing airport gate, taxi, and runway efficiencies. An analysis incorporating arrival management together with departure management is necessary to further understand the extent and magnitude of the benefit. Procedures for assuring equity between airlines are necessary to realize full benefits as well. Assurance of fairness and equity is also necessary for participants to stay away from gaming the system. This can be assured, however, via decision support tool that uses ASDE-X data ensuring virtual queuing. Departure management tool ensuring virtual queuing integrated with traffic flow manager, on the other hand, may ensure downstream en route efficiency. In similar vein, improved departure management tool, when integrated with ADS-B/Out data, may ensure even more robust efficiency gains. However, the magnitude of those efficiency gains and their value will have to be researched in the future.

New sets of operational definition and terminology and information standardization of these data will be necessary as well. Furthermore, policy choices must be made determining ownership of tools and procedures that produce the benefits of virtual queuing. Given the fact that many of the requirements involve explicit cooperation and coordination across stakeholders, an external regulatory push may accomplish these tasks rather smoothly. The role of the FAA and Airport Authority needs to be clarified that considers benefits beyond those considered by airlines including emissions, noise, and possibly reducing propagated delay. Fortunately, the successful experience of traffic flow management using collaborative decision making provides key guidance to ensuring effective implementation of virtual queue-based departure management system. Uses of these tools may prove to be extremely effective in reducing taxi out delays in the congested airports, propagated delays, improve en-route efficiency thus ensuring an improved operational environment for the entire NAS.

Departure management ensuring virtual queuing using new ASDE-X data has substantial potential for managing congested airports. This paper introduced new data, concepts and a framework to evaluate benefit for implementing such departure management. Using JFK departure as a case study, the paper established the upper and lower contours of those gains; and laid out the basic features of policy choices including institutional framework that will be necessary. Researching them and addressing those issues are fundamental in taking full advantage of these new data and bringing new decision support tools that guarantee virtual queuing leading to better surface management in the near future.

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