# An Approach for Estimating Current and Future Benefits of Airport Surface Congestion Management Techniques\*

Alex Nakahara<sup>†</sup> & Tom G. Reynolds<sup>‡</sup>

Massachusetts Institute of Technology Lincoln Laboratory, Lexington MA 02420, USA

Airport surface congestion can be a cause of significant increases in taxi times, fuel burn and emissions at major airports. Various surface congestion management techniques are being developed to help mitigate these issues at different airports, typically by holding aircraft at the gate during times of high congestion to reduce the number of aircraft on the active movement area. This paper presents an approach to estimate the benefits in terms of reductions in active taxi time and fuel burn of applying such techniques at a subset of US airports, both under current and expected future operations. Results show that the benefits of surface congestion management translate to billions of gallons of reduced fuel burn and huge environmental impact reduction over the next twenty years.

## I. Introduction

A IR traffic is expected to continue to grow in the future and methods for dealing with the increased demand on the system need to be designed and implemented. One method for improving efficiency at airports is surface congestion management (SCM), also commonly called departure queue management or departure metering. The concept generally involves holding "excess" aircraft at the gate or other predesignated location instead of releasing them onto the active movement area during periods of high departure demand, as shown in Figure 1. By restricting the number of aircraft on the surface, taxi-out delay, fuel burn and emissions can be reduced as aircraft that



Figure 1: Surface Congestion Management Concept

would otherwise be waiting in surface queues with engines on are instead held in appropriate locations with engines off. There are also potential secondary benefits of gate holds, such as increased passenger and bag connectivity.

In order to better understand the role surface congestion management can play in the air transportation system and to make the case for its deployment at different airports, benefits assessment activities are required. This paper presents a methodology to estimate the current and future benefits of surface congestion management and presents results from its implementation at a set of 8 key airports in the US.

# II. Surface Congestion Management Benefits Analysis

The analysis methodology for the benefits assessment of the surface congestion management capability is illustrated in Figure 2. The methodology contains three main components: Simulation; Throughput Saturation Curves; and Results Generation & Validation. Details of each of these components are discussed in the following sections, starting with Throughput Saturation Curves given its central importance to the approach.

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† Graduate Student, MIT Department of Aeronautics and Astronautics.

Technical Staff, MIT Lincoln Laboratory. Senior Member AIAA.



Figure 2: Analysis Methodology

# A. Throughput Saturation Curves

At the core of the methodology is the concept of throughput saturation curves, which relate departure throughput to an appropriate traffic metric (e.g., number of departing aircraft on the airport surface or in a departure queue). The concept is illustrated in Figure 3. As more aircraft push back from their gates onto the taxiway system, the throughput of the departure runway(s) initially increases because more aircraft are available in the departure queue(s). But as the number of aircraft continues to increase, the airport eventually reaches a saturation departure throughput. The saturation value depends on the airport configuration (due to different capacities); arrival demand (due to departure/arrival interactions); meteorological conditions (visual vs. instrument conditions); and controller technique. When the airport is operating beyond its saturation point, any additional aircraft that push back simply increase the time they are taxiing out with engines on without any gain in departure throughput. The objective of surface congestion management is to maintain the number of aircraft pushed back at a certain control level just above the saturation point. In this way, high departure throughput can be achieved without unnecessary surface congestion and the resulting excess delays and fuel burn by moving the operating point at congested times from above the control point back along the curve to the control point, as illustrated in Figure 3.



Traffic Metric, e.g. No. of aircraft on surface, Dep queue length, etc.

Figure 3: Throughput Saturation Curve

Prior work at MIT has automated the determination of benefits for *current day* operations by quantifying the reduction in active taxi time from moving the operating point on the saturation curve during congested times when it would otherwise be above the control point to the control point [1]. The average taxi time of flights taxiing when the number of actively taxiing aircraft, N is at the control value ( $N_{Control}$ ) is compared to the average taxi time of flights taxiing when the taxiing when  $N > N_{Control}$ . The number of flights in the congested regime is also calculated and the potential benefits are then calculated as:

Active Taxi Time Reduction Benefits = # Flights<sub>Congestion</sub> × (AverageTaxiTime<sub>Congestion</sub> - AverageTaxiTime<sub>Control</sub>) (1)

This taxi time reduction also leads to fuel burn and emissions reductions because engines are on for less time. This approach has been expanded for this paper to explore future year impacts as described next.

# **B.** Simulation

#### 1. Inputs

The data inputs identified in Figure 2 allow current-day throughput saturation curves to be determined for study airports using archived operational data such as ASPM [2] and ASDE-X surveillance data. This study uses ASPM for historical data which provides OOOI (gate OUT, wheels OFF, wheels ON, gate IN) times for individual flights, as well as airport configuration in 15 minute intervals, while the OFF times can be used to calculate the airport throughput in the same 15 minute intervals. Active taxi time reductions by employing surface congestion management techniques can be calculated as described above. These active taxi time benefits can be converted to fuel burn savings by multiplying by ICAO-standard fuel flow and emissions rates for different aircraft types [3] consistent with the fleet mix at different study airports (obtained from ASPM). The "current year" benefits results using this analysis methodology were validated in two separate ways: first, JFK and BOS have operational field trials of SCM techniques and the benefits estimates were compared to results from those trials [4,5]. Second, the results for 2010 based on the ASPM data were compared to those estimated using the "future years" simulation (discussed in the next section) using operational data from previous years.

## 2. Future Year Saturation Curve Prediction

The key challenge in finding future year benefits is finding the saturation curve in the future. As illustrated in Figure 3, saturation curves are not constant over time and can vary substantially due to aspects such as demand levels, infrastructure changes, operating enhancements and fleet mix changes. A method for deriving future saturation curves therefore needed to be developed. To be as realistic as possible, secondary variables such as the number of terminals and gates, the percentage of capacity in use, and the number of runways were considered in addition to demand and capacity. A simple linear model is not appropriate because, while saturation throughput could substantially change in either direction, there is an upper limit to the amount it can increase (due to aspects such as separation requirements) that a linear model would not capture. This limit is generally not known because it can vary significantly with factors such as fleet mix. Instead, future saturation curves were estimated using the Random Forest (RF) method [6]. This approach was chosen because it makes no assumptions about the functional relationship between the input/predictor variables and the output, and avoids biases by not assuming a particular function is the correct form to describe airport behavior. It uses groups of decision trees that test the importance of different parameters in order to predict values by calculating the average over all predictions from the individual trees.

The saturation point and saturation throughput are the target RF prediction variables that define the airport throughput saturation curves to first order. The saturation point is defined for the purposes of calculation as the first point at which the throughput reaches 95% of its maximum value. To eliminate the high variability due to small sample sizes (outliers at high N values with abnormally high throughput), the 2% of data with the highest N values were removed from the data set for the calculation of N\*. The saturation throughput is simply the mean throughput at the saturation point. The input parameters to the RF model to predict these saturation curve parameters were chosen using engineering judgment as well as the input of subject matter experts and included the mean and peak hourly demand and capacity, the usage of a configuration, the physical size of the airport, and the number of gates. The decision trees were trained, or 'grown', on data from 2000 to 2010, those being the years for which ASPM data exists. Data based on the capacity growth forecasts and future schedules, supplemented with parametric variation of

the curves as appropriate for representative days/conditions for the future study years, were input into the model to obtain the future year saturation curves.

### 3. Future Year Traffic Simulations

Once future year saturation curve parameters had been estimated, it was necessary to determine future year operating points relative to the future year saturation curve. The traffic simulation capability which had been previously developed and validated at MIT [1] was used for this purpose. It was modified to use the following future year inputs:

- Forecast annual demand by airport: FAA Terminal Area Forecast (TAF) 2010-2030 [7]
- Forecast capacity by airport: MITRE FACT2 [8]
- Future year "NextGen schedules" for 12 representative days in the years 2010, 2015, 2020, 2025 and 2030. These are "untrimmed" schedules which do not take into account future capacity or delay
- Physical airport data (Terminals, gates, runways, etc.) from airport websites

Using this input data, the simulation calculated taxi times for every flight over the course of a year in a given configuration by modeling the aircraft departure process as a queuing system. It took the future year schedules as its main input and assumed that the scheduled departure times were the pushback times for each flight. Taxi time,  $\tau$  is related to the size of the departure queue by:

$$\tau = \tau_{unimpeded} + \alpha R(t) + W_a(t) \tag{2}$$

where  $\tau_{unimpeded}$  is the average unimpeded time (by airline or overall),  $\alpha$  is a taxiway congestion factor, R(t) is the number of aircraft on ramps and taxiways at time t, and  $W_q(t)$  is the expected waiting time at time t. The simulation calculates the time for three different segments of taxiing: unimpeded time, taxiway congestion time and time in departure queue. In Figure 4,  $\alpha$  represents the Ramp and Taxiway interactions,  $W_q(t)$  is the time spent in the departure queue (which depends on the runway server), and  $\tau_{unimpeded}$  is the base time it would take if the ramp interactions and departure queue were 0.



Figure 4: Departure Process [9]

These three segments have tunable parameters:  $\tau_{unimpeded}$ ,  $\alpha$  and capacity (which affects  $W_q$ ). The average unimpeded time used was the average across all airlines in a specific configuration from 2010, because the physical layout of an airport can change suddenly and unexpectedly (e.g. if an airline moved terminals or left an airport). By using the overall taxi time, the robustness of the model is improved. There were no changes to the unimpeded time because of new construction because of the uncertainty in completion times and effectiveness. The taxiway congestion factor was calibrated from the present day training data by matching the amount of congestion predicted with the congestion actually seen. In [9] this factor is calibrated by matching the mean and median taxi times. Congestion matching was chosen because it more accurately predicts taxi times during congestion, which is the regime of interest.

The saturation throughput from the RF model was used to determine the service rate for the departure queue for different levels of arrivals to reflect the interdependence of the arrival and departure rates. The saturation throughput calculated by the RF model was an average value, so to translate that to different levels of arrivals, the difference between the average service rate and the rate implied by the saturation throughput was calculated. This difference was added to the rates for each level of arrival to determine the new service rates. The service rates were modeled as Erlang distributions, where the arrivals at the runway threshold were assumed to be random. Each runway

configuration at each study airport was modeled as a single server with infinite space for the queue, and aircraft are taken first-come, first-served.

With estimates of taxi time, the operating point on the future year saturation curve could be determined over the course of the future year day. Note N(t) is not the same as R(t) because it includes aircraft in the departure queue at the end of the runway. Benefits of surface congestion management relative to the baseline case for future years were calculated using Eqn. (1) as for the current year.

Note, the two main modifications made to [1] in this study were calibrating the taxiway congestion factor to the amount of congestion instead of the mean/median taxi times, and changing the service rates to match the values predicted by the Random Forest instead of using the values from the operational data. The second change was important because it reflects the change in airport performance due to secondary variables beyond capacity such as demand. Without it, the airport performance would be static (unless additional runways are planned, as at ORD).

In addition to these two modifications, the decision was made to model the 5 most-used configurations separately for each airport instead of choosing one "aggregate" configuration. There were several reasons for this decision. The simulation was supposed to be tailored to a specific configuration with average unimpeded times and service rates. By using an aggregate configuration, one dilutes the validity of the model. In addition, if an airport has configurations that vary in performance, the benefits of SCM would be greatly affected by assuming only one configuration. Because the simulation is configuration-specific, realistic configuration choices are needed. The weather and configuration choices from the base year (2010) were taken as typical and used for every future year.

After the future year saturation curves and operating points against them were calculated as described in the previous section, the benefits were summed across the 5 most common configurations. Using only 5 configurations caused an inconsistency between the simulation results and the field trial results for two reasons: firstly, low-use configurations can have disproportionate benefits from metering, meaning that only scaling the top 5 configurations underestimates the true benefits. Secondly, only curves for VMC conditions were used (due to limited IMC prediction data) which also underestimates the benefits because IMC conditions have more SCM benefits due to the reduction in capacity and increased congestion at these times. To account for these effects, a scaling factor was calculated for the "current year" results based on the difference between the sum of the benefits for the top 5 configurations and weather conditions. This factor was then used to scale up the future benefits so that they were compatible with the historic benefits and the field trial.

#### C. Results Generation & Validation

The future year estimates resulting from the approaches discussed above are "unconstrained benefits" because they do not account for the physical constraints to the number of flights that can be held by an SCM approach, e.g., limited number of gates or off-gate hold locations. The "practical benefits" shown in Figure 2 consider airport gates as a limiting resource. If there are too few gates, SCM might need to be scaled back. For each study airport, the approximate number of aircraft on the ground at a gate was calculated for the current year using ASPM data. The gate use count was calculated by adding one when an aircraft arrived at a gate (from the IN time) and subtracting one when an aircraft departed (from the OUT time). The count was calculated at each minute from midnight to midnight of one day and is airline-specific. Because the count starts at midnight, there were an unknown number of aircraft already on the ground. This resulted in a count that could be negative at times. To normalize for this, the absolute value of the minimum value (largest negative number) was added to the entire count for that airline under the assumption that each airline has 0 aircraft at a gate at one point during the day. This may not always be true, but the induced error is assumed to be small. The ability for an airport to conduct on-gate holds from SCM was then estimated by taking the difference between the number of gates in use at any given time and the total number of gates at the airport. When the number of required aircraft holds from SCM exceeded the number of free gates, it was assumed additional holds could not take place. The use of total available gates as the metric for how many aircraft could be held by an SCM approach makes several simplifying assumptions: it neglects gate ownership issues (gates at US airports are typically "owned" by a specific airline and are not a shared resource), the size of gates and their ability to handle different types of aircraft and whether or not an aircraft was moved off gate after arrival. It also does not explicitly show space available for off-gate holds. Off-gate holding space is very hard to quantify without interviews with staff at specific airports, but examination of LGA maps (the most constrained airport) identified several possible locations. We therefore assumed that off-gate holds could be used at all airports.

Gate utilization was calculated for each study airport and year and compared to the number of gates at (or

planned at) the airport. If the analysis showed that there would not be enough gates to accommodate SCM, "practical benefits" were restricted to the last year in which there were enough gates. Figure 5 shows estimated gate utilization at DFW and JFK for future years. While DFW is forecast to have little growth in demand for gates in the future, JFK is estimated to face increasing gate competition which could constrain SCM benefits by 2020.



Figure 5: Estimated DFW and JFK Gate Utilization (Future Schedules)

Several other airports were also estimated to exceed their gate capacity in future years. This illustrates a fundamental problem with the generation of future demand schedules: the only constraining capacity is the runway capacity, when in fact there are several others that can restrict an airport, such as gate capacity, security, and noise abatement. Because these factors are not considered in future schedules, their use can lead to overestimates of benefits because demand levels are higher than realistic levels at affected airports. While this work attempts to correct for this by restricting growth of benefits at airports with gate constraints, a better method would be to regenerate the future schedules with additional realistic constraints.

# III. Results

Eight airports were studied using the methodology outlined in the previous section: ATL, BOS, DFW, IAD, JFK, LGA, ORD and PHL. JFK and BOS were chosen because of their recent and ongoing field trials of SCM. The other airports were chosen to represent different types of airports. LGA is small and space constrained, PHL is larger but space constrained, DFW is large with relatively low demand compared to its capacity and is not space constrained, ORD and ATL are large but with high demand and IAD is a medium-sized airport. Detailed results for JFK are presented in the next section, but detailed results for the other airports can be found in [10]. JFK was chosen to present in detail here because of the validation work performed [4] and because it displays many of the important trends and traits in the study. Aggregate results in terms of taxi time and fuel burn benefits estimates are then presented for all the study airports in the following section.

### A. Detailed JFK Results

Results for JFK are shown in Figure 6. Figure 6a shows how demand has differed between 2000 and 2010, along with estimates of how it will evolve through 2030, and changes in capacity and taxi times. The historical demand is obtained from ASPM aggregate operations counts, while the future demand is from the future schedules [7]. The ASPM historical capacity is the average Airport Departure Rate (ADR) seen, and the future capacities are from [8]. As the demand increases into the future with no change in capacity, the unconstrained benefits from SCM drastically increase, as seen in Figure 6b. The rise in benefits is due to the simulated rise in taxi time, which indicates more congestion. The taxi time can be seen to closely mirror the demand, as might be expected when JFK is operating close to its capacity and with no major changes in capacity. Two benefits curves are presented in Figure 6b

representing the historical and future benefits. Historical benefits (benefits that could have been realized if SCM had been in place) between 2000 and 2009 were calculated with ASPM data and are seen to generally validate the MIT methodology because the 2010 (ASPM) and 2010 (MIT simulation) points are very close. The JFK field trial [6] allows further validation of the approach. The benefits from the field trial were estimated to be 15,000 hours of taxi time reduction in 2010 as illustrated by the black diamond in panels b and d, which is seen to be a very close match with both the historic ASPM and MIT simulation estimates using the throughput saturation curve method. Figure 6c has the gate utilization for future years. There is no change in the pattern of usage; each successive year simply moves the curve up, and gate utilization demand is seen to exceed the current number of gates after 2015. Figure 6d shows the practical SCM benefits when the gate constraints seen in Figure 6c limit benefits from 2020.



Figure 6: JFK Surface Congestion Management Benefits Results

# **B.** Aggregate Results

Figure 7 presents the estimated unconstrained and practical benefits in terms of gallons of fuel saving across the 8 study airports. The airports with major contributions to the unconstrained benefits are JFK, ORD and ATL. The other four airports are all at about the same lower level of benefits. When the practical benefits are examined, all three of these airports have significantly reduced benefits due to gate constraints, but they remain the top three airports in terms of SCM benefits.

Using the FAA-recommended future fuel price from 2010 to 2030 of \$2.43 [11], the monetized unconstrained fuel savings benefits are \$3.6 billion cumulative from 2010 to 2030 across the 8 airports studied, as shown in Table

1. Summing the practical benefits results in \$2.3 billion fuel saving using the same estimated fuel price, as shown in Table 2. These estimates assume 3.1 kg per gallon of jet fuel and airport-specific fuel burn rates (using ICAO taxi fuel rates) for the current aircraft fleet mix at each airport. Taking the average taxi times from the simulation and multiplying by the total number of flights, the total estimated time spent in taxi and the corresponding fuel burn can be calculated. For the 8 airports cumulatively from 2010 to 2030, in the unconstrained case there would be 6 billion gallons of fuel burned (\$14.4 billion at \$2.43/gallon), making the savings from SCM almost 26% of the total fuel cost in taxi. In terms of total fuel burn for flights at these 8 airports was estimated at 100 billion gallons, with a corresponding cost of \$244 billion. The SCM benefits are then 1.5% of the total fuel burn. For the practical case, the results are 5.3 billion gallons of fuel, \$12.8 billion, and 18% of total fuel cost for taxiing only and 97 billion gallons of fuel, \$236 billion and 1.0% of the total fuel burn. Care should be taken with the estimate of the percentage of total fuel burn because only domestic carriers are included, and the true percentage is probably lower. The percentages vary substantially by airport because of the nature of SCM.



Figure 7: Aggregate Fuel Burn Benefits Estimates

Airport			Unconstrained		
	Thousand			Savings as % of	Source of % of
	Hours Taxi	Million Gallons	\$ Millions	taxi-out fuel	savings as 70 01
	Time Reduction			cost	total fuel cost
ATL	1251	313	761	26%	1.5%
BOS	59	13	31	4%	0.2%
DFW	105	27	66	4%	0.2%
IAD	299	60	146	12%	0.6%
JFK	1839	661	1606	47%	6.8%
LGA	326	65	157	22%	1.0%
ORD	1108	270	656	26%	1.3%
PHL	446	90	218	20%	0.9%
TOTALS	5,432	1,498	3,641		

Table 1: 2010-2030 Unconstrained Benefits by Airport

	Practical					
Airport	Thousand Hours Taxi Time Reduction	Million Gallons	\$ Millions	Savings as % of taxi-out fuel cost	Savings as % of total fuel cost	
ATL	965	242	587	21%	1.2%	
BOS	59	13	31	4%	0.2%	
DFW	105	27	66	4%	0.2%	
IAD	177	36	86	11%	0.6%	
JFK	1060	381	926	35%	1.9%	
LGA	326	65	157	22%	1.2%	
ORD	390	95	231	10%	0.5%	
PHL	455	92	223	20%	1.1%	
TOTALS	3,537	949	2,307			

Table 2: 2010-2030 Practical Benefits by Airport

# **IV.** Conclusions

Surface congestion management is an effective solution to the problems of congestion at airports. This study has developed a methodology for estimating the benefits of SCM, and its use at 8 major airports has calculated a total of over \$2 billion in fuel savings over the next 20 years. These findings should be valuable to policy-makers as they conduct cost-benefit analyses to determine what new technologies should be deployed to address air transportation system challenges, and which sites might benefit the most.

This work has also highlighted a number of challenges inherent in this type of future year benefits assessment. In particular, future year forecasts of key input data such as demand and capacity on a system-wide and airport-specific level are highly uncertain, which directly impact the benefits which could be realized at any given airport. The current forecasts do not consider physical constraints such as numbers of gates and have optimistic capacity forecasts. As a result, the future demand will most likely be lower than these forecasts. All of these issues need to be explicitly identified so their implications can be explicitly considered when the results are being interpreted. For example, a very pessimistic lower bound on benefits can be calculated by assuming that demand remains at 2010 levels. In this case, the 8 study airports would have the \$38 million in benefits from 2010 in each subsequent year to give \$806 million over the period from 2010 to 2030, 0.1% of total fuel costs. This is substantially smaller than the \$2.4 billion in benefits in practical benefits previously estimated.

A related issue is that of gate space. As was shown, several of the study airports are forecast to face demand for gates that greatly exceeds the current capacity. While some airports such as ORD have plans for such a contingency, other airports such as JFK that are space constrained may not be able to accommodate all the holds SCM may require (and possibly may not be able to accommodate the forecast demand). The resulting cap on the demand has large impacts on both the benefits from SCM (and virtually every other proposed improvement) and planning for the US air transportation system in general.

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