Design, Testing and Evaluation of a Pushback Rate Control Strategy

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***Abstract*—Airport surface congestion results in significant increases in taxi times and fuel burn at major airports. This paper describes the implementation of a congestion control strategy at Boston Logan International Airport (BOS). The approach predicts the departure throughput in the next 15 minute interval, and recommends a rate at which to release pushbacks from the gate in order to control congestion. Two Android tablet computers were used for the implementation of the strategy; one to input the data, and the other to display the recommended rate to the air traffic controllers. Two potential decision-support displays were tested: a rate control display that only presented a color-coded suggested pushback rate, and a volume control display that provided additional support to the controllers on the number of aircraft that had called-ready and had been released. A survey of controllers showed that they had found the decision-support tool easy to use, especially the additional functionality provided by the volume control display. During 8 four-hour test periods in 2011, fuel use was reduced by an estimated 9 US tons (2,650 US gallons), and aircraft taxi times decreased by an average of 5.3 min for the 144 flights that were held at the gate, showing that such a congestion control strategy could yield significant benefits.**

I. INTRODUCTION

Airport surface congestion at major airports in the United States is responsible for increased taxi-out times, fuel burn and emissions [1]. Similar trends have been noted in Europe, where it is estimated that aircraft spend 10-30% of their flight time taxiing, and that a short/medium range A320 expends as much as 5-10% of its fuel on the ground [2]. Congestion is a key cause of these surface inefficiencies, and nearly half of the US emissions due to aircraft taxi-out processes occur at the 20 most congested airports in the country. It is therefore expected that a significant portion of these impacts could be reduced through measures to limit surface congestion.

A. Related work

A simple airport congestion control strategy is the *N-control* strategy that was first considered in the Departure Planner project [3]. Several variants of this policy have been studied in prior literature [4, 5, 6]. There have been other recent congestion management efforts, such as the metering of departures at New York JFK airport by PASSUR Aerospace, Inc. [7], the field evaluation of the Collaborative Departure Queue Management concept at Memphis (MEM) airport [8], the human-in-the-loop simulations of the Spot and Runway Departure Advisor (SARDA) concept at Dallas Fort Worth (DFW) airport [9] and the trials of the Departure Manager (DMAN) concept [10] in Athens International airport (ATH) [11].

In contrast to these approaches, the Pushback Rate Control strategy is a low-cost, aggregate and centralized approach that meters pushbacks from the gates rather than from the spots (the boundaries between the ramp area and the taxiways). It is implemented at the Airport Traffic Control Tower (ATCT) and does not require real-time data exchange with the airline operations centers. The focal point of our effort is to successfully address the uncertainty of the dispatch, the taxiing and the takeoff process so as to maintain runway utilization.

During summer of 2010, we developed and tested a version of the Pushback Rate Control protocol (henceforth referred to as PRC_v1.0) [12], which is an adaptation of the *N-control* policy. The main motivation for our proposed approach was an observation of the performance of the departure throughput of US airports. As more aircraft pushback from their gates onto the taxiway system, the throughput of the departure runway initially increases because more aircraft are available in the departure queue. However, as this number, denoted N, exceeds a threshold, the departure runway capacity becomes the limiting factor, and there is no additional increase in throughput. We denote this threshold as N^*. The dependence of the departure throughput on the number of aircraft taxiing out is illustrated for the most frequently used runway configuration at BOS in Figure 1. Beyond the threshold N^*, any additional aircraft that pushback simply incur taxi-out delays without increasing the airport throughput [13]. During periods of high demand, PRC_v1.0 regulates the rate of aircraft pushbacks from the gates so that the number of departures taxiing stays close to a specified value, N_{ctrl}, where $N_{\text{ctrl}} \geq N^*$, thereby ensuring that the airport does not reach highly-congested states.

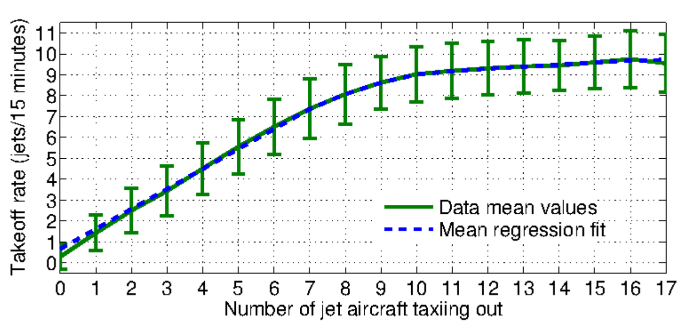

Fig. 1: Regression of the departure throughput as a function of the number of aircraft taxiing out, for the 22L, 27 | 22L, 22R configuration at BOS, under VMC during evening times.

II. A New Variant of Pushback Rate Control

A. Design requirements

The objective of the control strategy is to minimize the amount of taxiing-out traffic, and thus taxi-out times, while maintaining runway utilization. In addition, it must be compatible with current levels of information and automation in the airport tower, and capable of integration with current operational procedures, with minimal controller workload. Thus, the strategy does not require Collaborative Decision Making, and does not assume the ability to plan and re-sequence departures. Its design has to address the uncertainties in the entire taxi-out process, from call-ready to takeoff.

For these reasons, the desired form of a congestion control strategy is one that periodically recommends a pushback (release) rate to air traffic controllers [12]. The suggested pushback rate is updated at the beginning of each time-window, and is valid through that time period. For reasons outlined in prior work [12, 14], 15 minutes is a suitable choice of time-window for BOS.

Careful monitoring of off-nominal events and constraints is also necessary for implementation at a particular site. In the case of BOS, of particular concern are gate conflicts (for example, an arriving aircraft is assigned the same gate as a departure that is being held), and the ability to meet controlled departure times (Expected Departure Clearance Times or EDCTs) and other constraints from Traffic Management Initiatives. In consultation with the BOS ATCT, it was decided that flights with EDCTs would be handled as usual and released First-Come-First-Served. Similarly, pushbacks would be expedited to allow arrivals to use the gate if needed. Finally, prior analyses showed that, at BOS, departures of propellor-driven aircraft (props) do not interfere significantly with jet departures [15]. The main implication of this observation for the control strategy design at BOS is that props are exempt from the Pushback Rate Control.

B. State variables

At the beginning of each time-window, we observe the state of the airport system, and recommend a pushback rate. For the purposes of control, the state is described by the following variables:

1) Runway configuration and meteorological conditions
2) Number of jet aircraft taxiing from the gates to the departure runway (R)
3) Number of jet aircraft in the departure queue (Q)
4) Expected number of arrivals in the next 15 min. (A)
5) Number of props taxiing out (P)

All these variables are readily available in the current tower environment: R corresponds to the number of jet aircraft strips in the ground controller's rack, Q is the number of jet aircraft strips local controller's rack, P can be determined visually from the same racks, and A can be looked up in the Traffic Situation Display (TSD).

C. Control algorithm

The dynamic programming algorithm developed, PRC_v2.0, determines an optimal pushback rate for the next 15 minute period as a function of the state variables R and Q for each set of runway configuration and meteorological conditions. In doing so, it uses a queuing model for the system dynamics. The runway service times are modeled by an Erlang distribution A detailed description of the algorithm, the model, and the parameter estimation process can be found in an earlier paper [14].

The control strategy sets the pushback rate to balance two objectives, namely, to minimize the expected departure queue length and to maximize the runway utilization. The cost of underutilizing the runway is chosen to be equal to the cost of a queue of 25 departures, to reflect the fact that at BOS, such a long queue can lead to surface gridlock, and consequently, non-utilization of the runway.

1) Derivation of optimal policies: Given the cost function and system dynamics, the optimal control policies can be derived using standard dynamic programing techniques. For the runway configuration 22L, 27 | 22L, 22R during evening times and VMC, these are shown in Figure 2.

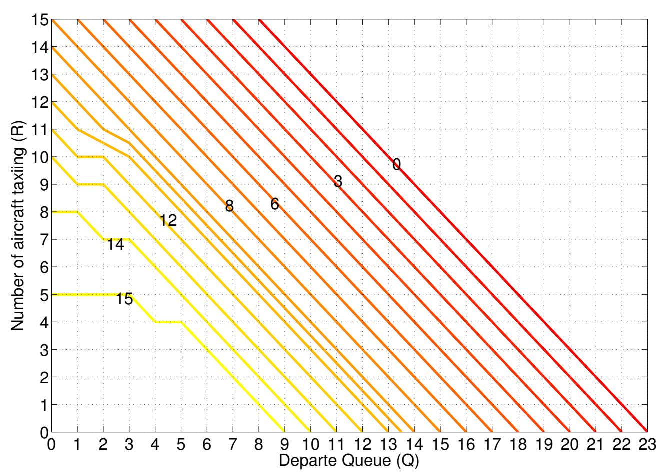

Fig. 2: Optimal pushback policy $\bar{\lambda}$ as a function of Q and R

Figure 2 shows the contours of the optimal pushback policy $\bar{\lambda}$ (number of jet pushbacks/ 15 minutes) as a function of the number of aircraft in the departure queue (Q) and the number of aircraft taxiing (R). As expected, the optimal pushback rates decrease for increasing values of Q and R. The final rate recommended to the controllers is rounded to the closest equivalent rate of 0, 1 per 3 min, 1 per 2 min, 2 per 3 min, 3 per 5 min, 4 per 5 min, or 1 per min.

III. Takeoff rate prediction

The runway service time distributions for the model used in PRC_v2.0 are determined using ASDE-X data from November 2010-June 2011. The analysis considers high-demand evening periods and different configurations [14]. However, parameters such as the variables A and P can provide a conditional forecast for the runway service time distribution. These parameters explain some of the variance of the departure throughput and provide a better estimate of the expected departure capacity. For example, the mean and standard error of the jet departure capacity in runway configuration 22L, 27 | 22L, 22R under visual meteorological conditions can be estimated from the regression tree of Figure 3. This regression tree is validated using 10-fold cross validation.

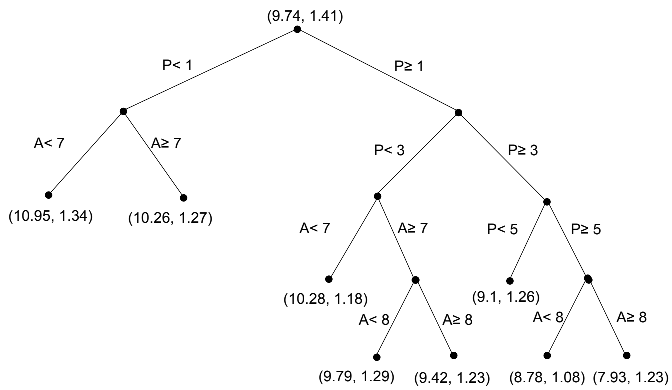

Fig. 3: Regression tree for parametric jet departure throughput predictions.

These conditional forecasts are incorporated heuristically into the algorithm PRC_v2.0 in the spirit of rollout algorithms [14]. We refer to this modified control protocol as PRC_v2.1. Since the conditional forecast is more accurate than the unconditional one, we conjecture that PRC_v2.1 is more optimal than PRC_v2.0.

IV. Design of a Decision Support Tool

The next step of our research is the investigation of the downstream deployment potential of Pushback Rate Control algorithms. To this end, we develop an application that uses the necessary inputs to automatically determine the suggested rate. The device used is a tablet computer, the 7-inch Samsung Galaxy Tab©, which has the advantages of being portable and compact. In addition, the Android operating system offers a convenient application development environment. Two tablet computers are used for the implementation of the strategy; the rate control transmitter and the rate control receiver. The rate control transmitter is used to input the data, and the the rate control receiver to display the recommended rate to the Boston Gate (**BG**) controller, who is responsible for authorizing aircraft to monitor ground control for their pushback. The two devices communicate with each other using a Bluetooth wireless link (Figure 4).

A. Inputs

The application developed calculates the expected takeoff rate and the recommended pushback rate using a look-up table for the PRC_v2.1 algorithm. The previously defined state

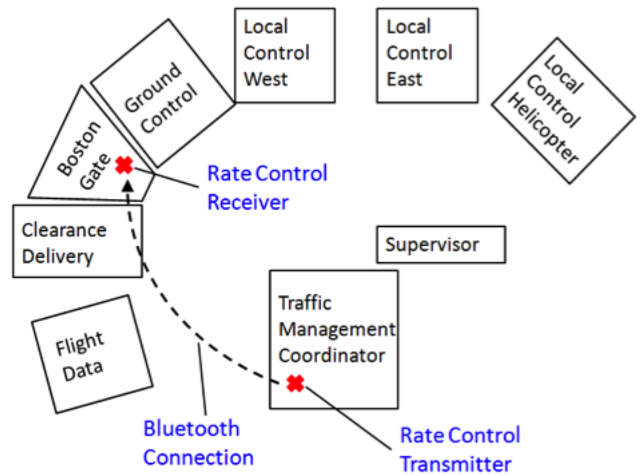

Fig. 4: Setup of rate control transmitter and receiver in the BOS ATCT.

variables are given as inputs: runway configuration, weather, expected arrival rate in the next 15 minutes, jets on ground control, jets on local control, and number of props taxiing out. The input interface is shown in Figure 5.

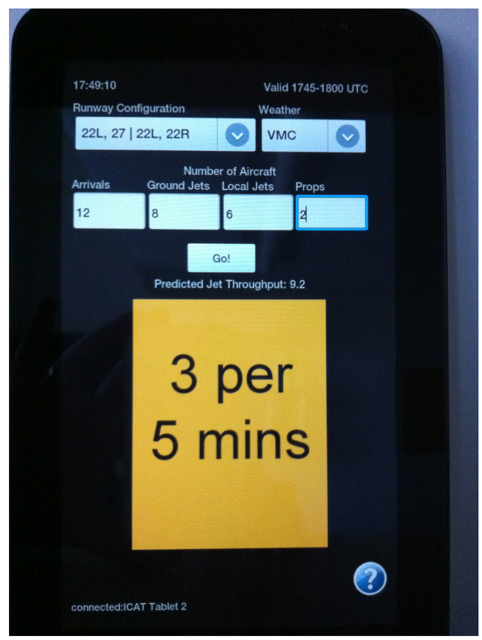

Fig. 5: Rate control transmitter, showing the input interface.

B. Outputs

Once the suggested pushback rate is determined and transmitted, the receiver conveys the information to the BG controller through one of two display modes: the rate control and the volume control displays.

1) Rate control display: In this mode, the output is simply an image of a color-coded pushback rate, showing the number of allowed pushbacks per interval of minutes. With this display mode, the BG controller keeps track of the time intervals and the number of aircraft that have already pushed back. When the demand for pushbacks exceeds the recommended rate, an aircraft is held until the next time interval starts. Again, the BG controller has to keep track of holding the aircraft and then releasing them when the next time interval begins.

2) Volume Control Display: This display mode helps BG controllers keep track of the number of aircraft that had called and been released. It was observed during the field trials in 2010 that many controllers used handwritten notes to keep track of the number of aircraft released, so as not to exceed the recommended rate. The volume control mode helps them with this task, and also provides visual cues of the timeline and upcoming actions.

On the volume control display, the 15-minute time period is broken down into smaller time intervals, based on the rate. For example, if the rate is 3 per 5 minutes, the display shows three rows of three aircraft icons, with each row corresponding to a 5-minute time interval. The current time interval is indicated by a small black arrow to the left of the time interval. Aircraft can only be released during an ongoing time interval. Other positions can only be reserved. Any unused release spots for a given time interval roll over to the next time interval. The following actions are available in the volume control display (illustrated in Figure 6):

1) Releasing a plane: If a flight calls for pushback, one of the aircraft icons in the ongoing time interval is selected. The color of the icon changes from black to gray, indicating that it has been released.
2) Reserving a plane: If a flight calls for pushback and there are no more positions available in the current time interval, the BG controller tells the aircraft to hold and reserves a position for it in a future time interval. This is done by selecting an aircraft icon on the display, which then rotates by 45 degrees to indicate that it has been reserved. When that aircraft is eventually released, the controller clicks on the aircraft icon again; the icon then rotates back and turns gray.
3) Reserving a position in a future time period: An aircraft position for an upcoming 15-minute time period can be reserved by clicking on the white space next to that time period. A rotated aircraft icon then appears in order to indicate a reservation. When the appropriate time period arrives and the suggested rate has been calculated, that aircraft icon will appear already reserved.

C. Tablet deployment

During the 2011 field trials, a member of the research team gathered and inputed data into the rate control transmitter. The rate control receiver was located next to the BG controller, who chose between rate control display and volume control display. It is expected that in an actual deployment, the traffic management coordinator (**TMC**) or the Supervisor would collect and input the data. In half of the test hours, the BG position was staffed by an individual controller, and in the other half, it was merged with another position – clearance delivery or the TMC (Figure 4). The merging of positions was conducted to investigate the potential implementation of PRC without requiring an additional controller at BG, which is typically only functional during times of extreme weather.

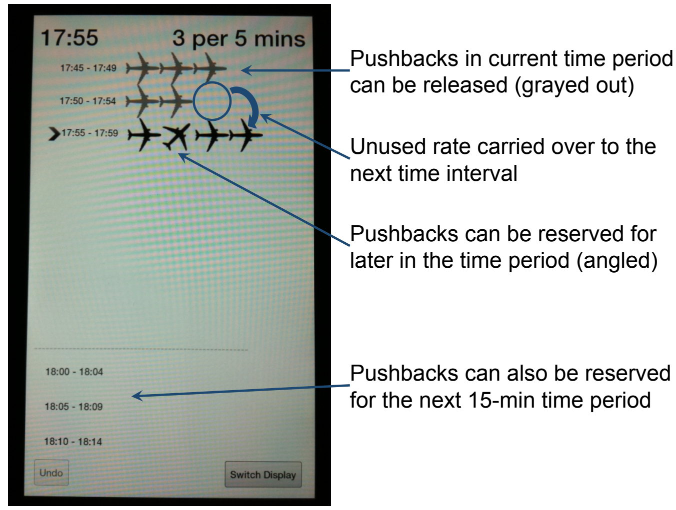

Fig. 6: Actions in the volume control display.

V. Results of Field-testing

Although the Pushback Rate Control strategy was tested at BOS during 19 demo periods between July 18th and September 11th 2011, there was very little need to control pushbacks when the airport operated in its most efficient configuration (4L, 4R | 4L, 4R, 9), or when demand was low. In only eight of the demo periods was there enough congestion for gate-holds to be experienced. A total of 144 flights were held, with an average gate-hold of 5.3 min. During the most congested periods, up to 44% of flights experienced gate-holds.

TABLE I
Summary of gate-hold times for the eight demo periods with significant gate-holds.

Date	Period	Configuration	No. of gate-holds	Total gate-holds (min)
7/18	4.45-8PM	22L, 27 | 22L, 22R	14	28
7/21	5.15-9PM	22L, 27 | 22L, 22R	42	384
7/22	5.15-8.30PM	22L, 27 | 22L, 22R	50	290
7/24	5.15-8PM	4L ,4R | 4L, 4R, 9	12	13
7/28	5.30-8PM	4L ,4R | 4L, 4R, 9	7	13
8/11	5.30-8.15PM	22L, 27 | 22L, 22R	6	9
8/14	5.00-6.30PM	22L, 27 | 22L, 22R	1	1
	6.30-7.30PM	4L ,4R | 4L, 4R, 9	0	0
9/11	5.30-6.30PM	4L ,4R | 4L, 4R, 9	0	0
	6.30-8.15PM	22L, 27 | 22L, 22R	12	23
Total			144	761

A. Congestion control

In this section, we describe the basic results of the Pushback Rate Control field-tests with regard to congestion control.

1) An illustrative example: Here, we examine a day with significant gate-holds (July 21, 2011). Figure 7 depicts the events of the demo period on July 21, divided into 15-minute windows. The top plot shows the demand for pushbacks (that is, the number of aircraft that called for push), the pushbacks that were cleared, and the resulting number of jet aircraft actively taxiing out. The center plots show the throughput predicted by our algorithm and the throughput measured using ASDE-X data. Finally, the bottom plot shows the average taxi-out times and gate-holding times for aircraft that pushed back in each time interval.

From the top plot in Figure 7, we observe that as the number of jet aircraft taxiing-out increases and exceeds 14, gate-holds are initiated in order to regulate the traffic to the desired state. For this configuration, the desired state is 13-14 aircraft on the surface. We see that the algorithm reduces this number, from 15 to 14, and then to 12.

The airport stays in the desired state despite the high variance of the departure throughput (middle plot of Figure 7) and the rounding-off of the recommended pushback rates. An objective of the PRC_v2.1 algorithm is to balance congestion management with predictability (and thus ease of implementation), and this is done fairly well. While the desired traffic level stays within 1 or 2 units of the target value, the recommended pushback rate does not fluctuate excessively, and stays centered around 8 aircraft per 15 minutes throughout the high-demand period, 1930 to 2030 hours.

With regards to the predictability of the pushback control strategy, we also note that the traffic level at the airport was successfully regulated to a similar extent during the high-demand period (1930 to 2030 hours) on all days of the field trials despite the different demand patterns, departure throughput, and the duration and number of gate holds.

2) Runway utilization: A key objective of the field-test was to maintain pressure on the departure runways, while limiting surface congestion. By maintaining runway utilization, it is reasonable to expect that gate-hold times translate to taxi-out time reduction. We confirm that runway utilization was not impacted by the control strategy by validating that the runway queue was always loaded with at least one aircraft. This validation was performed both visually and using ASDE-X data.

3) Translating gate-hold times to taxi-out time reduction and fuel burn savings: The main dimensions of the benefits that we address are the taxi-out time and fuel burn reductions. Intuitively, it is reasonable to use the gate-hold times as a surrogate for the taxi-out time reduction, as long as runway throughput is maintained: Effectively, we trade taxi-out time for time spent at the gate with engines off, as illustrated in Figure 7. We test this hypothesis through simulations of operations with and without metering, similar to the ones done for the 2010 field trials [12]. The simulations show that the total taxi-out time savings equal the total gate-hold times. Thus, the total taxi-out time reduction equals 761 minutes, or 12.7 hours. However, the simulated taxi-out time savings of a particular flight may not necessarily equal its gate-holding time.

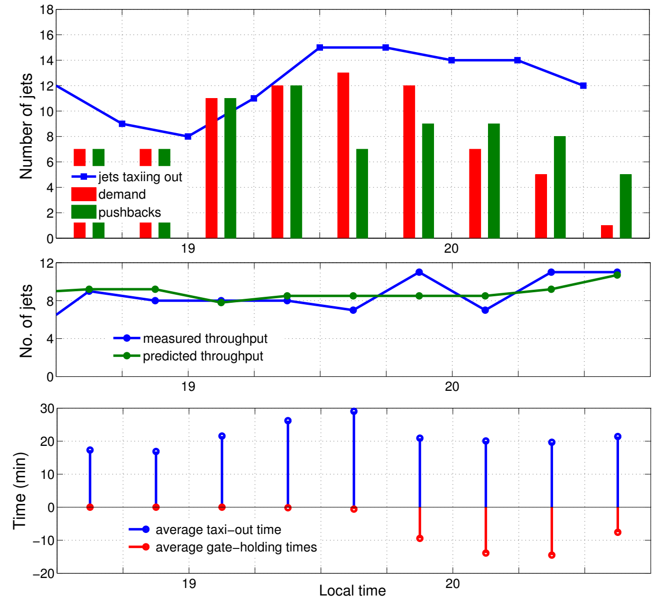

Fig. 7: Surface congestion at each time window, demand and pushbacks during each time window (top), departure throughput measurements and predictions (center) and average taxi-out times and gate holds (bottom) during each time window, for July 21, 2011.

In addition, we conduct a benefits analysis of the fuel burn savings by using the simulated taxi-out time savings times as a first-order estimate of the actual taxi-out time savings using the methodology outlined in previous work [12, 16]. The total fuel savings are estimated to be 2,650 US gallons, which translates to average fuel savings per gate-held flight of about 57 kg.

B. Distribution of benefits

Equity is an important factor in evaluating potential congestion management or metering strategies. The Pushback Rate Control approach, as implemented in these field tests, invokes a First-Come-First-Serve (FCFS) policy in clearing flights for pushback. One would therefore expect that there would be no bias toward any airline with regard to gate-holds incurred, and that the number of gateholds for a particular airline would be commensurate with the contribution of that airline to the departure traffic during the congested periods. Similarly, the gateholds times would be approximately equal to the taxi-time reduction seen by that airline. However, the actual fuel burn benefit also depends on its fleet mix. Figure 8 shows that while the taxi-out time reductions are similar to the gate-holds, some airlines (for example, the ones denoted Airlines 4, 13, 21 and 27) benefit from a greater proportion of fuel savings. These airlines are typically ones with several “Heavy” aircraft during the evening times.

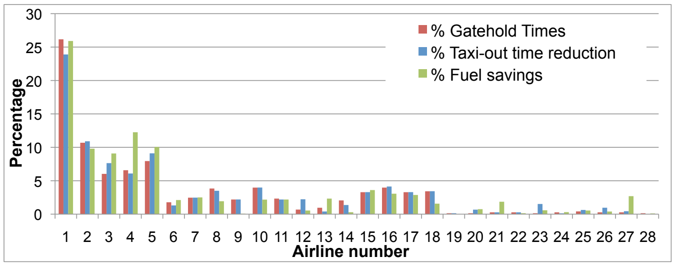

Fig. 8: Percentage of gate-hold times, taxi-out time reduction and fuel burn savings corresponding to each airline.

C. *Takeoff rate prediction*

As explained in Section III, we use the algorithm PRC v_2.1 for predicting the jets takeoff rate. Because of the sources of inaccuracy in both ASDE-X and ASPM data [12], we validated the predictions during shadow testing (Jun 30-Jul 17 2011) by means of visual observations and subsequently used them during the 19 days of the trials to predict the throughput. Table II reports the average error, average absolute error and root mean square error of the predicted throughput (relative to observed throughput) during 182 15-min periods of field testing.

For completeness, the corresponding errors of alternative prediction methods which we could have used are also shown:

- Predictions from PRC v_2.0, that is, the queuing model with the “unconditional” service time distribution in the evenings. This algorithm would input the number of aircraft traveling and queueing into the queuing model to predict the throughput without using arrivals and props demand information.
- Predictions from the demand curves (DC), that is, using Figure 1 for each configuration and weather conditions to predict the takeoff rate based on the total number of departing jets taxiing out.

Finally, we also compare the errors for the 93 periods where the traffic was 10 aircraft or more, because these are the times when gate-holds are most likely.

TABLE II
COMPARISON OF THE ESTIMATOR USED AND TWO ALTERNATIVE ESTIMATORS FOR THE JET AIRCRAFT TAKEOFF RATE.

	All traffic conditions			$\geq$ 10 jets taxiing		
Estimator	ME	MAE	RMSE	ME	MAE	RMSE
PRC v_2.0	-0.09	1.24	1.62	0.08	1.14	1.54
PRC v_2.1	-0.20	1.25	1.64	-0.03	1.14	1.58
DC	0.71	1.32	1.74	0.64	1.18	1.69

Table II shows that the regression tree based prediction algorithm used in PRC_v2.1 predicts the takeoff-rate reasonably well: The mean absolute error is only 1.14 during medium and high traffic conditions (10 jets or more). However, there is little benefit from using the parametrized service time distributions. By using the unconditional evening-times service time distribution, we could achieve the same, or even better prediction accuracy. While this could imply that the parametrized distributions are an artifact of over-fitting, Figure 3 captures an underlying trade-off between jet departure rates, props departure rates and arrival rates. We therefore hypothesize that the small size of the training dataset, or the few test days lead to high prediction errors. Another possible reason for the large variance is that we do not account for some significant hidden variables, such as summer convective weather. The model was trained using mostly non-convective days (November 2010- June 2011), but it was applied during the months of July and August which are subject to high convective activity. In particular, at 53 out of the 182 time windows experienced significant convective weather in the North-East US.

More importantly, we note that the prediction algorithm accuracy is in agreement with the uncertainty considered in the design of the pushback control strategy. For configuration 22L, 27 | 22L, 22R and when at least 10 jet departures were taxiing, the highest underestimation of the takeoff rate was 2.7. The algorithm tries to maintain a queue of at least 4 aircraft for this configuration [14]. Similarly, for configuration 4L ,4R | 4L, 4R, 9 and when at least 10 jet departures were taxiing, the highest underestimation of the takeoff rate was 3.73. For this configuration, the algorithm tries to maintain a queue of at least 5 aircraft. The above observations suggest that the inventory targeted by the algorithm at the queue was set at the correct level in terms of avoiding runway underutilization; a more aggressive congestion control policy would have resulted in an empty runway queue in these two cases. However, a reduction in the variance of the actual or predicted takeoff rate could lead to more aggressive control of the traffic. The importance of a sufficient inventory at the runway queue has also been noted by other researchers [11].

The demand curve based model (DC) has worse jet takeoff rate predictions than the other two models, and tends to overestimate the throughput. This model was trained with ASDE-X data, which underestimates the traffic levels because of the delay between the actual pushback and ASDE-X capture times [12]. A purely statistical predictive model therefore yields high errors reflecting ASDE-X measurement errors.

VI. EVALUATION OF THE DECISION SUPPORT TOOL

A survey of the controllers was conducted to gather their opinions on the study as a whole, and specifically on the implementation and use of the tablet. The survey was presented to the controllers after the field-tests had been completed. There are 21 respondents in total, 15 of whom were BG in 2010, 13 in 2011, and 12 during both years.

We solicit quantitative ratings on five topics: Whether they thought fuel burn decreased, whether surface traffic flows improved, whether throughput was adversely impacted, whether the new (tablet) display was easier to use that the color-coded cards used in 2010, and whether they found the new display easy to use. The histograms of the results are shown in Figure 9. We see that the survey responses are generally positive, and that the controllers like the new tablet displays as well. We also hypothesize that there may have been some confusion about the scale on the question of throughput, since several of the controllers who agree that the throughput was adversely impacted also agree that the surface traffic flow improved. This correlation suggests that there may have been some confusion due to the reverse scale on this question.

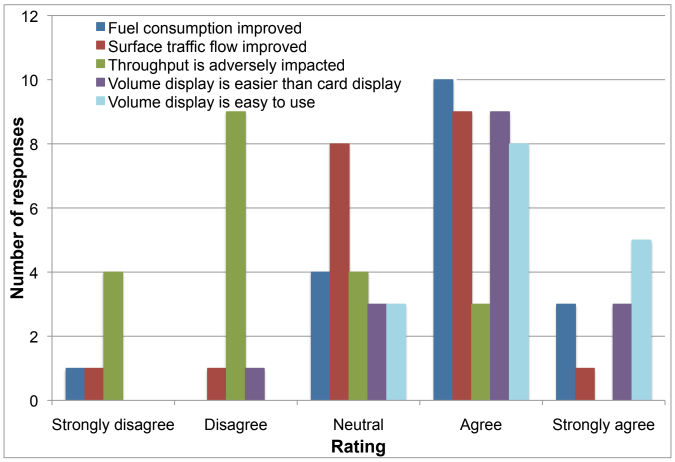

Fig. 9: Histogram of responses from air traffic controller survey regarding Pushback Rate Control at BOS.

Thirteen responses are also positive about combining BG and another position. Ten of these responses suggest Clearance Delivery, three indicate the TMC, and one each indicate Ground Control and Flight Data (more than one position could be indicated). The survey also shows that the controllers like the tablet volume control display format a lot. Among the comments on the best features are: "the ability to touch planes", "reserve spots", "count the planes and account for aircraft with long delays", "allows me to push & tells me to hold", and "easy to use & understand". Suggestions for improvement include increasing the icon sizes and maintaining more pressure on the runway. Finally, the controllers are satisfied with the modifications between 2010 and 2011, with one of them remarking: "Liked the improvement in just one year".

VII. Qualitative Observations

A. *Compatibility with traffic flow management initiatives*

An important goal of this study is to investigate the compatibility of Pushback Rate Control with traffic flow management initiatives. Under highly convective weather, the abundance of these programs leads to many target departure times, schedule disruptions or flight cancellations. As a result, congestion does not build up, and there is no metering.

However, there are days during which the traffic management programs do not lower demand significantly. July 18 was one such day. There were two Minutes-In-Trail (MINIT) programs during the departure push of this day: All westbound flights had 5 MINIT between 2245 and 2335 hours, and 3 MINIT between 2335-0030. At the same time, there was a 5 MINIT restriction for all flights over LUCOS. These programs spread out the departures, and decreased the opportunities for metering, but did not lower the overall departure demand. This resulted in a combination of the MINIT programs and the congestion metering program between 2245 and 2300 hours. The integration of the two programs was very simple and effective: The total number of flights released per time window was set by the metering program, and the mix by the MINIT program. For example, if the pushback rate were 3/5 min while westbound flights had 5 MINIT, the controller would release two flights with no MINIT restrictions along with a westbound departure. Similarly when the pushback rate was 4/5 min, the controller would release three flights with no MINIT restrictions along with a westbound departure.

The field tests also showed that the approach is capable of handling target departure times (e.g., EDCTs), but for that it is preferable to get EDCTs while still at gate. Flights with EDCTs were generally exempt from gateholds. However, on days in which the Gate and TMC positions were merged (for example, July 21), delays due to the controlled departure times could be absorbed as gate-holds. During the July 21 demo period, two flights with EDCTs called for push when gate-holds were in effect. The controller informed them that gate-holds are in effect, asked them to hold their push and called the appropriate centers to obtain their controlled departure times. Subsequently, he released them from their gate so that they could takeoff at their assigned times. Both flights took off a minute before their assigned times. In this way, the flights with EDCTs absorbed their delays at the gate and saved fuel, and were integrated with the rest of the traffic after pushback clearance. This made it easier for the controller to handle them and ensure that they met their controlled departure times.

B. *Increased predictability*

An additional benefit of the approach is the ability to communicate expected pushback times to pilots in advance. For instance, on July 21, more than 10 aircraft were on hold at the beginning of the periods 2000-2015 hours and 2015-2030 hours. Once the suggested pushback rate was given to the controller at the start of each time period, the controller communicated the expected release times to all aircraft on hold. These flights received their release times several minutes in advance, which could be useful in planning ground resources.

C. *Natural metering effect*

The suggested pushback rate in very low congestion time-periods is 1 per min. However, we noticed that the merging of the BG position with another position resulted in a natural rate of 1/min without explicit gateholds. For example, when the BG position was merged with the TMC, after the controller cleared an aircraft that called for push, he/she would have to spend the rest of the minute for a traffic management task (such as, calling the center to obtain an EDCT). As a result, the next aircraft would only be released after a minute, resulting in a natural metering of 1 per min unless a lower rate was recommended.

This effect offers a good opportunity for the operational deployment of a metering scheme at no added personnel cost. The gate position could easily be merged with another position, such as Clearance Delivery or the TMC.

VIII. Conclusions and Next Steps

This paper presents the results of the demonstration of Pushback Rate Control at BOS in 2011. We developed a Pushback Rate Control algorithm using dynamic programming to balance the objectives of maintaining runway utilization and limiting surface congestion. We also developed and field-tested a decision support interface to display the suggested pushback rate, which helped the controllers keep track of requests for pushback, gate-holds, and other metering constraints. During 8 four-hour tests conducted during the summer of 2011, fuel use was reduced by an estimated 9 US tons (2,650 US gallons), while carbon dioxide emissions were reduced by an estimated 29 US tons. Aircraft gate pushback times were increased by an average of 5.3 minutes for the 144 flights that were held at the gate. Finally, a survey of the air traffic controllers involved in the 2011 demo indicated support for the Pushback Rate Control approach, the manner of implementation, and the displays and communication protocols developed for the deployment of such strategies.

Future research would include the investigation of more flexible and advanced pushback policies, as well as the evaluation of the value of information (such as, a more accurate pushback schedule or departure route availability) in more refined control strategies.

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