Determination of Minimum Push-Back Time Predictability Needed for Near-Term Departure Scheduling using DEPARTS

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Abstract

This paper describes the functionality of the Departure Enhanced Planning And Runway/Taxiway-Assignment System (DEPARTS), and how this functionality could potentially help reduce taxi-out times at Hartsfield Atlanta International Airport (ATL). DEPARTS generates optimized recommendations on runway assignment, departure sequencing and departure fix loading for the air traffic control tower to reduce taxi-out times. DEPARTS has initially been developed as a concept exploration laboratory prototype for ATL.

This paper analyzes the effect of improved predictability of ready-to- push-back times and of the availability of real-time surface event data (i.e., actual push-back and taxi clearance times) on the potential operational benefit of pre-departure planning. Interim results are given, which will be completed after additional simulation experiments are performed. Operational issues in the improvement of ready-to-push-back time predictability are outlined.

Introduction

This research was motivated by CAASD participation in the RTCA Select Committee for Free Flight Implementation, 2003-2005 Capabilities Working Group [1]. One of the main areas identified for new research was to determine the relationship between the potential to improve the utilization of departure capacity with the predictability of planned push-back times. No system is currently being used at an airport to schedule runway assignments and to determine the departure runway sequence for future push-backs. The background and motivation for this research, as well as a high level description of the DEPARTS tool itself and how its capabilities might operationally be used, have been described in detail in a previous paper [2].

Other research efforts in the area of departure planning have been presented in the literature. For example, CAASD developed an early laboratory prototype of a departure planning tool for New York La Guardia Airport [3]. Researchers at MIT have written several papers on an overall departure planning architecture and on analysis of departure issues at Boston Logan Airport [4,5,6].

The key research questions addressed in this paper are: (1) by how much would the predictability of push-back times have to be improved in order to reduce taxi-out times through more accurate departure scheduling and (2) what additional operational information is needed to achieve this schedule predictability improvement. The quantitative benefits achievable by improving predictability should motivate the determination of answers to the second question.

The authors would like to thank the following FAA managers at the air traffic control tower/approach control located at Atlanta Hartsfield International Airport (ATL): Mr. Stanley Zylowski, the facility chief, and Mr. T.C. Meuninck, the developer of the Airport Resource Management Tool (ARMT). Both provided invaluable insights into the operations at ATL, as well as the ARMT data used as the basis for this research. The authors would also like to thank Mr. Carl Burke and Mr. Ho Yi of MITRE, who made substantial contributions to the implementation of the DEPARTS prototype.

Taxi-Out Time

The objective for near-term departure scheduling is to minimize the average taxi-out time over the next 10 to 30 minutes, to get flights into the air from the airport as early as possible without causing downstream traffic congestion in the terminal or en route airspace. Scheduled flights have pre-specified routes, including a departure fix, although that planned route can manually be changed prior to take-off. Ready-to-push-back time is typically not recorded for a flight, so actual push-back time is used as a surrogate. Taxi-out time is defined here as the elapsed time between the time at which a flight actually pushes pack from its gate and the time at which it is cleared for take-off.

Conceptually, taxi-out time has five major components:

1. *unimpeded taxi time*: the unimpeded taxi time from the departure gate to the departure runway threshold. This component is a function of the taxi-path chosen for that flight. This component is affected by the runway assigned to the aircraft, assuming that multiple runways are available for departures.
2. *additional waiting time caused by excess departure demand*: the waiting or queuing delay caused by the current departure demand exceeding the departure capacity. This component is solely a function of user scheduling to meet their business considerations and can only be ameliorated by reducing the scheduling of flights during peak periods. The sum of this and the previous component can be described as the minimal taxi-out time with perfect planning.

3. *additional waiting time caused by traffic flow management constraints:* this component affects specific flights delayed due to traffic flow restrictions. These restrictions, such as the metering of flights over a specific departure fix, are needed to reduce specific traffic flows departing an airport due to resource constraints in the departure terminal airspace, en route airspace, arrival terminal airspace or arrival airport. These constraints are external to the departure airport, but must be considered when scheduling flights from push-back to take-off. This component can be affected by departure planning. For example, a flight dispatcher may decide to change the departure fix in the filed flight plan if this change will avoid encountering a traffic flow constraint such as a Miles-In-Trail (MIT) constraint.
4. *additional waiting time caused by imprecise planning*: additional waiting time is caused by use of departure capacity in such a way that potentially available runway departure slots are wasted. This extra taxi-out time is caused when flight events are not scheduled from push-back to take-off to maximize the utilization of the available capacity and hence to minimize taxi-out time to the smallest level possible, given the departure demand, traffic flow restrictions in place and the available airport departure capacity. DEPARTS generates an optimal plan given the input information it receives, and so excludes this taxi-out time component.
5. *additional waiting time caused by unpredicted response to an existing plan*: This extra time is caused by the fact that an aircraft will not precisely follow an existing plan, having a different actual push-back or taxi-out time than that included in the near-term departure plan. This added waiting time will always exist, as unpredictable events happen, and as the information made available to a scheduling tool such a DEPARTS does not incorporate all factors that can affect push-back and taxi-out times. This component of taxi-out time is the primary focus of this research. This additional waiting time is reduced as the predictability of the push-back times is improved. Perfect prediction of these planned times would reduce this additional waiting time to zero.

Traffic managers, ramp controllers and air traffic controllers make a number of decisions to control departing flights, from assigning the departure runway, assigning a gate push-back time, setting a ramp exit sequence, or a final departure runway lineup sequence. The departure sequence for a runway is important as the minimum time between departures to avoid wake turbulence depends on the weight class of the leading and trailing aircraft. For example, the minimum time for a small aircraft following a heavy aircraft is longer than the time for a small aircraft to follow a small aircraft. Optimal assignment of a flight to a runway and optimal sequencing of flights to a departure runway can thus reduce the time required to depart flights. It is assumed that the optimal runway assignment and sequencing can be determined within 10 to 30 minutes before a flight is ready-to-push-back. This is because the actions that the traffic manager, ramp controller and air traffic controller need to perform do not need to be planned very far in advance to optimize the taxi-out time for a specific flight. Also, in practice flight plan information is not provided until about 30 minutes prior to the ready-to-push-back time, so planning prior to this time would less accurate.

DEPARTS Prototype

The Departure Enhanced Planning And Runway/Taxiway-assignment System (DEPARTS) laboratory prototype is being developed by CAASD. DEPARTS is a near-term scheduling model that will recommend optimal runway assignment, taxi clearance and takeoff clearance times for individual departures. DEPARTS is a decision support tool that depends on the existence of a near-real time airport information management system to provide its key inputs, and does not itself collect this information. This prototype has been developed initially for ATL, based on:

- ATL's independent parallel runway operations for arrivals and departures
- The availability of a unique set of airport and flight status information from ARMT.

ARMT incorporates flight status data from the Atlanta Surface Movement Advisor (SMA), a prototype developed for ATL by NASA Ames Research Center in conjunction with the FAA and the major airline users at ATL. ARMT gathers additional flight information from the ATL Automated Radar Terminal System (ARTS) and the manual scanning of bar coded paper flight strips at the ATL air traffic control tower. This manual bar code scanning is used to produce a near real-time recording of taxi clearance and takeoff clearance times. ARMT also captures the traffic flow management constraints, airport configuration and weather conditions currently in effect.

At ATL, the air traffic control tower assigns flights routed via a specific departure fix to a specific runway. The set of runway assignments for the eight ATL departure fixes is referred to as a "departure split". The eight departure fixes, which are located just inside the boundary of the associated terminal airspace, are North One (N1), North Two (N2), East One (E1), East Two (E2), South One (S1), South Two (S2), West One (W1) and West Two (W2).

DEPARTS can optimize a set of actions for all flights departing in the next 10-30 minutes in about a minute of run time. DEPARTS algorithms are intended to ultimately be used in near real-time to recommend the:

- traffic flow management actions to change the current departure split, which determines the runway assignment for each flight
- ramp control tower and air traffic control tower actions with respect to flight push-back times, ramp exit times and expected takeoff times
- departure fix crossing times which are based upon a standard transit times from take-off to fix crossing for that departure split and aircraft type. DEPARTS currently optimizes taxi-out times for ATL, not departure fix crossing times, as the ATL standard transit times have not been adapted to date, even though the model capability exists.

DEPARTS does not explicitly model flight trajectories in the terminal area, but incorporates all traffic flow constraints applied to departures. The DEPARTS technology is intended to provide recommendations, not to replace the human decision-making process. DEPARTS is currently a laboratory research tool, and has not been evaluated in the field.

The following three figures show the sample screens for the primary outputs of DEPARTS, as adapted to ATL. All figures are from the same scenario (i.e., set of user inputs) and time horizon (i.e., same starting and ending time). The data displayed in these three figures is from an actual DEPARTS model run, for illustration only.

Figure 1, the split comparison table, provides the expected taxi-out times, takeoff delays from unimpeded taxi-out times and runway load balance information by runway for the best set of departure splits identified by DEPARTS. The "name" column is the split name typically used by ATL tower, while the "cat" column is the split category: Current, Standard or Non-standard. Standard splits are those which separate the traffic in the TRACON, so that no flight need cross the path of a flight from the opposite runway. Only standard splits have been used for the analysis described later in this paper. Each departure split is identified by the runway assignments given for each departure fix in the eight columns labeled "N1", "N2",…, "W2".

The "Obj Value" column contains the optimal objective function value for each split, which operationally equivalent to the sum of the taxi-out times for each flight with a scheduled push-back time during the projection horizon (in seconds). "NE/SW" is the standard split with the best objective function value in this table. The remaining columns in the table give the maximum and average takeoff delays overall, the delays for each runway (North and South), and the resulting number of departures scheduled for each runway. Takeoff delay is calculated as the difference between the predicted taxi-out time and the unimpeded taxi-out time for that flight, over a specific taxi path.

Figure 2, the takeoff delay by split graph, provides the expected cumulative takeoff delay in minutes (Y-axis) by scheduled push-back time in minutes (X-axis) for each split as a different line graph. The cumulative takeoff delay at time t is the sum of the total taxi-out delay for all flights that are predicted to push-back between time zero, the beginning of the planning horizon, and time t. In this figure, the "NE/SW" split is predicted to give the least cumulative takeoff delay when looking at a 20-30 minute planning horizon. This split would be selected if it was to be used for all flights that push back in the following 20-30 minutes.

Figure 3, the recommended departure sequence table, shows a table of the recommended runway assignments for each flight in the model horizon, the recommended times for the various events from push-back to takeoff clearance, and the actual push-back delay and estimated takeoff delay. Push-back delay occurs if a flight actually pushes back from the gate after its scheduled departure time. DEPARTS does not currently project push-back delays. Large push-back delays typically occur when a flight is held for connecting passengers or an equipment problem occurs. The adverse effect of push-back delays on departure planning can be mitigated by adjusting the scheduled departure time for a flight when the delay is first anticipated, so the scheduled push-back time reflects the actual anticipated ready-to-push-back time.

The key advisory information produced by DEPARTS in this table are the recommended runway assignment, predicted taxi clearance times and takeoff clearance times. The columns in the table to the left of the taxi clearance time, with the exception of runway (listed as (N)orth or (S)outh in the table) are all input to DEPARTS, while the other columns are calculated by DEPARTS.

Split Comparison

Scenario: Baseline with MITs
Starting: 2000/08/01 19:15:00
Ending: 2000/08/01 19:45:00

Name	Cat	N1	N2	E1	E2	S1	S2	W1	W2	Obj Value	Max Delay	Avg Delay	N Deps	N Max Delay	N Avg Delay	S Deps	S Max Delay	S Avg Delay
NW/SE	C	N	N	S	S	S	S	N	N	154527.355273	18:30	03:46	32	13:31	04:38	23	18:30	02:34
NE2W1/SE1W2	N	N	N	S	N	S	S	N	S	153352.537091	18:30	03:22	29	13:15	03:42	26	18:30	03:00
EN1W1/SN2W2	N	N	S	N	N	S	S	N	S	153370.279273	18:30	03:14	28	13:45	03:30	27	18:30	02:57
EN1S2W1/N2S1W2	N	N	S	N	N	S	N	N	S	153383.804364	18:30	03:15	29	13:45	03:24	26	18:30	03:04
NS2E2W1/S1E1W2	N	N	N	S	N	S	N	N	S	153401.483273	18:30	03:24	30	14:02	03:37	25	18:30	03:07
NE1W1/SE2W2	N	N	N	N	S	S	S	N	S	153476.503273	18:30	03:18	28	13:05	03:45	27	18:30	02:50
EN1S2/WN2S1	N	N	S	N	N	S	N	S	S	153720.193091	18:30	03:14	24	12:59	03:30	31	18:30	03:02
NE/SW	S	N	N	N	N	S	S	S	S	153478.026909	18:30	03:12	28	12:59	03:34	27	18:30	02:50
NE1W2/SE2W1 (v18)	S	N	N	N	S	S	S	S	N	153606.778182	18.30	03.18	31	12.44	04.07	24	18.30	02.15
NW2/SEW1	S	N	N	S	S	S	S	S	N	154090.333818	18:30	03:32	27	12:45	04:27	28	18:30	02:39
NE1/SWE2	S	N	N	N	S	S	S	S	S	154465.973091	18:30	03:29	23	12:29	03:59	32	18:30	03:08
NWE1/SE2	S	N	N	N	S	S	S	N	N	155080.556727	18:30	03:51	36	14:04	04:33	19	18:30	02:31
NEW2/SW1	S	N	N	N	N	S	S	S	N	155439.203273	18:30	03:51	36	13:46	04:32	19	18:30	02:35
N/SEW	S	N	N	S	S	S	S	S	S	157059.453818	18:30	04:21	19	12:29	04:49	36	18:30	04:06

Figure 1. Split Comparison Table

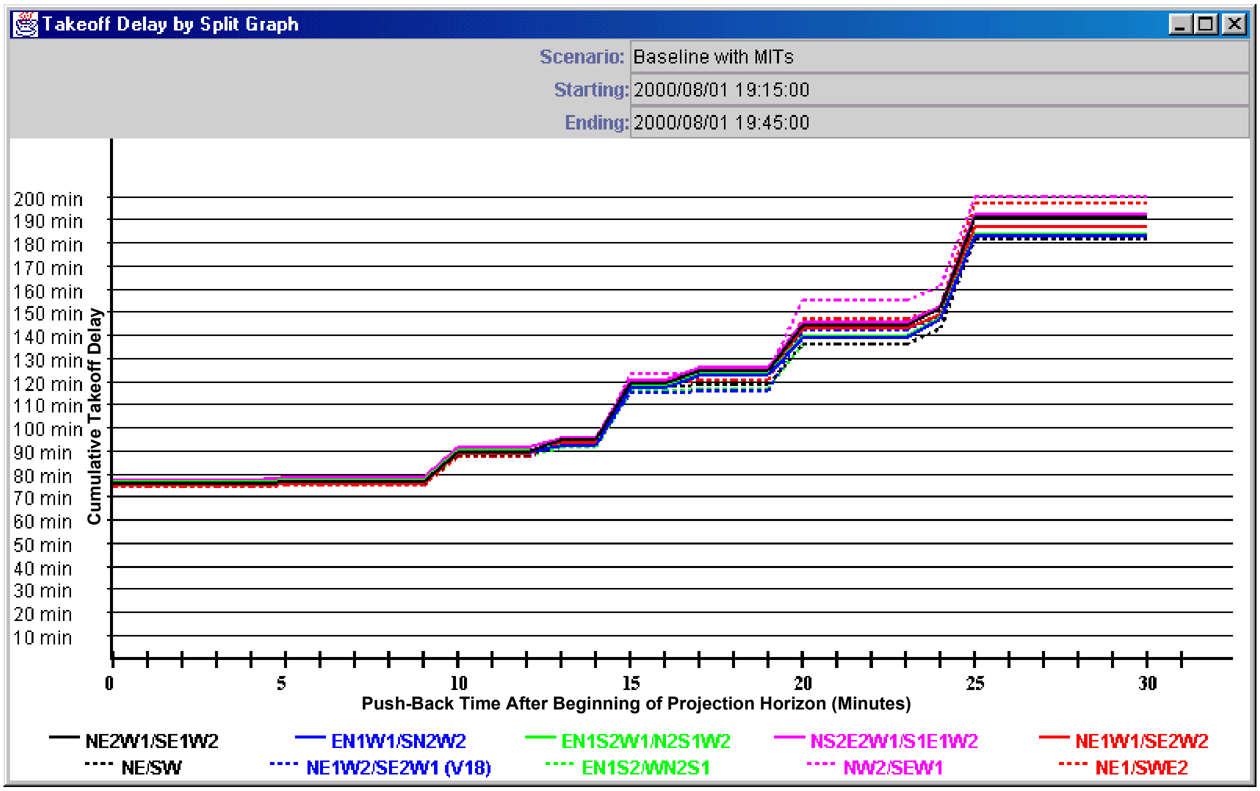

Figure 2. Takeoff Delay by Split Graph

Recommended ATL Departure Sequence

Scenario: Baseline with MITs
Split: NE/SW
Starting: 2000/08/01 19:15:00
Ending: 2000/08/01 19:45:00

ACID	Type	Class	Gate	Ramp	Rwy	DTA	Dest	Sched Depart	Push Back	Taxi Clear	Takeoff Clear	Push Back Delay	Take off Delay
MDW44	CARJ	L	D05	5	N	E2	RDU	19:40:00	19:40:00	19:45:18	19:50:06	00:00	00:00
MEP106	DC9Q	L	C29	4	N	N1	MKE	19:05:00	19:10:07	19:13:05	19:18:23	05:07	00:00
TRS20	B712	L	C16	3	N	N1	MDW	19:10:00	19:15:00	19:19:00	19:24:55	05:00	00:00
TRS374	DC9	L	C01	4	N	N1	MLI	19:15:00	19:15:00	19:20:18	19:29:55	00:00	04:19
TRS200	DC9	L	C06	3	N	N1	DEC	19:15:00	19:15:00	19:20:16	19:34:55	00:00	08:44
DAL802	MD80	L	T03	1	N	N1	ORD	19:10:00	19:15:00	19:20:06	19:40:25	05:00	12:59
DAL1569	B72Q	L	B32	2	N	N1	SDF	19:25:00	19:25:00	19:27:41	19:45:25	00:00	11:19
CAA626	CRJ2	L	C21	4	N	N1	FWA	19:30:00	19:30:00	19:33:27	19:50:53	00:00	12:08
AAL1263	F100	L	T11	1	N	N1	ORD	19:39:00	19:39:00	19:42:03	19:55:53	00:00	06:30
UAL1459	B72Q	L	T11	1	N	N1	ORD	19:40:00	19:40:00	19:43:03	20:00:53	00:00	10:30
DAL1916	MD80	L	B22	2	N	N2	CMH	19:00:00	19:01:00	19:08:49	19:15:14	01:00	03:56
CAA63	E120	S	C29	4	N	N2	CRW	18:10:00	19:06:00	19:11:01	19:20:20	56:00	06:04
TRS956	DC9	L	C11	4	N	N2	CAK	19:10:00	19:15:00	19:19:16	19:25:42	05:00	01:08
TRS910	DC9	L	C14	3	N	N2	DAY	19:25:00	19:25:00	19:29:06	19:35:41	00:00	00:40
USA1720	B73Q	L	D29	5	N	N2	PIT	19:28:00	19:28:00	19:31:33	19:41:12	00:00	04:51
CAA193	AT72	L	C35	4	N	N2	TRI	19:40:00	19:40:00	19:42:39	19:47:57	00:00	00:00
TRS552	DC9	L	C03	4	N	N2	BUF	19:40:00	19:40:00	19:45:06	19:53:14	00:00	02:50
DAL1932	MD80	L	T07	1	N	N2	BOS	19:40:00	19:40:00	19:43:58	19:58:14	00:00	06:56
NWA9710	DC9Q	L	D16	4	S	S1	ATL	18:25:00	19:12:17	19:15:29	19:21:00	47:17	00:37

Figure 3. Recommended Departure Sequence Table

Sensitivity of Taxi-Out times to Input Parameter Predictability

The operational benefits obtained by using the departure plan recommended by DEPARTS algorithms will depend on the predictability of the ready-to-push-back times. Differences between the actual ready-to-push-back times and the previously predicted ready-to-push-back times would change the basis from which the departure plan was determined, and this departure plan may no longer minimize the taxi-out time realized.

To analyze the sensitivity of operational benefits as a function of push-back time predictability, a modeling approach is taken that:

- simulates different predictability levels of push-back times
- incorporates the actual traffic demand data and airport configuration and capacities
- uses the actual median inter-departure times for each pair of leading and following aircraft weight class, based on actual operational data
- models push-back time prediction error using random samples from an empirical distribution
- uses the DEPARTS model to generate different outcomes with different days of operation
- constructs a functional relationship between average taxi-time for the demand periods used and the predictability of push-back times

The DEPARTS model was embedded in a simulation model to estimate the statistical effect of different levels of ready-to-push-back time prediction errors on the distribution of the resulting achieved taxi-out times over an entire day. Different simulations were made at 0%, 20%, 40%, …, 140% of the push-back time Mean Absolute Prediction Error (MAPE). The technical details of these randomized simulations are discussed in the next section.

MAPE is defined in the following equation:

$$MAPE = \left(\sum_{i=1}^{n} | PPE_i |\right) / n$$

where:

n = number of push-backs scheduled during time period
i = departure flight index
$PPEi$ = push-back time prediction error for departure i
$PPE_i = APT_i - SPT_i$
APT_i = actual push back time for departure i
SPT_i = scheduled push-back time for departure i

Each ATL operational day was modeled as starting at 10:00 Greenwich Mean Time (GMT) and ending at 04:00 GMT on the following day. No operational benefit is achieved by optimizing departure schedules during the other six hours of the day when departure demand is less than departure capacity. Each operational day was modeled as a series of DEPARTS model runs, each with a ten minute projection time horizon. This simulation was done using the following two steps for each of the 108 ten-minute projection time periods for each scenario on each operational day:

1. *Choose Optimal Departure Split Given Predicted Push-Back Times*: Based on the scheduled push-back times, use DEPARTS to choose the optimal departure split and resulting takeoff clearance times (i.e., departure sequence) that will minimize the total taxi out time for the period. The scheduled departure times used in each simulation are calculated as a sum of the actual ARMT departure time plus a random error chosen from an empirical distribution for that scenario, as discussed in the next section.
2. *Choose Optimal Departure Sequence Given Actual Push-Back Times and Split Chosen*: Based on the optimal departure split chosen in the previous step and the actual departure times realized, use DEPARTS to simulate the departure sequence that will actually be achievable by a highly competent ground controller. The departure split fixes the departure runway used by each flight. The projection time horizon is incremented by ten minutes after the second step is completed.

In both steps, flights with simulated takeoff times that occur after the end of the time horizon are treated as flights taxiing from the gate to their assigned departure runway at the beginning of the next time period.

DEPARTS fully optimizes a departure schedule given the scheduled departure times in the first step, and optimally sequences the flights given their actual push-back times and pre-determined runway assignment in the second step. The second step employs a more restricted version of the optimization model. In the second step, the optimization is restricted to not reorder two flights in a runway departure sequence from their original First In First Out (FIFO) sequence if their expected queue arrival times are more than two minutes apart. The queue arrival time is defined as the earliest time at which a flight could take-off from a specific runway if it could taxi unimpeded from its departure gate to the runway threshold. The matching of the restricted optimization's behavior and actual ATL controller behavior has been calibrated in part with existing data and considered adequate for this sensitivity analysis but has not been operationally verified.

The results of this simulation experiment are summarized in Figure 4. This graph depicts daily average taxi-out benefit over the actual average ARMT taxi-out time for that date (Y-axis) as a function of the MAPE (X-axis). The daily average taxi-out benefit is calculated as:

$$\sum_{i=1}^{n} (actTOT_i - simTOT_i) / n$$

where:

n = number of push-backs scheduled during operational day
i = departure flight index
$actTOT_i$ = actual ARMT taxi-out time for flight i
$simTOT_i$ = simulated taxi-out time for flight i

A different daily average taxi-out time benefit is plotted for each operational day, MAPE level and random replication. 21 August 2000 was a Monday in which ATL operated an east-bound runway configuration, with 1186 departures during the operational day. 28 August 2000 was a Monday in which ATL operated a west-bound runway configuration, with 1232 departures during the operational day. Two replications for 21 August and one replication for 28 August are depicted. In addition, the average across both replications for 21 August is plotted in black.

Note that there is only one replication for the 0% MAPE case, as the prediction errors for all departures are zero. For 21 August there is a 0.36 minute average reduction in taxi-out time when the MAPE is decreased from 100% to 0% of the average MAPE (0.45 minute for 28 August). For both days, about half of the benefit of lowering MAPE occurs when the MAPE is reduced from 20% to 0%. Additional operational dates, additional randomized replications, and experiments with MAPE greater than 140% are needed to confirm these results. These additional experiments are underway.

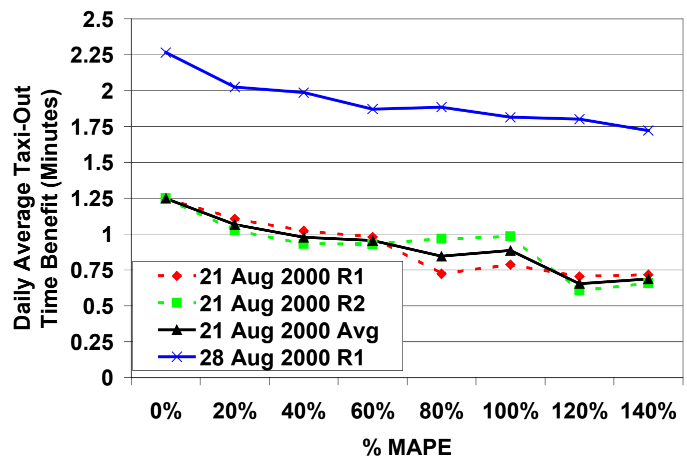

Figure 4. Taxi-out time Sensitivity to Push-Back and Taxi-Out Prediction Errors

The average taxi-out delay, as measured by ARMT for these two operational days was 15.8 minutes for 21 August and 19.1 minutes for 28 August. Repeated experiments have indicated that DEPARTS benefits increase during days with higher average actual taxi times.

These simulation results are relative to the ATL MAPE. It is likely that the average taxi-out time benefit across different airports is directly proportional to the reduction in each airport's absolute MAPE level. This hypothesis needs to be tested after DEPARTS has been adapted in the laboratory to model airports other than ATL. Figure 5 shows the standard deviation of push-back time prediction error at 15 major U.S. airports, based on August 2000 Airline Service Quality Performance (ASQP) data. Flights pushing back more than two hours after their P-Time have been removed from the data set. ATL is at the high end of the range in predictability, with a 31.6-minute standard deviation (SD), while Washington Dulles (IAD) is at the low end of the range of predictability, with a 52.4 minute SD.

Airport	Prediction Error Standard Deviation
IAD	52.4
JFK	47.4
LGA	46.9
EWR	46.3
ORD	42.5
BOS	37.8
PHL	37.4
SFO	36.0
DTW	32.5
PHX	32.5
LAX	31.8
ATL	31.6
MSP	28.5
DFW	27.4
STL	27.2

Figure 5. 15 Major U.S. Airports Ordered By Prediction Error Standard Deviation

Scenario name	Ready-to-push-back times known?	Actual push-back and clearance times known?	Daily Average Taxi-Out Benefit
Ten minute ready-to-push	10 minutes prior	yes	1.25 minutes
Five minute ready-to-push	5 minutes prior	yes	0.85 minutes
Zero minute ready-to-push	not known	yes	0.38 minutes
Baseline airport data only	5 minutes prior	no	-0.35 minutes

Figure 6. Daily Average Taxi-Out Benefit for Non-Randomized Simulation Experiments

A separate set of non-randomized experiments was performed using 21 August 2000 data. For these experiments actual scheduled ready-to-push-back times were used, i.e., no randomized errors were used. The conditions and daily average taxi-out benefit for each of these experiments are summarized in Figure 6.

For the ten, five and zero minute ready-to-push scenarios, actual push-back times were used for push-backs occurring during the first ten, five and zero minutes, respectively, of each ten minute "choose optimal departure split" step. The scheduled push-back times were used for the remainder of the departures. For the "choose optimal departure sequence" step, actual push-back times were used for all departures, as for the randomized scenarios. The reduction in benefits from the 10 to 5 to zero minute ready-to-push scenario reflects the corresponding increase in push-back time prediction error. These scenarios reflect the observation that it should be operationally easier to predict push-backs that will occur at times nearer the current time. For example, it should be easier to predict an accurate ready-to-push-back time five minutes in the future than a time ten minutes in the future.

It should be noted that the daily average taxi-out time benefit for the zero minute ready to push case for 21 August (0.38 minutes) is different than the benefit for the 100% MAPE case in the randomized runs above (0.89 minutes). The significant difference between these simulations is that the zero minute ready-to-push scenario used actual prediction errors for August 21 for all flights, while the randomized runs used a random sample of all of the prediction errors from August 2000 after statistical outliers were removed. This difference will be investigated further after additional randomized experiments are completed.

The last scenario in Figure 6, "baseline airport data only", shows the potential benefit of using the DEPARTS model with no advance knowledge of ready-to-push-back times other than the P-times. In addition, this scenario simulates the effect of having no surface departure flight information other than the scheduled push-back time, departure gate and the actual radar acquisition time. The flight plan, scheduled push-back time and departure radar acquisition time can be derived from information contained in the Enhanced Traffic Management System (ETMS). It should be noted that when this scenario has been run for other dates in August 2000 it has shown a positive benefit. Additional dates must be run to confirm the absolute DEPARTS benefits at ATL.

Simulation Methodology

The source of predicted push-back times for a flight is the P-Time contained in the flight plan filed for that flight. For ATL departures during August 2000 the average P-Time is about 6.8 minutes earlier than the average actual push-back time, both as recorded in ARMT, after outliers were removed, as discussed below. This 6.8 minutes difference is a statistical bias that can be removed by using an adjustment factor. Removing this bias improves the MAPE of the resulting scheduled push-back time over that of the original P-Time. The unbiased scheduled push-back times are used in the simulation for all experiments, as this adjustment would be done whether current or improved P-times were used.

Given the data set of 19,652 observations of push-back time prediction errors for August 2000, after 1066 outlier observations with values outside the range of -60 minutes to +60 minutes were discarded, we generated probability distributions of data corresponding to improved ready-to-push-back time predictability. As discussed previously, we used the MAPE as the figure of merit for this analysis. We generated distributions corresponding to 20%, 40%, …, 140% of the real-world MAPE.

The first step of this process was to attempt to model the data as being drawn from a classical distribution. The data has two modes (two "humps", one lower than the other), and might be a mixture of Gaussian distributions. Although the visual fit of the data vs. a mixture of two Gaussian distributions looked satisfactory, the Chi-Square goodness-of-fit test failed strongly (the null hypothesis that the data were drawn from a mixture of two Gaussian distributions was rejected at $p<0.00001$).

An alternate approach was undertaken. Using basic probability theory, it is possible to induce a new mean and standard deviation into the sample via a transformation:

$Z_i = (X_i – XBAR)/SD$
$X_i' = (Z_i * SDnew) + XBARnew$

where:

X_i = original push-back prediction error
XBAR = mean push-back prediction error calculated from sample
SD = standard deviation of the push-back prediction error calculated from sample
Z_i = standardized push-back prediction error
SDnew = desired standard deviation for transformed push-back prediction error
XBARnew = desired mean for transformed push-back prediction error
X_i' = transformed push-back prediction error

The goal of this transformation is to achieve the desired MAPE over the transformed data set. The MAPE is a single parameter that reflects both the mean and standard deviation, and it is necessary to specify both XBARnew and SDnew for the transformation. However, there is no unique relationship between MAPE and this pair of parameters. That is, an infinite series of pairs will generate a desired MAPE, since both parameters have continuous values. It was decided to preserve the coefficient of variation (i.e., SDnew/XBARnew) in the various transformations. The coefficient of variation was used to drive the selection of unique XBARnew and SDnew for the 20%, 40%, …, 140% MAPE cases that needed to be generated. This approach is depicted in Figure 7, for 0% to 100% of MAPE.

This approach generates an empirical distribution of prediction errors that are drawn from at random for each simulated operational day. The advantages of this approach are several:

- it preserves the shape of the original distribution
- it preserves the relationship of SD to XBAR from the original distribution
- it preserves the proportions of un-biasing factors used on different groups of flights (for our data, these were based on airline and aircraft type). This un-biasing would logically be done in any fielded tool that was confronted with a consistent bias between scheduled and actual push-back times.
- it generates a sample size (the entire 19,652-member population is transformed) adequate for a Monte-Carlo experiment

% MAPE	Desired MAPE	Achieved MAPE	XBAR	SD	Coefficient of Variation
0%	0	—	0	0	—
20%	102	100.2	80	148.8	1.86
40%	204	200.4	160	297.6	1.86
60%	305	300.3	240	446.0	1.86
80%	407	400.7	320	595.2	1.86
100%	509	—	409	755.0	1.86

Figure 7. Parameters for Various PTIME Error Distributions

Operational Approaches to Reduce Push-Back Prediction Error

More frequent update of predicted ready-to-push-back times as conditions change could be made by ramp personnel and the flight crew. Ramp personnel can update the time based on their knowledge of connecting passengers, baggage loading, meal servicing, fueling, flights blocking push-back from that gate, required aircraft maintenance, etc. Flight crews also know the status of their aircraft and their pre-flight check; if an unforeseen delay in push-back is anticipated due to incomplete paperwork or equipment problems, they can input an update. To facilitate easy updates of ready-to-push-back times, there must be an easy interface to make these updates. Ideally, a data link facility would exist at the ramp or cockpit to input changes that would be communicated automatically to update the P-time in the flight plan stored in the Air Route Traffic Control Center (ARTCC) host computer. This update would also be transferred automatically to ETMS, the central repository for flight planning data in the NAS.

Conclusions and Future Work

The determination of the sensitivity of the average taxi-out time realized to the push-back prediction errors is an important research question. This paper describes interim results showing the sensitivity and benefits of reducing these errors at ATL. This sensitivity analysis is a initial step needed to estimate quantitative benefits that would justify the development of decision support tools to perform departure planning, and to justify efforts to improve the quality and predictability of information used by these tools. The quantification of the effect of these prediction errors, and reducing them to an operationally acceptable level, is essential to the future successful implementation of any departure planning system. Additional work is needed to determine the push-back predictability level which would balance the potential benefits of increasing this predictability versus the system costs of obtaining this increased predictability.

Increases in push-back time predictability have potential benefits throughout all phases of flight. Improvements in push-back time predictability are critical to the successful management of traffic flow after departure, in maintaining an airline's arrival bank integrity at hub airports, and in maintaining the desired level of passenger on-time performance. These benefits may outweigh the direct operating cost benefits attributable to reducing average taxi-out times. This is a fruitful area for additional research.

In 2002, this research will continue to develop the DEPARTS lab model at a second major airport, with characteristics and data sources different from those at ATL. It is hoped that real time surface position information can be obtained for this airport, so that the incremental benefit of this additional information for departure planning can be estimated. The adaptation of DEPARTS to a second airport with different characteristics is necessary to ensure that the DEPARTS algorithms are applicable to a wide variety of airports, and to refine and extend the ATL benefits analysis discussed in this paper to other airports.

Author Biographies

Wayne Cooper, a Lead Engineer with MITRE, has spent 19 years in the design and development of optimization-based decision-support tools and in the development of statistical analyses for the areas of aviation, ground transportation, energy and military manpower planning. He is the principal designer of DEPARTS. Mr. Cooper received a M.S. in Operations Research from the Georgia Institute of Technology and a B.S. in Systems Engineering from the University of Florida.

Dr. Ellen Cherniavsky, a Senior Engineer with MITRE, has over 18 years experience in aviation systems engineering. Prior to coming to MITRE she was with Brookhaven National Laboratory where her work focused on energy system optimization modeling. She holds a Ph.D. and M.S. in Operations Research from Cornell University and a B.S. in Mathematics from Stanford University.

Jim DeArmon, a Lead Engineer with MITRE, has worked for the last several years in research and modeling of air traffic flow dynamics. He holds a Master's degree in Operations Research, and has taught graduate courses at the University of Maryland. He has written numerous papers in aviation and applied math. He is a member of the Editorial Advisory Board of the journal *Computers and Operations Research* (Pergamon Press).

Glenn Foster, a Senior Engineer with MITRE, has spent the previous several years developing DEPARTS algorithms and in performing detailed studies of traffic management flow restrictions. Prior to this, Mr. Foster had 13 years of experience applying modeling and simulation techniques in the areas of warfare modeling, space surveillance, and postal workflow operations. Mr. Foster received two M.S. degrees, one in Applied Mathematics from the Johns Hopkins University, and one in Computer Science from the George Washington University.

Dr. Michael Mills, a Senior Engineer with MITRE, has spent the past several years analyzing oceanic air traffic control procedures and in developing algorithms in DEPARTS. Dr. Mills holds M.S. and Ph.D. degrees in Engineering Sciences and Applied Mathematics from Northwestern University.

Dr. Satish Mohleji is a Principal Engineer with MITRE. For over 30 years, he has been involved in developing concepts and prototype simulations for air traffic management, navigation, flight guidance, and aviation weather systems. He provided support to the ICAO /FANS Committee to determine cost/benefits for upgrading the air traffic control systems using satellite-based communications, navigation and surveillance technologies in various regions of the world. Dr. Mohleji has numerous publications on future Air Traffic Management System development to improve flight efficiency and reduce operating costs.

Dr. Frank Zhu, a Senior Engineer with MITRE, has been involved in the design and development of the DEPARTS Optimization model. He received a Ph.D. in Physics from Drexel University.

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