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USING SURFACE SURVEILLANCE TO HELP REDUCE TAXI DELAYS*

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ABSTRACT

Taxi delay is the largest of all aviation movement delays. However, taxi-out delays have not received attention equal to that focused on airborne delays because taxi-out delays often result from downstream problems. Also, until recently, there was no practical means of tracking surface movements. New surface surveillance technology will revolutionize surface management by providing data for planning, timing, and monitoring surface operations. This paper proposes a simple aid to help manage departure taxi queues and help exploit existing departure capacity, while avoiding the delays that result from saturated queues and unbalanced runways. The proposed decision aide will use archived surveillance data to quantify queuing behavior and model departure capacity, and it will use real-time surveillance to track capacity changes and monitor the state of the taxi queues.

INTRODUCTION

Taxi delay results in the largest direct operating cost to US air carriers of all delays. Fig. 1 shows that the average taxi-out delay in minutes per flight is approximately twice the airborne delay.[4] Although aircraft burn fuel roughly 5 times faster when airborne, crew and equipment costs make the spend-rate for taxiing aircraft about 2/3 that for airborne aircraft. Consequently, the cost of taxi-out delay exceeds that for airborne delay by about 1/3, totaling more than one billion dollars annually.

On average, taxi-out delay is 3 times larger than taxi-in delay. This situation suggests that surface aids will likely focus first on departures. Most taxi-out delays are associated with surface queuing processes that are visible to the surface surveillance system. In contrast, management of the taxi-in process would require access to airborne surveillance data. Therefore surface planning aids for arrivals would need to be integrated that focus on with ARTS terminal surveillance data or the Center-TRACON Automation System (CTAS).[11] Surface aids departures could rely solely on surface surveillance and flight plan data, and could operate independently of ARTS and CTAS.

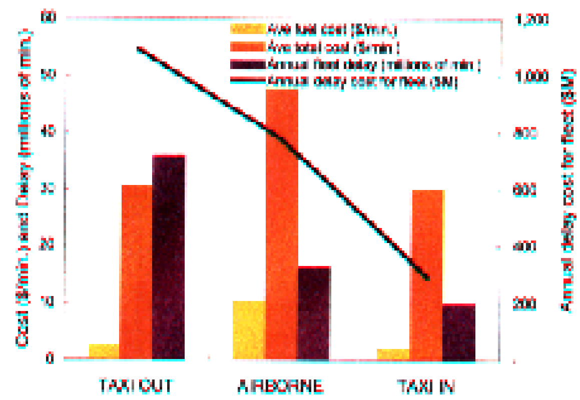

Figure 1. The cost of delay - U.S. airline fleet cost estimates for 1999 from (ATA, 2000).[4]

Efforts to reduce taxi-out delay have not been as vigorous as those focused on airborne delay. One likely reason is that taxi-out delay often stems from downstream problems such as capacity limitations in terminal and en route airspace as well as at the destination airport. Delay statistics show a 70% correlation between taxi-out delay for departures from DFW and airborne delay for flights to DFW.[6] This means that, on days when arrivals incur longer delays, departures at the same airport usually take more time to get off the ground. Consequently, there has been a sense that little can be done on the surface to reduce taxi-out cost.

The airport surface has been the only domestic aviation domain without an automatic means of digitally tracking and identifying aircraft. There has been no practical means of tracking surface movements to understand or control the taxi process, other than using reported push-back and wheels-off times.

High performance cooperative surface surveillance with aircraft identification has now been demonstrated.[20] This new technology will provide an opportunity to revolutionize air traffic management on the airport surface. There has been considerable research in the application of surface surveillance for enhancing

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surface safety.[8, 19] There has been some research in analyzing and understanding taxi delays.[12] An attempt was made to mitigate taxi delays by predicting queue lengths from schedule data.[13] However, no work has been reported on the use of surface surveillance to help enhance surface efficiency and reduce taxi delay. Surface surveillance will help improve the understanding of taxi delay mechanisms and will provide data for characterizing operational constraints, planning taxi operations, timing taxi clearances, and monitoring aircraft compliance.

The airport surface has characteristics that make it attractive for implementing automatic surveillance-based decision support tools. The surface is the only aviation domain in which most aircraft follow a relatively small number of rigidly constrained paths. This may make it feasible to use surveillance information alone to evolve a database that fully characterizes the geometry of the taxi paths. Generic adaptation algorithms could be designed to use this taxi path data to automatically adapt surface decision support tools to each new airport site. Automatic adaptation would significantly reduce the cost of implementing surface decision support tools relative to terminal and en route tools.

It appears feasible to develop operational software that uses surface surveillance information alone to track runway configuration changes in real time. By adding flight plan data to the surveillance data, automatic algorithms should be able to determine the current surface queuing delay status for each runway and aircraft. Other databases could relate taxi delay to demand and relate demand to the day of the week and the time of day. Operational algorithms could use these delay and demand databases in conjunction with measurements of departure queuing status to automatically predict the near-term departure throughput for each runway. With the addition of surveillance data for arriving aircraft, operational algorithms could also predict near-term arrival throughput.

A well-designed surface surveillance system can provide complete coverage of the important delay-controlling queues on the airport surface. Surveillance coverage of airport surface queues can provide the visibility into surface traffic flow that is essential to close the loop on suggested control actions. Surface surveillance provides a means of determining departure throughput performance. It allows unambiguous determination of the departure runway of each aircraft. By contrast, the ARTS surveillance system cannot reliably associate departures with runways because of its low-elevation coverage cut-off. This is particularly true when the departures turn immediately after takeoff.[3]

A simple taxi-out aid could use this surveillance information to predict the queue length for the next few minutes and advise optimum near-term target pushback rates. Such advisories would have the advantage that they would not require any manually generated information from controllers or aircraft operators. There would be no need for controllers to provide the current runway configuration and no need for pushback predictions from aircraft operators.

A SIMPLE TAXI-OUT AID

The most elementary taxi aid would display surface traffic with aircraft identities to all parties interested in surface traffic management. Distributing surveillance information with aircraft tags would likely benefit aircraft operators and controllers and would require little research other than finding means to manage the tags to avoid display clutter. The functionality envisioned in this paper goes further and provides decision support aids based on surface surveillance that would attempt to directly help controllers and air carriers work together to improve surface movement efficiency. This is done by providing a simple visualization of the queuing situation along with pushback advisories to optimize the taxi-out process and balance runways.

At airports with multiple runways, surveillance data alone presents a good tactical view of the airport, but sometimes paints a confusing picture of the strategic situation. Early in the taxi-out process, it is not always clear which runway each aircraft is heading for. Although the total number of taxiing aircraft may be apparent, it is difficult to see the queue lengths for individual runways. The surveillance display also does not provide information on predicted taxi times.

Experience with the Surface Movement Advisor (SMA) program at Atlanta's airport conclusions from current NASA-sponsored research on causes of departure delay and inputs from aircraft operators who routinely experience departure delays all suggest that an automation aid to help visualize and control taxi queue lengths for departing aircraft would benefit both controllers and aircraft operators.[5,13,16,12,14,1,2,3,9,8]

This paper proposes such a simple taxi-out aid to help with queue management. Figure 2 shows a notional operator interface for the aid when used at an airport with dual departure runways. The interface is presented merely as a concrete illustration of the proposed information content. It has not been prototyped or tested for operator acceptability.

It displays the status of the taxiway system and depicts the queuing situation at multi-runway airports by associating each aircraft with a runway and depicting the airport in a simplified map format similar to those used for mapping subway lines. It shows the loading of the taxi paths as well as the runway queues, indicating the progress of all aircraft taxiing towards each departure runway.

The runway maps are divided nominally into Pushback, Taxi, Runway Crossing Queue, and Runway Queue sections. The taxi and Queue sections contain bins consisting of columns of boxes indicating numbers of aircraft. Each box corresponds to an aircraft. Clicking on a box displays a data tag with the aircraft ID. In the figure, runway 18C has two planes waiting to take off in its runway queue. Where a taxi path crosses an active runway, the graph is split by a crossing queue as shown for Runway 18R.

The Taxi section is shown with 10 bins. Typically, each taxi bin contains no more than one aircraft. Large airports use more taxi bins to keep the individual taxi bin occupancy to a single aircraft.

A Crossing Queue section has a single column showing the number of aircraft waiting to cross the active runway. When an aircraft first enters a runway crossing queue or a runway queue, its box changes color to indicate that it is now under local control. Finally, the graph for each runway ends in a Runway Queue section containing a single column showing the number of aircraft waiting at the runway entrance for takeoff clearances.

Each runway also has a pushback rate advisor. When the departure demand is low, there is no need to limit the pushback rate. Thus, although the display operates continually, its principal benefit occurs in departure push conditions. The height of the bar recommends a pushback rate for that runway. A positive bar indicates that the pushback rate can be increased, and a negative bar advises a reduced rate. In a departure push the goal is to zero the bars for both runways. Zeroing the bars optimizes the pushback rates and equalizes the taxi times for the last aircraft in each of the runway queues. (Note that the last aircraft in a runway queue may not be the most recent aircraft to push back for that runway.) The display also indicates the estimated taxi time for the last aircraft in each runway queue.

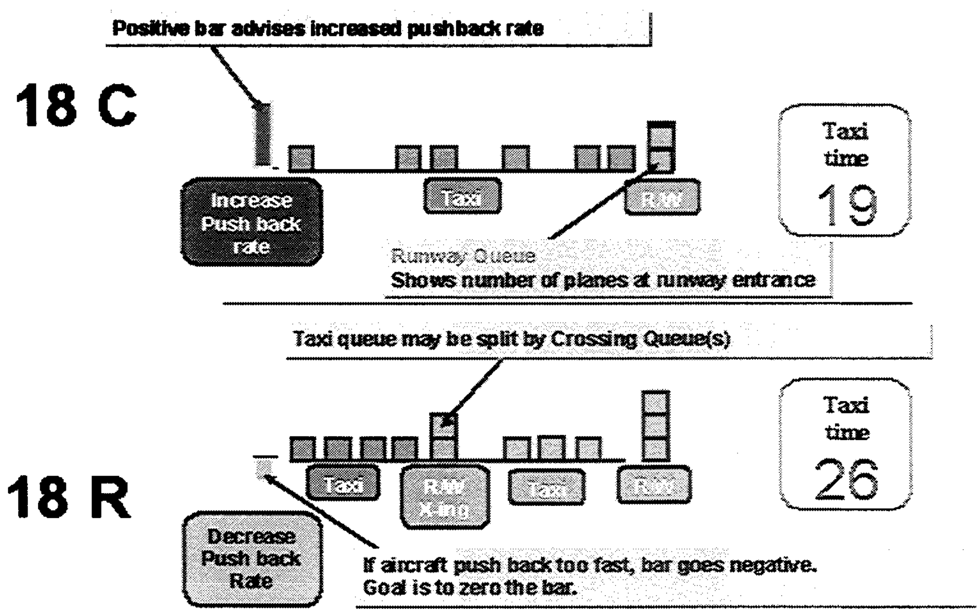

Figure 2. Nominal display for an airport with dual departure runways

Equalizing the taxi times for the last aircraft in the queues balances the runways despite differences in their overall taxi path lengths or differences in their departure capacities. Runway capacity differences can be caused by departure airspace constraints or by differences in mode of operation. For example, a runway dedicated to departures has greater departure capacity than one shared by arrivals. Balancing the taxi times assures that the flow to one runway does not dry up earlier than the flow to the other at the end of a departure rush. The simple taxi-out aid does not attempt to balance taxi delays. Balancing taxi delays (where delay for each runway is reckoned relative to its minimum taxi-out time) could assign too many aircraft to the runway with the longer taxi path.

USING THE TAXI AID

Large hubbing airports with multiple departure runways often allow airline gate/ramp control personnel to control the pushback and ramp taxi process for their own aircraft. They interact with the FAA Clearance Control, Ground Control, and Local Control positions.

After FAA Clearance Control has issued a flight plan clearance and handed off the flight strip to FAA Ground Control, the next step in the departure process occurs when the pilot notifies the carrier's Gate/Ramp Control that he is ready to push back. Gate/Ramp Control issues the pushback clearance and clears the aircraft to the desired taxiway entrance spot. Upon reaching the spot, the pilot monitors the Ground Control frequency in anticipation of a taxi clearance.

Ground Control positively identifies each aircraft that is ready to enter the surface movement area and, when ready, clears it to enter the taxiway. Ground Control handles the aircraft until it first approaches an active runway. Transfer to FAA Local Control may take place before crossing an active runway or before entering the departure runway, whichever occurs first. Ground Control hands off the flight strip to Local Control and authorizes the pilot to switch to the Local Control frequency. Local Control then issues all remaining clearances including the takeoff clearance.

If two or more carriers simultaneously push back aircraft for departure, FAA Ground Control establishes the overall taxi-out order to sequence the aircraft on the runways in a fair and equitable manner subject to departure flow control and wake vortex spacing restrictions. Ground Control also exercises short-term control over the runway balance and the queue lengths for the individual runways by managing taxi out from the ramp area.

Surface surveillance displays will be used in the tower, the Traffic Management Units in the TRACON, the en route Center (where it could help predict near-term departure demand), and the airline operational centers and gate and ramp control positions. The simple taxi-out aid will be used at all the same locations.

In departure pushes FAA tower controllers estimate the size of departure queues by monitoring the occupancy of the flight strip bays and by visually observing the aircraft on the runways and taxiways. The taxi-out aid provides Ground Control with a direct estimate of the current runway balance and suggests the optimum apportionment of aircraft to multiple departure runways. By comparing the queue size to the visual scene or to the tower flight strip bays its users can assure that it accounts for all the aircraft, assigns each aircraft to its proper departure runway, and accurately shows the distribution of the aircraft along the paths to the runways. Users can click on aircraft boxes to display data tags confirming aircraft identity and status.

Gate/Ramp controllers often have difficulty directly observing the details of the other carriers' departure operations or the overall departure demand and capacity. The taxi-out aid provides the needed visibility and suggests near-term limits to the pushback rate for all of the carriers. Individual carriers can then infer their own pushback rate limits by comparing the pushback advisories with their recent departure flow performance.

The simple taxi-out aid facilitates collaborative decision making among the carriers and ATC by providing all participants with common situational awareness. They collaboratively determine the throughput performance objectives for the airport and enter the desired departure rate into the simple taxi-out aid. They can change the control performance goals at any time, resulting in immediate changes to the displayed pushback rate advisories. When a single carrier dominates the departure push the pushback advisories more directly apply to the dominant carrier, simplifying the cooperative management of gate or ramp holds between the hubbing carrier and FAA Ground Control.

THE PUSHBACK ADVISORY ALGORITHM

The taxi-out aid automatically determines the relationship between departure throughput, taxi-out time, and effective queue length for each taxiway/runway path. The effective queue for a runway includes all aircraft on their way to the runway as well as the aircraft in the physical queue that the runway entrance. The relationship between these performance measures is obtained by continually measuring, tracking, and archiving each of these quantities. The taxi aid analyzes the archived data under all operating conditions to determine and model the needed relationships.

Figure 3 illustrates the relationships used to develop the departure performance database. It relates the overall mean departure throughput to the effective queue length for BOS in August 1991, which includes all aircraft that have pushed back but not yet taken off.

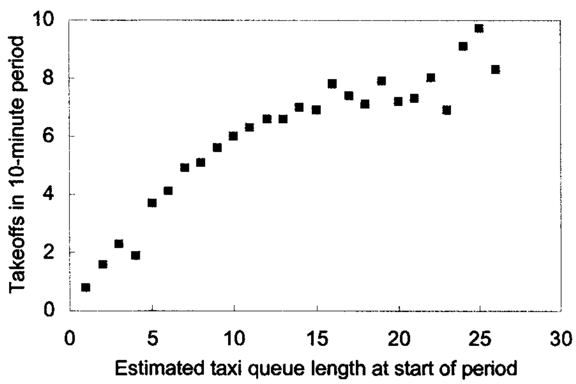

Figure 3. Mean departure rate vs. taxi occupancy for BOS, Aug 1991 - from (Shumsky 1997).[15]

Taxi-out delays exhibit classical queuing behavior. In departure rushes, aircraft fill the taxiways, queues grow at runways, the ambient runway/airspace departure capacity limits the takeoff rate, and delay increases faster than the queue length. The service rate of a queue is always the minimum of the demand and the capacity. Figure 3 shows that when there are less than 15 departure aircraft on the taxiways, there are gaps in the flow to the runway, and the takeoff rate is determined mainly by the departure demand. When there are many more aircraft on the taxiways than 15, there is usually a queue of aircraft at the runway entrances. The takeoff rate is then determined by the departure capacity of the airport. The variability in mean takeoff rate for large queue lengths reflects the variation in airport capacity that occurred during the 1-month data-gathering period. If the operator desires a total throughput of seven aircraft in 10 minutes, this curve tells him that the queue length should be about fifteen. Increasing the queue length above 15 will have little operational effect other than to increase taxi-out delays.

The taxi aid bases the pushback limit calculation on the principle that the rate of growth of the departure queue is determined by the difference between the pushback rate and the runway take-off rate. The taxi aid determines the pushback limit from the queuing conservation relationship:

$$P = N_T - N_0 + D,$$

where P is the number of pushbacks during the next T minutes; N_T is the desired queue length T minutes in the future; N_0 is the present queue length, and D is the number of takeoffs expected during the next T minutes.

The desired future queue length, N_T is obtained from the performance database after a throughput goal has been established by the users. The present queue length, N_0 is obtained from surface surveillance. The number of takeoffs during the next T minutes is obtained by predicting the departure rate over the next T minutes.

To predict the departure rate the simple departure aid uses historical data relating queue length to departure rate. The departure rate is determined by the departure capacity of the airport when the departure queue is large. In a departure push the departure capacity varies slowly and can be reliably tracked and predicted in real time with no knowledge of the weather, the runway configuration, or the arrival/departure mix.[15] Shumsky was able to forecast the takeoff rate 30 minutes into the future with a RMS error of about two departures per hour. He achieved his best capacity estimates by fitting an analytical approximation to data of the type shown in Fig. 3. He used an exponential curve fit to provide a static model of the relationship between queue length and departure rate. He then added a dynamic term to adjust the curve up or down at 10-minute intervals. The dynamic adjustment linearly tracked the observed takeoff rate by smoothing over the residuals of the takeoff estimate at each update interval.

Shumsky did not have surface surveillance data to help refine his estimate. Knowing the runway configuration, the distribution of aircraft on the surface, and the balance between arrivals and departures for each runway makes it possible to improve the static estimates by modeling families of curves for different operating conditions. Tracking repeatable daily or hourly variations can further improve the estimation process.

The taxi aid also estimates the total taxi-out time for the next pushback to help balance the queues. The relationship between effective queue length and taxi time is also obtained from the performance database. This is illustrated in Figure 4, which relates the mean taxi-out time to the queue length for the entire departure taxiway system at Boston (BOS) from January to March 1997. This curve indicates that a queue length of 15 aircraft produces an expected taxi-out time of 36 minutes. The mean taxi-out delay relative to the unimpeded delay can also be obtained from this figure:

the taxi delay is approximately 36 - 12 = 24 minutes for a queue length of 15 aircraft.

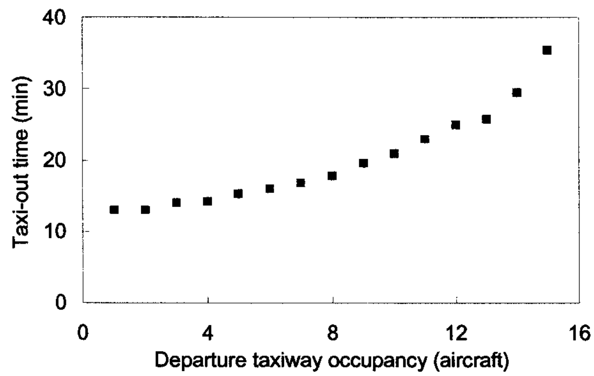

Figure 4. Dependence of mean taxi out time on the aircraft count in the BOS departure taxiway system at the time of pushback - from (Idris et al, 1999).[12]

To estimate the departure queue length in real time for a multi-runway airport, the taxi aid associates each aircraft with a departure runway and automatically detects changes in departure runway assignment. At pushback the taxi aid estimates the departure runway for each aircraft from the filed flight plan for the aircraft and the current runway configuration. The taxi aid checks the position of the aircraft at each subsequent update against a site-adapted list of departure taxi routes for that configuration to confirm that the aircraft is still taxiing towards the same runway.

OTHER DATA SOURCES

Although the simple taxi-out aid needs only flight plan data and surface surveillance data to function, additional data types would be valuable for surface movement predictions. Pre-departure pushback status information and automatic pushback notices from all aircraft operators at the airport, final approach surveillance data from ARTS, CTAS data, and data on operational constraints in departure airspace would all improve the performance of taxi aids.

These data sources would help extend departure demand predictions farther into the future to better support strategic planning. Pre-departure status information from aircraft operators would be very useful if it were reliably available for all departures. Taxi aids will require timely automatic pushback data at an airport whose surface surveillance does not provide reliable coverage in the ramp area. It is essential to measuring the gate and ramp performance of the surface surveillance system as the first step in implementing a taxi aid at an airport.

CTAS data includes arrival planning information as well as ARTS approach surveillance data. These would both be necessary for more advanced taxi aids that manage arrivals as well as departures.

Other information would be useful in the future to refine the departure capacity estimates. Aircraft type information (which is included in the flight plan) would help determine wake vortex spacing requirements on take-off.[7] Although it is possible to automatically detect runway configuration changes in near real time from either ARTS surveillance data or surface surveillance data knowledge of planned configuration changes would obviously improve the predictability of departure capacity.[3] Finally, information on current and planned departure airspace restrictions would help improve both the capacity estimates and the archived data used for modeling constraints on departure sequencing and timing.

BENEFIT MECHANISMS

The principal benefit expected from the simple taxi aid is a reduction in direct operating costs for aircraft operators from reduced taxi-out delay. The aid will also reduce environmental pollution and controller workload. It will achieve these benefits by helping controllers and aircraft operators determine when to use gate and ramp holds to avoid overloading departure queues at individual runways. At airports with two or more departure runways, it will help reduce departure delays by balancing the queues to prevent under-utilization of one runway while overloading another. Predicting such unbalances early will help reduce expensive delays for aircraft that are not yet committed to depart on a particular runway.[13] However, when runways become unbalanced because of procedures that rigidly map departure fixes to runways, the solution will likely involve procedural changes to allow an aircraft to depart from a runway not normally associated with its planned departure fix.

In addition to avoiding runway saturation and runway imbalances, it also helps ground controllers plan taxi clearances and assign departure runways in order to provide continuous streams of traffic for all departure runways. The magnitude of these benefits can be determined initially by analysis and then by using controller-in-the-loop simulations and re-enacting demanding departure taxi scenarios. Baseline tests can be run on the scenarios to quantify the resulting departure delays with and without the help of pushback advisories.

Although the initial functionality will be limited to pushback advisories and departure queue length predictions, its use of surface surveillance and digital flight plan data to predict surface movements will be a necessary first step in enabling more efficient management of surface movements and in supporting future functionality. Future efficiency-enhancing functionality based on the simple departure aid could:

- help coordinate arrival and departure planning by accurately predicting departure times,
- estimate taxi-in as well as taxi-out delays for individual aircraft,
- help provide runway assignment and sequencing advisories for arrivals as well as departures,
- help support procedures that permit an aircraft to depart from a runway not normally associated with the departure fix designated in its flight plan,
- help reduce runway crossing delay by reducing taxi time variances and excess buffers,
- help improve reconfiguration planning,
- help increase landing throughput by monitoring runway occupancy times, and
- help reduce de-icing delays by monitoring de-icing queues and time violations.

All of these efficiency enhancements will require the runway adaptation, surveillance and flight plan processing, surveillance data analysis, capacity prediction, and display generation capabilities that are required in a the simple taxi-out aid. These capabilities will also provide the basis for important surface safety functionality.

RISKS

The fundamental risk inherent in any activity to develop decision support tools is the failure to identify the main operational problems and the consequential failure to deliver dollar, workload, or environmental benefits at the selected site. Data is needed to verify assumptions about delay and cost mechanisms at candidate sites. The surface surveillance system and FAA delay reporting systems must be used along with operational logs and consultation with controllers and aircraft operators to determine the principal causes of taxi-out delay .

Failure to achieve user acceptance is a fundamental risk. The controller interface design and development process involves significant research risk. Familiarization, training, and display modifications will be required, and simulations will be needed with and without the pushback advisories and queue distribution graphics to determine if they are useful and reduce workload for the users.

It will also be necessary to find space for a new display in the tower. Experiments with trial interface designs must begin as soon as possible in a tower environment. The NASA tower cab simulator is ideal for this purpose. Adapting the NASA simulator to the chosen airport should begin as soon as the test site has been chosen. This adaptation is expensive, so there are budgetary risks involved in this site decision. However, evaluation of generic displays could begin immediately with a tower cab simulation of any airport.

Major research risks were noted above in discussing functionality and data interfaces. An important risk is the performance and accuracy of the key capacity tracking and prediction algorithms used to estimate the future departure queue length. These estimates will rely on processing and tracking routines that continuously monitor, record, and analyze operational surface surveillance at each airport. Although data tracking is performed routinely in Air Traffic control surveillance systems, it is not commonly done to automatically obtain and update operational information needed for decision support automation.[3,10] If it is not possible to predict departure capacity with sufficient accuracy solely from recent observations of departure queues and takeoff rates, it may be necessary to obtain additional sources of data.

Important programmatic and technical risks involve access to, continued availability of, and coverage of the surface surveillance data. Surveillance data is key to automatically determining the current queuing status for each departure runway and automatically predicting near-term departure demand. The FAA is developing a commercial surface multilateration system intended to provide reliable surveillance and identification of all aircraft with operating transponders on airport movement areas. The data is fused with data from surface surveillance radars, with data from the ARTS terminal airborne surveillance system, and with flight plan data.

The FAA has initiated development of an operationally deployable digital surface surveillance system known as ASDE-X. This program is intended to lead to an operational capability that includes multi-lateration in conjunction with a low-cost primary radar operating at X-band.

A minor regulatory change is needed to obtain reliable surveillance and identification coverage for all aircraft in the ramp and movement areas. Transponder multilateration, which is the key to low-cost, clutter-free surveillance on the surface, depends on transmissions from aircraft transponders. Official FAA procedures must change at airports with multilateration systems to mandate that aircraft on the airport ramp and movement areas leave their transponders operating at all times rather than turn them off as currently required. Because there appears to be no technical or interference problem from continuous operation of transponders on the surface of major airports there is no technical or operational impediment preventing this regulatory change.[20]

There is a small technical risk that surface surveillance may not provide reliable coverage in ramp and gate areas because of blockage of transponder transmissions by airport structures or by the airframes of other aircraft. Recent tests at DFW addressed the coverage issue.[21] The gate coverage appeared good based on limited operation within the ramp and gate areas. Multilateration coverage can always be improved by the addition of additional ground sensors. In addition, a few aircraft will not be visible because they have been intentionally wired to reduce controller workload by automatically switching off their transponders when they are on the ground. One of the early research activities in any program to develop surveillance-based taxi aids must be a complete characterization of the coverage issue.

REFERENCES

1. Anagnostakis, Idris, Clarke, Feron, Hansman, Odoni, and Hall (2000) “A Conceptual Design of a Departure Planner Decision Aid," 3rd USA/Europe Air Traffic Management R&D Seminar, Napoli.

2. Anderson, Carr, Feron, and Hall (2000), “Analysis and Modeling of Ground Operations at Hub Airports," 3rd USA/Europe Air Traffic Management R&D Seminar, Napoli.

3. Andrews (2001), “Radar-Based Analysis of the Efficiency of Runway Use," AIAA GNC Conf., Montreal.

4. ATA (2000), “Approaching Gridlock” Air Transport Assocation www.airlines.org/public/gridlock/ag2a.htm

5. Bhaumik et al (1996), "Surface Movement Advisor SMA Operations Manual," SMA Project Office NASA Ames Research Center Moffett Field, California, SMA-152, June 1, 1996.

6. CODAS (2000) “Federal Aviation Administration Office of Aviation Policy and Plans, Consolidated Operations and Delay Analysis System," www.apo.data.faa.gov.

7. Dasey (1998), “A Departure Wake Vortex Monitoring System: Concept and Benefits”, 2nd USA/Europe Air Traffic Management R&D Seminar, Orlando.

8. Eggert (1994), “Demonstration of Runway Status Lights at Logan Airport”, Linc. Lab. J. 7, 169.

9. Edelman (2000), “Surface Management," Briefing to Surface R&D Technical Interchange Meeting, 7/11/2000, MIT, Cambridge, MA

10. Erickson and Prusak (1994), “Flight Time Modifier Flight Time Data Modifier," Proceedings of the National Traffic Management Conference, Reston VA 1/24/94.

11. Erzberger (1990), “Integrated Automation Tools for the Center and the TRACON”, The Journal of ATC, 32(4).

12. Idris, Anagnostakis, Delcaire, Hansman, Clarke, Feron, and Odoni (1999), “Observations of Departure Processes at Logan Airport to Support the Development of Departure Planning Tools," Air Traffic Control Quarterly, 7(4).

13. Lawson (1998), “Surface Movement Advisor (SMA)”, J. Air Traffic Control, January-March, 1998.

14. Pujet, Delcaire, and Feron (2000) "Input-Output Modeling and Control of the Departure Process of Congested Airports," Air Traffic Control Q., 8(1).

15. Shumsky (1997), “Real Time Forecasts of Aircraft Departure Queues," Air Traffic Control Quarterly, 5(4).

16. Signor (1999), “Operations Concept for the Surface Management System (SMS) Prototype," NASA Ames Research Center Aviation Surface Technologies Area Team Report SMS-102, Moffett Field, CA.

17. Signor (2000), "Surface Management System Research & Development Plan Volume I – Technical Plan," NASA Ames Research Center Aviation Surface Technologies Area Team Report SMS-101, Moffett Field, CA.

18. Vail (2000), “Operational Concept for an Airport Surface Management System (ASMS)”, Briefing to Surface R&D Technical Interchange Meeting, 7/11/2000, MIT, Cambridge, MA.

19. Wilhelmsen (1994), "Preventing Runway Conflicts: The Role of Airport Surveillance, Tower-Cab alerts, and Runway Status Lights," Linc. Lab. J. 7, 149.

20. Wood and Bush (1998), "Multilateration on Mode S and ATCRBS Signals at Atlanta's Hartsfield Airport." MIT Lincoln Laboratory Project Report ATC-260, available to the public through NTIS, Springfield, VA 22161.

21. Wood (2000), "Multilateration System Development History and Performance at Dallas/Ft Worth Airport," Proceedings, 19th Digital Avionics Systems Conference, October 2000, Philadelphia.