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Surface Management System Field Trial Results

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NASA Ames Research Center, in cooperation with the FAA, has completed research and development of a proof-of-concept Surface Management System (SMS). This paper reports on two recent SMS field tests as well as final performance and benefits analyses. Field tests and analysis support the conclusion that substantial portions of SMS technology are ready for transfer to the FAA and deployment throughout the National Airspace System (NAS). Other SMS capabilities were accepted in concept but require additional refinement for inclusion in subsequent development spirals. SMS is a decision support tool that helps operational specialists at Air Traffic Control (ATC) and NAS user facilities to collaboratively manage the movements of aircraft on the surface of busy airports, thereby improving capacity, efficiency, and flexibility. SMS provides accurate predictions of the future demand and how that demand will affect airport resources – information that is not currently available. The resulting shared awareness enables the Air Traffic Control Tower (ATCT), Terminal Radar Approach Control (TRACON), Air Route Traffic Control Center (ARTCC), and air carriers to coordinate traffic management decisions. Furthermore, SMS uses its ability to predict how future demand will play out on the surface to evaluate the effect of various traffic management decisions in advance of implementing them, to plan and advise surface operations. The SMS concept, displays, and algorithms were evaluated through a series of field tests at Memphis International Airport (MEM). An operational trial in September, 2003 evaluated SMS traffic management components, such as runway configuration change planning; shadow testing in January, 2004 tested tactical components (e.g., Approval Request (APREQ) coordination, sequencing for departure, and Expected Departure Clearance Time (EDCT) compliance). Participants in these evaluations rated the SMS concept and many of the traffic management displays very positively. Local and Ground controller displays will require integration with other automation systems. Feedback from FAA and NAS user participants support the conclusion that SMS algorithms currently provide information that has acceptable and beneficial accuracy for traffic management applications. Performance analysis results document the current accuracy of SMS algorithms. Benefits/cost analysis of delay cost reduction due to SMS provides the business case for SMS deployment.

I. Introduction

The Advanced Air Transportation Technologies (AATT) Project at NASA Ames Research Center is working with the FAA to study automation for aiding airport traffic management. SMS research began in early 2000, applying many of the lessons learned from NASA's previous research and development of the Traffic Management Advisor (TMA), and concluded with the FAA trials described in this paper. While NASA is continuing advanced SMS research, the SMS technology described in this paper is being transferred to the FAA.

The remainder of this section presents an overview of SMS functionality and the research architecture. The following section describes the various simulations and field trials. The subsequent sections describe analysis of SMS

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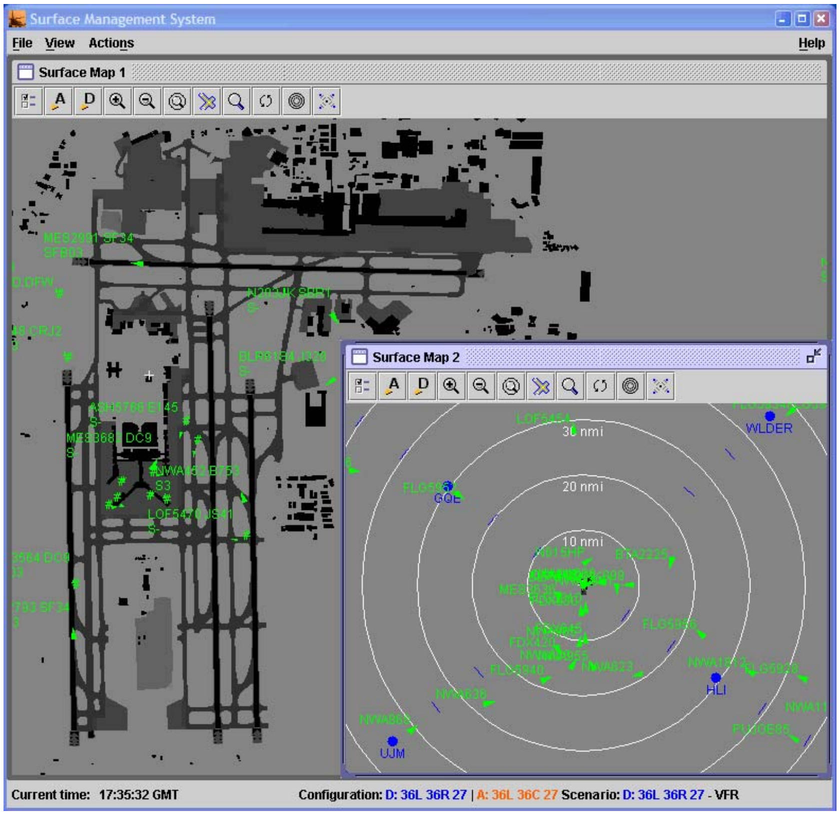
algorithm performance, human factors assessments, benefits and cost estimates, and technology transfer. The paper finishes with conclusions and an extensive list of previous SMS publications that provide additional details on many of these topics.

A. SMS Overview

SMS is a decision support tool that provides information and advisories to help FAA controllers and traffic managers as well as NAS users to collaboratively manage aircraft on the surface and in the terminal area of busy airports. A more detailed description of SMS is available in references [1-2]. SMS has three fundamental capabilities: 1) the ability to predict the movement of aircraft on the airport surface and in the surrounding terminal area (i.e., what will happen assuming current traffic management initiatives), 2) the ability to use this prediction engine to plan surface operations (i.e., what would happen assuming various other traffic management initiatives), and 3) the ability to disseminate this information and provide appropriate advisories to a variety of users.

These fundamental capabilities allow SMS to provide information and advisories that are customized to the needs of each user. SMS supports a variety of users: the Local and Ground controllers and Traffic Management Coordinator (TMC) or Controller in Charge (CIC) in the ATC tower (ATCT), the TMCs in the Terminal Radar Approach Control (TRACON) and Air Route Traffic Control Center (ARTCC), the ramp controllers and supervisor in ramp towers, and the dispatchers and ATC coordinator in Airline Operations Centers (AOCs). In addition, SMS information benefits the Enhanced Traffic Management System (ETMS) which supports the ATC System Command Center (ATCSCC).

By creating shared awareness of the future airport situation, SMS allows the ATCT, TRACON, ARTCC, to coordinate traffic management decisions as well as FAA and air carrier users to collaborate. SMS-provided information is expected to be most helpful during irregular operations, when knowledge of daily schedules gained through experience cannot be used to predict the timing of future demand and how best to operate the airport to accommodate that demand.



Current time: 17:35:32 GMT Configuration: D: 36L 36R 27 | A: 36L 36C 27 Scenario: D: 36L 36R 27 - VFR

Figure 1. SMS Map Display

Near-term predictions of departure sequences, times, queues, and delays for runways or other resources support tactical control of surface operations, while longer time-horizon, aggregate forecasts (i.e., total demand for a resource per interval of time) support strategic surface planning. SMS supports tactical and strategic decisions made by FAA and NAS user operational specialists through a variety of tools and advisories. For example, the Runway Usage Planner (RUP) identifies the most efficient runway configuration schedule, while the Configuration Change Advisory Tool (CCAT) allows controllers to trial-plan configuration changes. The What-If tool allows controllers to evaluate in advance the impact traffic management initiatives such as Mile-in-Trail (MIT) will have on the airport, and to allocate resources to arrival and departure demand to minimize delays and avoid gridlock. SMS departure runway assignment and sequence advisories increase efficiency. The APREQ coordination tool reduces communication required to assign departure release times to restricted flights and SMS improves compliance with EDCT and MIT restrictions by predicting when a flight should be expedited or delayed.

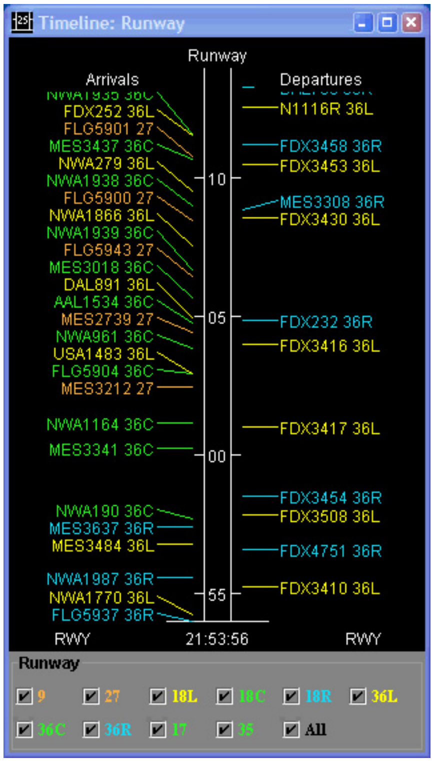


Figure 2. SMS Timeline

SMS utilizes four types of displays to convey information and advisories: map displays, timelines, load graphs, and tables. A map display (Figure 1) provides the location and direction of motion for each aircraft on a two-dimensional diagram and includes flight-specific information in data blocks. Timelines (Figure 2) show when an aircraft is predicted to occupy a physical location (e.g., a runway threshold, spot, or parking gate) but do not show the current location of the aircraft. Load graphs (Figure 3) display the aggregate amount of current and forecasted demand on an airport resource. Flight and status tables provide flight-specific information (e.g., OUT and OFF times and departure runway) in a tabular format, as shown in Figure 4.

B. Architecture

For the purpose of testing and considering deployment options, SMS was organized into three components: TM, CT, and TFM. The Traffic Management (TM) component consists of SMS features intended to support strategic airport planning. The TM component, evaluated through simulation, shadow testing, and an operational trial, reduced taxi times and delays for both arrival and departures through improved airport resource management, coordination between ATC facilities, and situation awareness of surface traffic.

The Controller Tools (CT) component contains the SMS capabilities intended to support tactical aircraft control by Local and Ground ATCT controllers and ramp controllers. Information and advisories for the tower controllers include flight information (e.g., assigned parking gate), departure runway and sequence advisories (e.g., to implement plans developed through the use of the TM component), APREQ release times to reduce communication effort, and advisories to reduce workload required to comply with EDCT and MIT restrictions.

The Traffic Flow Management (TFM) component consists of sharing SMS data with NAS-wide systems. Accurate and dynamically updated information from SMS (e.g., predicted takeoff times) reduces unnecessary enroute delays (e.g., MIT restrictions due to poor predictions of sector volume). The TFM component was evaluated through simulation and analysis.

Figure 5 shows the system architecture for SMS during the field trials in Memphis. SMS uses real-time location and identity information about aircraft on the airport surface, which it received in Memphis from the FAA Safe-Flight 21's Airport Surface Detection Equipment Model X (ASDE-X) prototype. SMS also received airborne surveillance information for the terminal airspace from the Safe-Flight 21 system, which it used along with ETMS data to predict landing times for the arrivals.

SMS receives flight plans, surveillance of arrivals outside the terminal area, and air carrier updates to planned departure times for each flight from ETMS. To correctly model inter-departure times, SMS must consider downstream restrictions. ETMS also provides EDCTs for aircraft affected by ground holds. Non-interference testing of SMS, to demonstrate that SMS does not disrupt ETMS or any other NAS system, was conducted at the FAA's William J. Hughes Technical Center prior to installation of each version of the software. Testing and FAA review also demonstrated that SMS complied with FAA security and filtering requirements. The current airport configuration, planned configuration changes, MIT restrictions, and APREQ times must be manually entered.

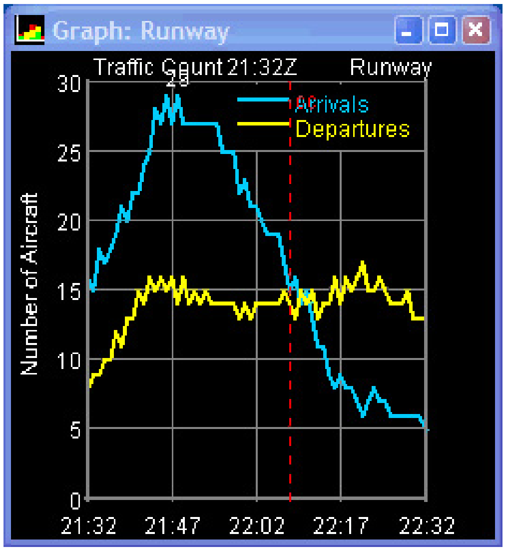
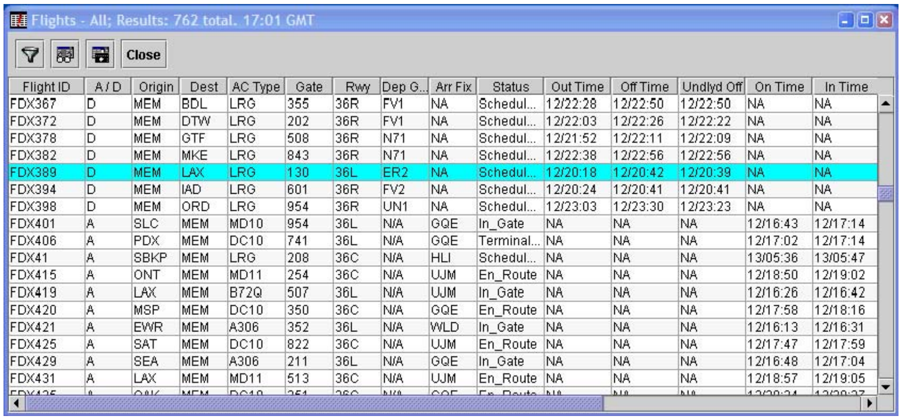


Figure 3. SMS Load Graph

SMS information was presented on separate displays in the air carrier facilities. Eventually, the SMS information will be provided via a standard interface, so that the NAS users can integrate it into their automation systems. In Memphis, SMS is connected to FedEx's Ramp Management Automation System (RMAS) system to receive parking gate information. SMS needs to know at what gate each arrival will park to predict taxi-in times as well as surface conflicts between arrivals and departures. SMS also receives flight status information (i.e., ready to push and pushed back) from RMAS to compensate for flights that do not appear in the surface surveillance data. Eventually, the air carriers will provide this data through either ETMS or the standardized interface across which they receive SMS data. This approach avoids the need to interface separately to every air carrier's ramp tower automation system.



Flight ID	A / D	Origin	Dest	AC Type	Gate	Rwy	Dep G...	Arr Fix	Status	Out Time	Off Time	Undlyd Off	On Time	In Time
FDX367	D	MEM	BDL	LRG	355	36R	FV1	NA	Schedul...	12/22:28	12/22:50	12/22:50	NA	NA
FDX372	D	MEM	DTW	LRG	202	36R	FV1	NA	Schedul...	12/22:03	12/22:26	12/22:22	NA	NA
FDX378	D	MEM	GTF	LRG	508	36R	N71	NA	Schedul...	12/21:52	12/22:11	12/22:09	NA	NA
FDX382	D	MEM	MKE	LRG	843	36R	N71	NA	Schedul...	12/22:38	12/22:56	12/22:56	NA	NA
FDX389	D	MEM	LAX	LRG	130	36L	ER2	NA	Schedul...	12/20:18	12/20:42	12/20:39	NA	NA
FDX394	D	MEM	IAD	LRG	601	36R	FV2	NA	Schedul...	12/20:24	12/20:41	12/20:41	NA	NA
FDX398	D	MEM	ORD	LRG	954	36R	UN1	NA	Schedul...	12/23:03	12/23:30	12/23:23	NA	NA
FDX401	A	SLC	MEM	MD10	954	36L	N/A	GQE	In_Gate	NA	NA	NA	12/16:43	12/17:14
FDX406	A	PDX	MEM	DC10	741	36L	N/A	GQE	Terminal...	NA	NA	NA	12/17:02	12/17:14
FDX41	A	SBKP	MEM	LRG	208	36C	N/A	HLI	Schedul...	NA	NA	NA	13/05:36	13/05:47
FDX415	A	ONT	MEM	MD11	254	36C	N/A	UJM	En_Route	NA	NA	NA	12/18:50	12/19:02
FDX419	A	LAX	MEM	B72Q	507	36L	N/A	UJM	In_Gate	NA	NA	NA	12/16:26	12/16:42
FDX420	A	MSP	MEM	DC10	350	36C	N/A	GQE	En_Route	NA	NA	NA	12/17:58	12/18:16
FDX421	A	EWR	MEM	A306	352	36L	N/A	WLD	In_Gate	NA	NA	NA	12/16:13	12/16:31
FDX425	A	SAT	MEM	DC10	822	36C	N/A	UJM	En_Route	NA	NA	NA	12/17:47	12/17:59
FDX429	A	SEA	MEM	A306	211	36L	N/A	GQE	In_Gate	NA	NA	NA	12/16:48	12/17:04
FDX431	A	LAX	MEM	MD11	513	36C	N/A	UJM	En_Route	NA	NA	NA	12/18:57	12/19:05

Figure 4. SMS Flight Table

During various field trials, SMS presented information and advisories to the Local and Ground controllers as well as the CIC/TMC in the ATCT, to the TMCs in the TRACON and ARTCC, and to both ramp and AOC users at FedEx and Northwest Airlines (NWA). In addition, SMS data can be provided to ETMS to improve traffic flow management products that use predictions of takeoff times. The human factors need to minimize the number of displays in front of ATCT controllers may motivate sharing of displays rather than installing dedicated SMS displays. Consequently, SMS's eventual deployment configuration may incorporate SMS data elements into the displays associated with other systems (e.g., ASDE-X or the STARS ATCT display). In addition, to improve maintainability, the SMS software algorithms could be hosted as part of some other automation system (e.g., ETMS). Integration of SMS with these other systems is beyond the technical scope of the current task and would limit the flexibility required during the research phase. The NASA team is working with the FAA to define the appropriate deployment architecture for SMS.

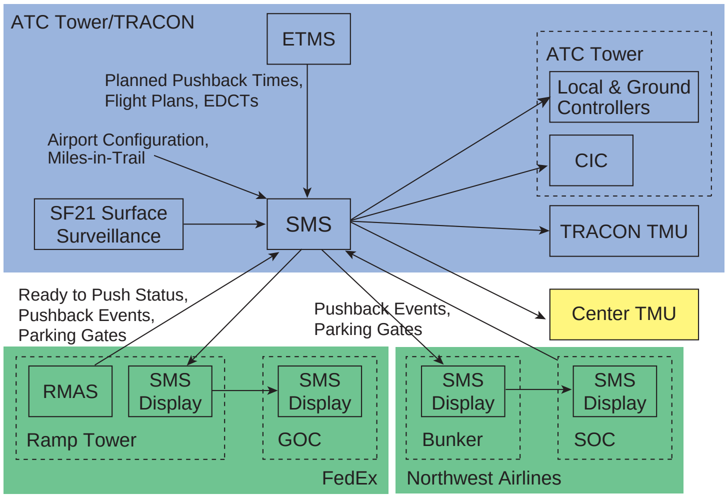


Figure 5. SMS Architecture at Memphis International Airport

II. Field Trials

Significant attention was given to human factors activities especially early in the design process, to ensure usability, suitability, and acceptability of SMS. Feedback from eventual users was solicited through focus groups, simulations, shadow-mode tests, field trials, and daily use. Questions repeatedly addressed what functionalities are appropriate for each user group, how information should be presented so that it is suited to the tasks being supported, and what level of system performance is necessary for benefits and user acceptance. Attention was given to designing SMS interfaces to minimize usability concerns for accessing or interpreting information. Impact of using SMS on workload was also measured. In cases where the display of SMS information will depend on the FAA's chosen deployment architecture, research focused on information content rather than final display design. Results from each activity were used to refine SMS and prepare for subsequent demonstrations.

A. Future Flight Central Simulations

Following an initial focus-group, two real-time, controller-in-the-loop simulations of SMS were conducted in the Future Flight Central (FFC) ATC tower simulator at NASA Ames Research Center. During the simulations, the Dallas-Fort Worth International Airport (DFW) was modeled. FAA controllers from DFW participated, using SMS to help control simulated traffic in FFC. Simulations involved FAA representatives from several other airports as well as representatives from several airlines also participated. This broad involvement ensured that SMS research focused on capabilities that would be applicable to a wide range of airports.

There was strong support for the SMS concept, while substantial guidance was offered for refinements. In particular, Local and Ground controllers indicated that the tactical nature of their responsibilities did not allow them to plan over a longer time horizon. Therefore, all of the strategic decision support was subsequently directed toward traffic management personnel. Controllers also reported that overlap between SMS information and paper flight progress strips (FPS) led to increased workload, as controllers checked both sources. Although training preceded testing, the novelty of a surface map display with flight data blocks resulted in a significant learning curve. Additional results from these simulations are discussed in [3-4].

B. Ramp Tower Field Trials

Initial SMS field trials were conducted in FedEx's ramp tower at MEM over two weeks in August and October, 2002. During the October test, SMS was also demonstrated in the NWA MEM Operations Center. Operational evaluation of SMS began in the ramp tower environment to reduce risk associated with subsequent demonstrations in FAA facilities.

SMS was installed at the administrator's position and one ramp controller position (Figure 6). The administrator's job is to coordinate the 4 ramp controllers to optimize overall operations, primarily during a departure push. The primary administrator's task relevant to SMS is managing the flow of aircraft out of the ramp to load the runways evenly and control the queue lengths. To accomplish this, the administrator advises ramp controllers when to hold aircraft at their gates.

Figure 6. FedEx Ramp Controller Using SMS During SMS Field Tests

The ramp controllers are responsible for the tactical movements of aircraft on the ramp, including approving aircraft pushbacks and monitoring aircraft movement. The administrator's and ramp controller's SMS displays were configured to support their specific tasks and varied between arrival and departure rushes.

Prior to the trials, human factors engineers observed ramp tower personnel performing their jobs to collect baseline data. A combination of information sources – looking out windows, listening to ATC radio frequencies, existing automation – provides a good view of the current state of the airport. SMS's predictive information is not currently available. Consequently, ramp tower personnel tend to react as things occur rather than plan ahead.

During the trials, human factors observers recorded SMS usage, user comments and questions, and administered questions designed to evaluate usability, suitability, and acceptability. SMS was reported to be most useful to ramp controllers during the arrival rush and most useful to the administrator during the departure push. During the arrival rush, controllers found estimated gate arrival times and landing sequence to be most useful. During the departure push, the administrator found the number of aircraft taxiing to each runway, the number currently queued at each runway, and the number approved for pushback to each runway most useful. Administrators also used SMS to remain aware of late arrivals.

In preparation for the TM shadow testing, FAA controllers from MEM and other airports observed SMS during the ramp tower tests and provided comments through structured interviews about how SMS would apply at each of their facilities. Additional details and results are discussed in reference [5-6].

SMS has subsequently been networked to existing FedEx computers and displays to allow access to the information at each position in the ramp tower, as well as elsewhere within FedEx, without adding additional hardware to the crowded ramp tower. FedEx has continued to operationally evaluate SMS for NASA since October, 2002 and considers the tool extremely valuable to its operations.

C. FAA Traffic Management Shadow Test

Shadow testing of SMS TM capabilities was conducted in January and February, 2003 [7]. Support from the Memphis FAA facilities and members of the National Air Traffic Controllers Association (NATCA) was instrumental to the success of the field trials. Shadow testing uses live or recorded data but allows the user to exercise SMS in a non-operational environment, to verify that it is ready to be tested operationally. Results from the TM shadow tests were used to prepare for the operational trial. Participants included two TMCs from Memphis ARTCC (ZME) and air traffic personnel from Memphis tower/TRACON who fill the positions of cab coordinator or CIC.

Shadow testing studied SMS support of specific tasks – ARTCC: APREQ coordination, MIT impact; TRACON: arrival runway assignment impact; tower: configuration change schedule. In addition, SMS support of situation awareness was studied in each facility. Participants responded positively to the SMS concept, citing its potential to help both traffic managers and controllers. Participants felt SMS focused too much on the tower and needed to expand TRACON and ARTCC roles. They commented that SMS would benefit by being demonstrated in a larger TRACON TMU. SMS accuracy was reported to be acceptable for traffic management applications but would require improvement for controller use. Participants recommended that SMS be integrated with STARS/ARTS and the Host automation system to improve data quality.

D. FAA Traffic Management Operational Trial

The operational trial (OT) of the SMS TM capabilities, conducted at the Memphis ATC facilities in September, 2003, served as a means to validate the SMS operational concept and system-level requirements for the TM component. The operational trial satisfied a major milestone of the FAA's Operational Evolution Plan (OEP). During the OT, SMS was used by SMS-trained controllers who were not "on position." These participants communicated SMS information and advisories to the controllers responsible for communicating with aircraft at that time. In addition, a TMC from DFW confirmed the applicability of SMS to the Dallas-Fort Worth environment.

The most basic capabilities of the SMS TM component include the situation awareness provided by the timeline, load graph, and table displays. These features have been evaluated in all research events and continue to be well received. Operational trial participants reported that these displays are mature and ready for deployment. Note that this conclusion included consideration of the accuracy of the data presented. According to the participants, the accuracy of SMS data, including predictions, was sufficient for traffic management use. Similarly, the SMS What-If tool and CCAT were deemed acceptable both in interface and accuracy. The concept of the RUP was well received by the controllers but the algorithmic performance was not considered to be sufficient.

One of the hypotheses of the OT was that the SMS TM component can be deployed independent of the CT component. Although the test proved this hypothesis for the majority of the SMS traffic management tools, results showed that the APREQ coordination tool requires departure release times to be displayed directly to tower Ground and Local controllers to avoid increased workload due to the communication requirements. The concept for the APREQ coordination tool was, however, accepted by both the ARTCC and tower controllers. Data collected during the OT was also used to assess the accuracy of SMS. Results of this analysis are discussed in a subsequent section and used to specify the required level of accuracy for system benefit and user acceptance.

E. FAA Local and Ground Shadow Test

The Local and Ground controller shadowing, conducted in the Memphis ATC facilities as well as FedEx ramp tower in January, 2004, provided feedback on the usefulness and benefits of the CT component of SMS. An operational trial of the CT component, although justified by the shadow test, was outside the scope of the current contract. During the shadow test, participants used stand-alone SMS displays. Prior simulation studies had showed the need to minimize the number of displays a Local or Ground controller must look at. Therefore, an operational trial would require that SMS information be integrated into existing displays. The expected architecture would be for SMS information to be integrated into the ASDE-X and STARS tower displays.

Results indicated that SMS information such as airline-assigned parking gate or hand-off spot should be incorporated into the data blocks on the controller displays. Presentation of SMS or TMC advised runway assignments via the flight data block was found to be beneficial, especially in managing aircraft just before and after a scheduled configuration change. SMS's ability to advise spot sequences was also tested. Participants reported that the advisories require additional algorithmic work before they would be beneficial.

The APREQ coordination tool was re-evaluated with display of approved departure release times directly to the Local and Ground controllers and was reported to be useful and acceptable to the participants. APREQ release times as well as EDCTs resulting from a ground delay program and MIT restrictions should be displayed in the Local and Ground controllers' data blocks on the ASDE-X map display. Additional results and details concerning the Local and Ground shadowing are contained in [8].

III. Human Factors Results

As previous NASA Air Traffic Management (ATM) research has demonstrated, involving the eventual users throughout the development process significantly increases the operational applicability and acceptability of the final product. To this end, NASA and the FAA formed a user cadre, consisting of ATCT controllers, traffic managers/supervisors, and air carrier representatives, which provided feedback on the SMS concept, performance, and interfaces at each of the demonstration activities described above. Reference [8] contains a thorough human factors assessment of SMS.

All users appreciated the "at a glance" nature of the map. However, display clutter was a theme in feedback concerning the map. Adding additional information to data blocks may increase this problem and mitigation techniques are needed. Whereas Local and Ground controllers rejected timelines and load graphs, stating the need for all information to be available on a single display, traffic managers found the trend information available through timelines to be very useful.

Typically, users' first interaction with SMS would be to compare SMS information with information available from other sources to develop confidence in SMS and familiarity with how to find particular information. After becoming comfortable, users generally preferred SMS-provided information, using SMS to replace previous, less efficient information sources. Eventually, users and organizations identified opportunities to improve how jobs are done, made possible by the new technology. Only air carriers spent sufficient time using SMS to reach this stage.

Numerous elements of the SMS concept address collaboration, both between FAA facilities and between FAA and NAS users. SMS information and decision support for collaboration that already occurs without automation tended to be accepted (e.g., tower and TRACON using SMS data to plan airport configuration changes). SMS capabilities that introduced new collaboration (e.g., presenting air carrier-provided gate availability information to tower controllers) were not studied sufficiently for a conclusion to be drawn. There was insufficient opportunity to evaluate some parts of SMS, such as the MIT tools. MEM does not experience significant MIT restrictions affecting departures. Although research focused on broadly applicable capabilities, certain capabilities are less relevant at some airports, as also seen in the benefits results.

IV. Performance Analysis

To guide algorithm development, a substantial amount of performance analysis has been conducted. However, as the SMS algorithms are improved in response to these analyses, the analyses quickly become out of date. The following is a selection of studies that show the performance of the SMS algorithms at the September, 2003 TM operational trial. The SMS prediction algorithms are discussed in references [9-12].

Accurate prediction of the future state of the airport surface poses several unique challenges. Although the restriction of aircraft to the taxiways and runways simplifies the problem, the ability of aircraft to stop and turn almost in place makes predicting trajectories and progress along those trajectories more difficult than predicting the motion of airborne aircraft which must remain within a narrow speed and performance range. Furthermore, each airport geometry and local procedures are unique and the configuration and rules (e.g., visual vs. instrument approaches) in use at a particular time are continually changing and difficult to forecast.

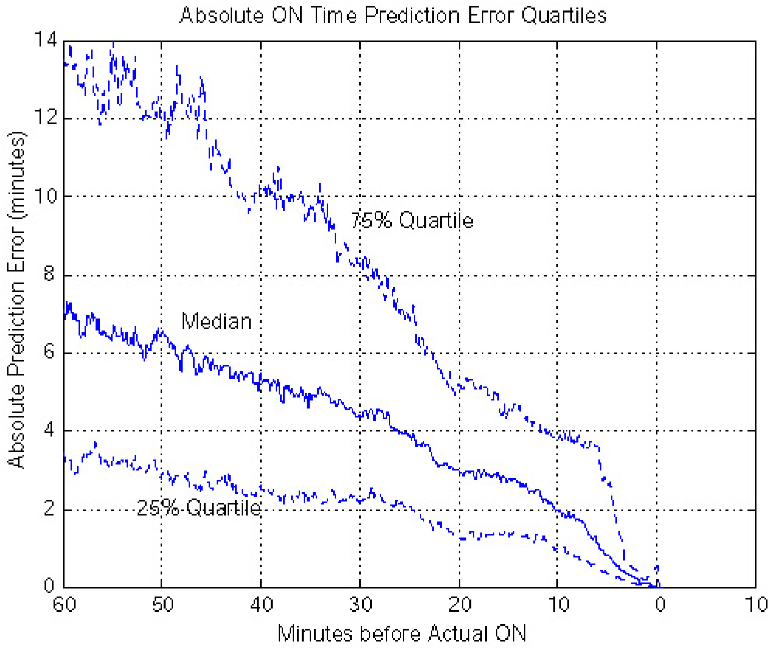


Figure 7. Absolute ON Time Prediction Error

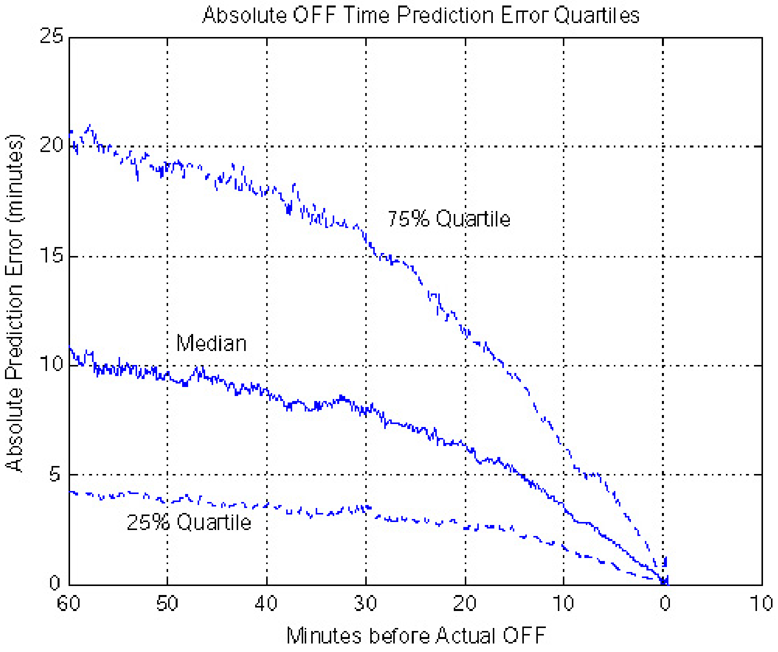


Figure 8. Absolute OFF Time Prediction Error

Future demand is also known with less certainty. Although arrivals are visible well in advance of landing, departures may pushback and begin taxiing with little correlation to their filed times (especially General Aviation flights). Even after a departure pushes back, unpredictable mechanical issues can delay taxi or require returning to the gate.

Despite these challenges limiting the possible prediction accuracy, the research proved that predictions of the achieved accuracy can have significant benefits and be acceptable to controllers for traffic management use. Note that the accuracy of aggregate predictions used in SMS traffic management applications is higher than that for individual aircraft (i.e., if SMS predicts an aircraft sequence incorrectly the predicted throughput rate may still be correct). SMS tactical applications require predictions only a few minutes into the future, a time scale for which flight specific predictions are most accurate.

Surface surveillance quality contributed significantly to prediction errors. For example, not detecting an aircraft approaching the runway because the aircraft's transponder is off causes both departure sequence and takeoff time errors, as well as reducing the efficiency of runway balancing or configuration advisories. The analysis was not able to estimate the theoretical performance with perfect surveillance.

Figure 7 plots the median absolute ON time prediction error as a function of prediction time horizon between 0 and 60 minutes, along with the 25% and 75% quartiles. Figure 8 plots the median absolute OFF time prediction error. For a 30 minute look ahead, 75% of the errors are less than 15 minutes and 25% are less than approximately 4 minutes. In contrast, for a 10 minute look ahead, 75% of the errors are less than 5 minutes. The absence of surface surveillance for some departures close to takeoff (due to transponders not being on) contributed significantly to OFF time prediction errors. In the absence of surveillance data, SMS would assume the flight was still parked at its gate; the flight would then appear on the runway. The presence of surface surveillance well before takeoff also introduced significant errors. The noise in the aircraft position data would cause SMS to detect the aircraft as having pushed back from the gate and, therefore, ready to taxi to the runway. Errors in pushback times, especially for GA flights, were the largest error source.

The errors in predicting ON and OFF times for individual flights tend to cancel when aggregating these predictions into demand for the airport as a whole or a particular resource such as a specific runway. Figure 9 plots the error in SMS predictions of departure demand in 15 min time bins for a 45 minute look ahead. 48% of 45 minute predictions are within 1 aircraft and 69% of predictions have error of 2 or less aircraft.

Figure 10 shows the arrival and departure runway prediction accuracy as a function of the time prior to actual landing or takeoff. Departure runway accuracy, the higher of the two lines, does not change noticeably until aircraft start moving toward the runways and surface surveillance becomes available. Arrival runway accuracy does not change noticeably until the aircraft enter the terminal area. Note that the effect of errors in predicting runways for individual flights is diluted in predicting airport demand because runway errors tend to cancel. Also, ON and OFF time predictions were found to be relatively insensitive to runway compared to other error sources. The data in Figure 10 assumes the airport configuration is known correctly.

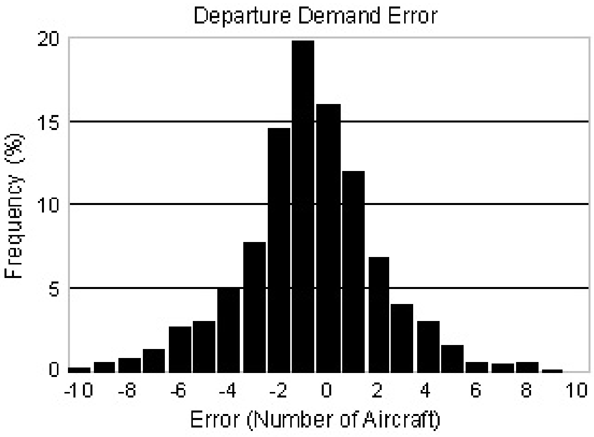


Figure 9. Departure Demand Prediction Error

Analysis of SMS's ability to predict runway queue lengths demonstrated that SMS's accuracy was good within a 15-minute prediction horizon. The queue length error was calculated by subtracting the actual queue length from the predicted queue length for each one-minute sample from the OT data. Figure 11 plots the queue length prediction error, combining data for all runways, broken down by four prediction time horizons (2, 5, 10, and 15 minutes). SMS predictions of runway queue length 15 minutes in the future had errors of 3 aircraft or less over 94% of the time; 87% of 15-minute predictions had errors of 2 aircraft or less, and 71% had errors of 1 aircraft or less. Note that this analysis included only observations when there were flights actually in the queue or predicted to be in the queue. Hence, these statistics do not include observations when there were actually zero aircraft in the queue and zero aircraft predicted to be in the queue. Note that runway prediction errors may cancel in the prediction of queue length. Detailed analysis results and interpretation is available in [8].

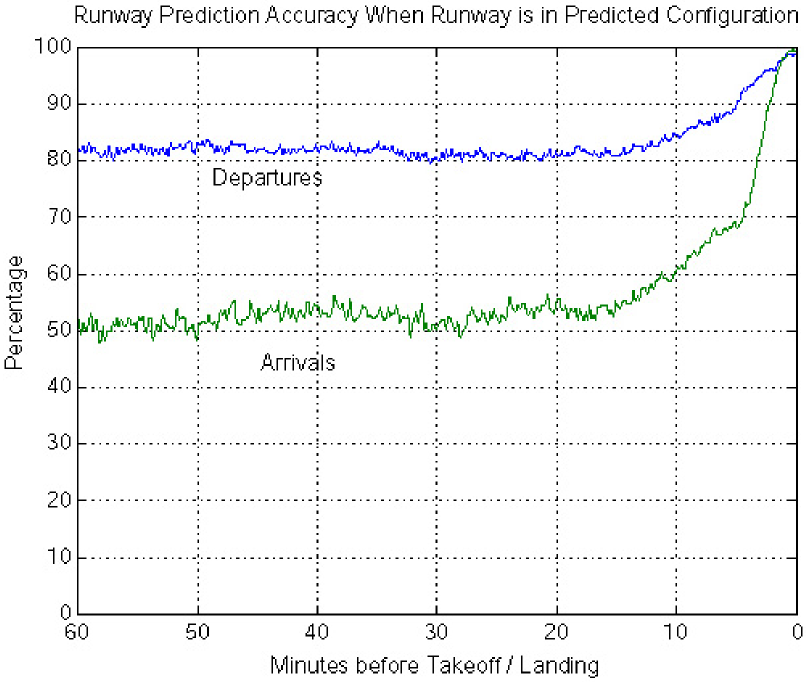


Figure 10. Arrival and Departure Runway Prediction Accuracy

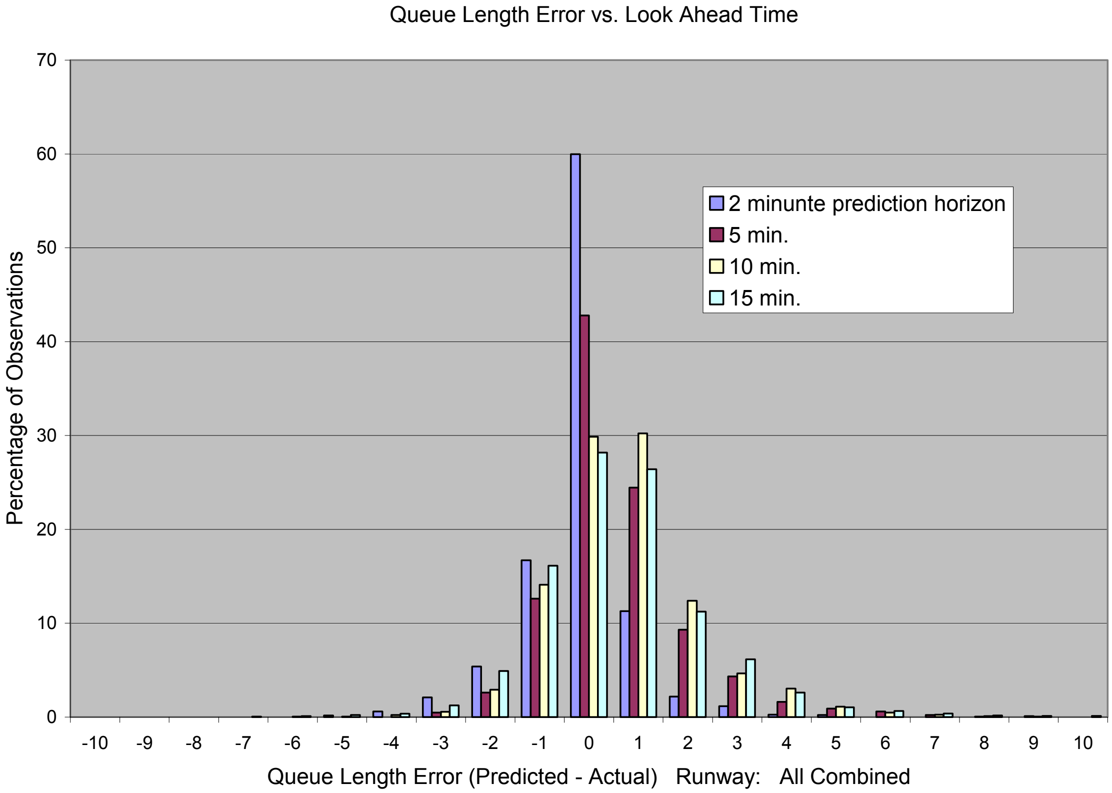


Figure 11. Queue Length Prediction Error

V. Benefits and Cost Estimates

Initial benefits modeling was used to focus SMS development toward capabilities anticipated to provide the largest benefits. Subsequent analysis focused on these benefit mechanisms to increase the accuracy and confidence in the results.

The fact that SMS was not used by FAA personnel for an extended period of time prevents benefits from being measured directly by comparing metrics from the period of use to those from a baseline period. Rather, SMS benefits have been estimated through analysis, where the models have been calibrated to data from periods of SMS use.

In addition to DFW, MEM, and Louisville International Airport (SDF), SMS has been adapted for Atlanta's Hartsfield International Airport (ATL) and John F. Kennedy International Airport (JFK) as part of benefits and cost work, illustrating the portability of SMS to other airports. Results from this detailed modeling were extrapolated to other airports to estimate benefits for various deployment scenarios. Results assume a 20 year life-cycle after the last system is commissioned.

Although several air carriers have used SMS for an extended period of time, they have not provided quantitative benefits information. Rather, they have qualitatively described how SMS improves their operations including anecdotes. The fact that they continue to use SMS is perhaps the strongest qualitative benefit result.

Table 1 summarizes the single-year benefits for the primary SMS benefit mechanisms, in terms of technical metrics. Three deployment scenarios were considered: 8 airport deployment of the TM and controller tool CT SMS components, 18 airport deployment of the TM and CT components, and a 52 airport deployment of the TM, CT, and TFM SMS components. Table 2 shows the single-year cost savings (i.e., technical metrics converted to 2004 dollars). Table 3 separates the deployment of the SMS components in each scenario and incorporates cost estimates to create benefit/cost ratios for each option. The SMS benefits are expected to significantly exceed the deployment costs in each scenario. Note that the benefit to cost ratio increases as SMS is deployed to a larger number of sites, which is expected because non-recurring costs are spread over more installations. Also, the benefits of the CT component exceed those of the TM component.

Deployment scenarios were based on the three previously described SMS components. Although parts of the CT component could be deployed independently, in Table 3 the CT deployment scenarios assume the TM component is also deployed. Additional details including the process used to generate these results are provided in [8, 13].

Benefit Mechanism	Performance Metric	8 Airports	18 Airports	52 Airports
Departure Predictions	Delay Minutes Saved			563,900
Arrival/Departure Tradeoff	Delay Min. Saved	403,000	969,400	1,466,400
Efficient Spot	Delay Min. Saved	135,500	244,800	504,700
Runway Allocation	Delay Min. Saved	1,097,300	1,648,000	3,066,400
Total		**1,635,800**	**2,862,300**	**5,601,400**

Table 1. Single-year SMS Benefits Summary in Minutes of Delay Saved

Benefit Mechanism	DFW	MEM	ATL	JFK	8 Airports	18 Airports	52 Airports
Departure Predictions							$31.8M
Arrival/Departure Tradeoff	$0M	$4.1M	$0M	$1.3M	$22.7M	$54.6M	$82.6M
Efficient Spot	$1.2M	$0.4M	$1.8M	$0.6M	$7.6M	$13.8M	$22.4M
Runway Allocation	$7.7M	$7.2M	$12.8M	$0M	$61.8M	$92.9M	$172.8M
Total	**$8.9M**	**$11.7M**	**$14.6M**	**$1.9M**	**$92.2M**	**$161.3M**	**$315.7M**

Table 2. Single-year SMS Benefits Summary (2004 Dollars)

	TFM	TM 8 Airports	TM 18 Airports	CT 8 Airports	CT 18 Airports
Total Discounted Life-Cycle Benefit	$364M	$629M	$957M	$1,372M	$2,056M
Total Discounted Lift-Cycle Cost	$59M	$99M	$129M	$123M	$158M
Breakeven Year	2008	2008	2008	2008	2008
Net Present Value	$284M	$440M	$774M	$1,167M	$1,773M
Benefit/Cost Ratio	6.2	6.3	7.4	11.2	13.0

Table 3. Summary of Life-cycle Benefits and Cost for SMS Deployment Scenarios (2004 Dollars)

VI. Technology Transfer

Previous programs have highlighted the challenge of transferring NASA-developed technology to the FAA in a way that will allow the FAA to successfully and affordably deploy that technology. SMS technology transfer was planned from the beginning of the project and remained a focus throughout to address these lessons.

One critical aspect of technology transfer is transferring the detailed information about a complex system to a new organization without requiring "re-learning" by the new organization. To facilitate the transfer of knowledge about SMS, the FAA was involved from the very beginning through the Interagency Integrated Product Team (IAIPT) between NASA and the FAA. The Free Flight Program Office named an FAA Program Manager for coordination of SMS activities. Later in the research, SMS was transitioned to the FAA Terminal Business Unit (ATB), now called ATO Terminal Services (ATO-T), which is responsible for SMS deployment. The FAA has named the version of SMS being considered for deployment the Surface Traffic Management System (STMS). Also as part of this effort, NASA developed extensive specifications and other documentation of the as-built system to allow the FAA to fully understand the SMS design and what research led to that design.

NASA coordinated closely with the FAA throughout the work to ensure that the concept and resulting technology would be accepted by the FAA and able to be deployed throughout the NAS to achieve the intended operational benefits. Throughout the development of SMS, the tradeoff between the performance of SMS algorithms and resulting benefits and the complexity of the algorithms and adaptation data required to support those capabilities was carefully considered. Significant deployment issues have been avoided by adopting the simplest technical approach that would satisfy the requirements.

Although initially hoped that the majority of the NASA SMS software could be directly reused by the FAA, the nature of research software development requires flexibility and rapid prototyping that result in software that is not as maintainable as if the final requirements had been known in advance.

SMS has satisfied the requirements for Technology Readiness Level (TRL) 6 on the NASA scale of research maturity; the NAS user components have satisfied the requirements for TRL 7 based on continued daily use by FedEx and NWA, and at SDF. The SMS prototype has also demonstrated applicability at multiple airports and the ability to be easily adapted to new airports. However, based on lessons learned, the FAA may determine that some redesign of the implementation is necessary before SMS could be broadly deployed. For example, the need to avoid new displays in the ATCT environment will require that SMS be integrated with other existing systems such as ASDE-X, the STARS tower display, and the Traffic Situation Display (TSD).

VII. Summary and Conclusions

SMS research began in early 2000 with the goal of developing and field testing a proof-of-concept SMS to identify the appropriate functionalities, develop algorithms capable of achieving the required performance (and determining that performance), understanding basic user display requirements, and validating predicted benefits. The proof-of-concept SMS, currently running at Memphis and Louisville airports, accomplished each of these objectives.

Many of the SMS capabilities were considered useful and acceptable in their current form. Users reported others as having potential but requiring additional refinement; this second class could be studied further by NASA or the FAA and deployed in a future development spiral. Researchers concluded that the current lack of surface automation limited the near-term acceptance of advanced airport surface decision support concepts. ATCT operations are conducted with minimal automation support today – large windows, paper flight progress strips, and a radio are the primary tools. Some of the capabilities studied were more revolutionary than evolutionary and, therefore, current lack of user acceptance does not imply the concept would not be accepted in the future. The ATCT environment may evolve significantly over the next several years as ASDE-X becomes available and controllers devise new ways to use the information.

Moreover, many towers do not currently have dedicated traffic managers, because there has never been enough information to allow a traffic manager to plan airport use. Consequently, tower controllers are accustomed to operating in a reactive way as information becomes available, rather than strategically planning or optimizing. This also may change, increasing the application of SMS.

Many challenges arose during SMS research due to the lack of reliability and accuracy of the surface surveillance data. Many of these issues were caused by transponders being turned off while aircraft were on the airport surface – causing aircraft to not be visible to the surface surveillance system until they turned their transponder on at the runway. The prototype surveillance system also saw aircraft in the ramp area jump randomly at times. Unless surface surveillance improvements associated with the deployed ASDE-X resolve this, surface surveillance is not appropriate for detecting OUT and IN ramp events.

The successful completion of this effort has provided NASA and the FAA with a valuable step forward in improving the capacity, efficiency, and flexibility of operations on the airport surface. Historically, the airport surface has seen less automation than other parts of the NAS; SMS is poised to provide the type of automation at the airport that is currently available in other domains. Numerous opportunities for near and long-term research and development have been identified and could be incorporated into SMS as future releases.

A. Future Work

SMS continues to operate in the Memphis ATCT/TRACON Facility Manager's office; several groups within FedEx use SMS daily, and NWA uses SMS at its AOC in Minneapolis, MN. In conjunction with NASA and the FAA, SMS is currently being modified for SDF.

A large number of opportunities for continued research and development have been identified. As part of a more thorough survey of other airports, a larger group of FAA users should comment on SMS to assure operational applicability throughout the NAS. Human factors work associated with integrating SMS information onto the displays of existing automation should be begun to reduce deployment risks. ASDE-X surface surveillance data is anticipated to be more reliable than that used during this research, as aircraft compliance with transponder procedures increases.

Analysis of SMS performance with reliable surface surveillance data would also support FAA deployment of SMS. Integration of SMS with other automation, such as STARS for arrival runway data or TMA for more accurate arrival time predictions, could further improve SMS performance.

NASA is also continuing advanced SMS research. Several of the SMS advisory were determined to require further refinement prior to deployment in subsequent development spirals. Application of SMS information to TFM could be demonstrated by connecting SMS to ETMS. Explicit inclusion of weather information and environmental considerations would improve SMS usability. Finally, integration of SMS at multiple dependent airports could be studied as a way of reducing departure restrictions through improved coordination.

VIII. Acknowledgments

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