Thirteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2019)

Field Evaluation of the Baseline Integrated Arrival, Departure, and Surface Capabilities at Charlotte Douglas International Airport

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Abstract—**NASA is currently developing a suite of decision support capabilities for integrated arrival, departure, and surface (IADS) operations in a metroplex environment. The effort is being made in three phases, under NASA's Airspace Technology Demonstration 2 (ATD-2) sub-project, through a close partnership with the Federal Aviation Administration (FAA), air carriers, airport, and general aviation community. The Phase 1 Baseline IADS capabilities provide enhanced operational efficiency and predictability of flight operations through data exchange and integration, tactical surface metering, and automated coordination of release time of controlled flights for overhead stream insertion. The users of the IADS system include the personnel at Charlotte Douglas International Airport (CLT) air traffic control tower, American Airlines ramp tower, CLT terminal radar approach control (TRACON), and Washington Center. This paper describes the Phase 1 Baseline IADS capabilities and field evaluation conducted at CLT from September 2017 for a year. From the analysis of operations data, it is estimated that 538,915 kilograms of fuel savings, and 1,659 metric tons of CO_2 emission reduction were achieved during the period with a total of 944 hours of engine run time reduction. The amount of CO_2 savings is estimated as equivalent to planting 42,560 urban trees. The results have also shown that the surface metering had no negative impact on on-time arrival performance of both outbound and inbound flights. The technology transfer of Phase 1 Baseline IADS capabilities has been made to the FAA and aviation industry, and the development of additional capabilities for the subsequent phases is underway.**

Keywords - Surface Scheduling and Metering; Collaborative Decision Making; Integrated Arrival, Departure, and Surface (IADS)

I. INTRODUCTION

Flight operations in a metroplex airspace pose many challenges to the stakeholders including air navigation service providers, flight operators, and airports due to the complexity of the entire system. Operations in a metroplex environment involve surface operations in multiple airports, large or small, and arrivals and departures to and from these airports that are interacting with each other while sharing the same terminal airspace resources. Various constraints are imposed to flights over the control points such as runways, arrival/departure fixes, and en-route meter points in order to balance demand and capacity from both local and global traffic flow management perspectives. Although some decisions are made through the aids of automation, the solutions are often fragmented and the performance of the whole system is far from optimal, especially due to large uncertainties.

In support of the Next Generation Air Transportation System (NextGen) [1] National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) have been collaborating to develop a concept of integrated arrival, departure, and surface (IADS) operations for many years. NASA's research in the IADS domain includes the Spot and Runway Departure Advisor (SARDA) [2], the Precision Departure Release Capability (PDRC) [3], and the Terminal Sequencing and Spacing (TSAS) [4] research. SARDA provides gate pushback advisories to the ramp controller to improve efficiency of surface operations and reduce fuel burn. PDRC improves overhead stream insertion calculations performed by FAA's Time Based Flow Management (TBFM) tool through improved prediction of departure takeoff times and runway assignment. TSAS research is the combination of TBFM for terminal area scheduling and Controller Managed Spacing (CMS) that assists air traffic controllers to maintain inter-arrival spacing.

In 2015 NASA started the Airspace Technology Demonstration 2 (ATD-2) sub-project to develop and demonstrate the IADS capabilities in three phases over five years. Charlotte Douglas International Airport (CLT) was selected as the airport for the field demonstration. The Phase 1 Baseline IADS capabilities include 1) data exchange and integration, 2) tactical surface metering, and 3) departure scheduling and electronic negotiation of release time of controlled flights for overhead stream insertion. The entire process of development and field evaluation has been carried through a close partnership with the FAA, American Airlines (AAL) Integrated Operations Center (IOC) and CLT Hub Control Center (i.e., ramp tower), FAA air traffic control facilities including air traffic control tower (ATCT or Tower), CLT Terminal Radar Approach Control (TRACON), Washington Air Route Traffic Control Center (ARTCC or Center), and pilot community at CLT. The primary focus of the Phase 2 field evaluation is on the fusion of strategic surface

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ATD-2 sub-project is sponsored by the National Aeronautics and Space Administration (NASA) Airspace Technology Demonstration (ATD) Project.

metering, that is to extend the horizon of prediction of demand-capacity and scheduling for surface metering. The Phase 3 field evaluation is focused on the scheduling of departures in a metroplex environment, where departures from multiple airports share the same constrained terminal airspace resources.

This paper describes the field evaluation of the Phase 1 Baseline IADS demonstration conducted at CLT beginning at the end of September 2017 through September 2018 and presents the results of key performance and benefits metrics. The paper is organized as follows. Section II provides the motivation and a brief survey of previous research conducted in the IADS domain. Section III describes the operational concept of the Phase 1 Baseline IADS system. Section IV presents the results from the Phase 1 field evaluation in terms of system usage and key performance and benefits metrics. Section V concludes with a summary of key findings from the Phase 1 demonstration and plans for further development and testing of additional features.

II. BACKGROUND

A. *Challenges*

As a robust economy growth is in forecast, the NAS in the U.S. is facing serious challenges to meet growing traffic demand in air transportation with the given capacity that airports and terminal/en-route airspace can handle [5]. It is extremely costly and time consuming to build a new airport or add a new runway to an existing airport. Airlines operating at major hub airports tend to schedule multiple flights at times close to each other, which results in resource competition and significant congestion on the airport surface. With lack of appropriate planning tools and coordination with ATCT, the ramp controllers tend to push back aircraft from gates as soon as flights are ready after the boarding process is completed, which often results in large excess queue time and extra fuel consumption. Most of the time, a sequence of departure takeoffs is determined based on the 'first-come, first-served' (FCFS) operation without adequately considering aircrafts' weight class, departure routes, or traffic flow constraints imposed by downstream air traffic control facilities. Poor departure takeoff time prediction for the aircraft under Traffic Management Initiatives (TMIs), such as APREQ[1] (Approval Request) [6], often results in overly conservative release times assigned to the aircraft. As a result, without proper coordination between ATCT and the Ramp, aircraft may spend extra time on the airport surface, causing more congestion, extra fuel burn and emissions.

Currently, there exist decision support tools available at traffic control facilities, but most of the tools are intended to serve their own objectives without knowledge of the holistic picture. Electronic data are not readily exchanged, nor integrated amongst tools, and verbal communications cause system inefficiency and increased controller workloads.

B. *Previous IADS Research*

In the early 2000s, NASA in coordination with the FAA developed the Surface Management System (SMS) to assist ATCT and ramp tower personnel to enhance efficiency, capacity, and flexibility in airport surface operations through accurate prediction of surface traffic demand. SMS was tested in both human-in-the-loop (HITL) simulation and operational environments for Memphis International Airport [7]. The FAA Surface Trajectory Based Operations (STBO) project further developed its capability into the Collaborative Departure Queue Management (CDQM) tool that aims to reduce the departure runway queue length using a count-based, ration-by-schedule (RBS) technique that allocates departure slots to the airlines [8]. In 2012, the FAA developed an IADS concept of operations in the mid-term, where the operations are managed through IADS scheduling and sequencing with accurate prediction of flight ready times and departure takeoff times. The decisions are made via a collaborative decision-making process with increased data exchange and situational awareness among stakeholders [9].

In Europe, departure queue management through a Collaborative Decision Making (CDM) process, called the Airport CDM (A-CDM), has been developed and implemented at many airports [10,11]. A-CDM system provides pre-departure sequence planning by calculating off-block times to reduce runway queue and surface congestion. Since its beginning in the early 2000, A-CDM has generated operational benefits both from local and network perspectives, including taxi-out time savings, fuel burn savings, and emissions reduction, and increased predictability [11]. Furthermore, in support of Advanced-Surface Movement Guidance and Control System (A-SMGCS), research has been conducted to develop surface planning tools to provide trajectory-based runway and taxi schedules based on optimization techniques with the objective of increased throughput and reduced taxi delay and emissions [12].

NASA researchers developed runway and taxi scheduling algorithms for airports modeled as a node-link network using optimization techniques, and assessed performance and benefits in terms of taxi time and throughput [13-16]. The runway and spot[2] release scheduler reflecting FAA's Surface Collaborative Decision Making (S-CDM) Concept of Operations (ConOps) [17], called the SARDA, was developed for ATCT local and ground controllers and evaluated for Dallas/Fort Worth International Airport (DFW) in HITL simulations [18-22]. SARDA's spot release planner (SRP) provided spot release advisories to the ground controller and runway sequence advisories (for both takeoffs and crossings) to the local controller. The experiment results showed that 45-60% reduction in excess taxi-out time was achieved for both medium and heavy traffic scenarios [23]. In 2014, SARDA's scheduling algorithm was extended to provide tactical gate pushback advisories to the ramp controller. The concept was evaluated for CLT surface operations in a HITL simulation with current ramp controllers from American Airlines (then US Airways). The results showed that the tool helped reduce excess taxi-out time by one minute per flight [2].

The PDRC is a tactical departure scheduling tool developed to provide ATCT Traffic Management Coordinators (TMCs)

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[1] APREQ is a tactical departure scheduling procedure designed to coordinate the departure's release time from the origination airport to facilitate stream insertion or the merging of traffic at a downstream schedule point.

[2] "Spot" is the hand-off point between the airline ramp control and Tower control, marked on the pavement with a number.

with the capability of automatic scheduling of release times for departures subject to APREQ restriction for overhead stream insertion [24,25]. PDRC sends improved takeoff time estimates to the En Route Departure Capability (EDC) of the research version of TBFM to calculate runway release times for APREQ flights. The calculated release times are sent back to ATCT through the data communication interface. A field test was successfully conducted in an operational environment in 2011 at NASA's North Texas research facility in Dallas/Fort Worth [25].

III. ATD-2 OPERATIONAL CONCEPT

The operational concept of ATD-2 IADS system covers the operations in metroplex airspace that includes multiple airports, both well and less equipped, and terminal airspace where arrivals and departures to and from these airports share the meter points on the boundary of the terminal airspace (see Fig.1). Well-equipped airports are equipped with a ground surveillance system, such as Airport Surface Detection Equipment Model-X (ASDE-X), and automation tools for ATCT and airline ramp operations. The Ramp manages ramp operations, including gate pushback, taxi, and resolving gate conflicts between arrivals and departures. Tower controllers control the traffic in the airport movement area (AMA) to ensure safe separation during taxi and runway operations (i.e., takeoffs, landings, and crossings). The Tower TMC, in coordination with TRACON, makes decisions as to how the runways are utilized to maximize throughput and balance the loads between runways. In addition, the Tower TMC coordinates with Center for implementing TMIs, such as Miles-in-Trail, Ground Delay Program, Ground Stop, and APREQ restrictions due to downstream flow constraints. For example, Tower TMC coordinates with Center Traffic Management Unit (TMU) and receives release times of departures affected by APREQ restriction. The Tower TMCs and ramp managers communicate traffic management decisions with each other. In current operations, much of these communications among control facilities are still made via phone calls, which takes longer response time, and causes higher workloads and potential for errors.

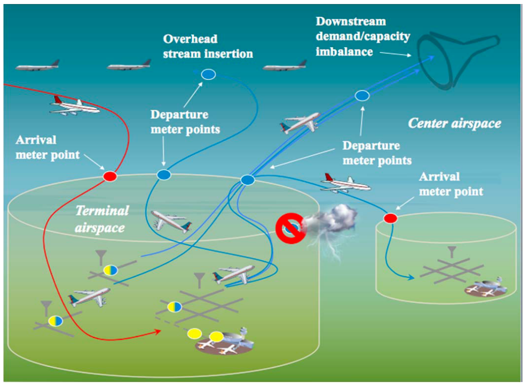


Figure 1. ATD-2 end-state concept environment [26].

The goal of the ATD-2 Phase 1 Baseline IADS system is to demonstrate operational benefits (e.g., reduced excess taxi time and fuel savings) as well as human factors benefits (e.g., situational awareness and workloads) [26] for CLT IADS operations through the three major capabilities: 1) data exchange and integration, 2) tactical surface metering, and 3) scheduling of overhead stream insertion of departures under APREQ restriction. The rest of this section presents a brief description of each capability.

A. Data Exchange and Integration

Data exchange and integration is the foundational capability of the ATD-2 IADS system. It not only provides improved situational awareness among users, but ultimately enables the system to generate accurate prediction of aircraft trajectories and future demand-capacity imbalances, which is crucial to surface scheduling and metering. The IADS system allows multiple users to interact with one another through automation. The IADS system receives flight plans, gates, earliest off-block times (EOBTs), aircraft position, TMIs, and many others from multiple sources, including FAA's System Wide Information Management (SWIM) feeds, flight operators' data feed, and commercial sources such as FlightStats data service [27]. The feature called 'Fuser' is at the center of data integration, where inputs from disparate sources are ingested and mediated, and a consistent set of data are produced and used by the rest of the system. The decisions made or information input to the system by ATCT (e.g., departure fix closure, runway utilization, TMI restrictions, etc.) and the Ramp (e.g., ramp closure, runway assignment requests, etc.) are shared with each other electronically without delay.

Figure 2. STBO Client – main interface for ATCT TMC.

Figure 3. Ramp Manager Traffic Console (RMTC).

Figs. 2 and 3 show the main user interface displays for Tower and the Ramp users, respectively, that show various information at individual flight level as well as airport operations through data exchange and integration. Detailed information about data flow and architecture of the Fuser is found in ATD-2 Technology Description Document [28].

B. Surface Modeling and Scheduling

The Surface Modeler updates the state of each flight and predicts the gate, spot, runway, and taxi route from surface surveillance, FAA's TBFM/Traffic Flow Management System (TFMS)/Terminal Flight Data Manager (TFDM) SWIM, and flight operator data feeds, along with user inputs. The Surface Modeler's main goal is to predict undelayed trajectories of aircraft on the surface. Each departure aircraft's undelayed takeoff time (UTOT) is calculated by adding the transit time, from either current aircraft position or the gate to the runway, to the current time or aircraft's EOBT. Similarly, prediction of gate-in time of arrival aircraft is calculated from its transit time from runway or aircraft's current position to the gate. The undelayed transit times for departures and arrivals on the surface are obtained from the historical data [29]. In addition, gate conflicts and Long-on-Board (LOB) are predicted by the Surface Modeler and informed to the users.

The Surface Scheduler schedules the target takeoff times (TTOTs) of departure aircraft based on UTOTs, then separates them according to a set of pre-determined rules. The separation rules consider multiple factors, including aircraft wake turbulence category, runway utilization intent (e.g., dual usage runway or converging runway operations), controlled takeoff times due to TMIs, departure fix separation, and runway crossings. Either a FCFS or 'first-scheduled, first-served (FSFS)' scheduling algorithm is used depending on the flight's status, such as 'taxiing' or 'scheduled out' (i.e., aircraft has not pushed back) as well as the surface metering status (i.e., active or off). The ATD-2 Surface Scheduler algorithm schedules TTOTs by reflecting the dynamic traffic situation on the surface and intents of the flights. The outcome of the scheduler function is the estimates of demand and capacity for each departure runway, which will provide the basis for surface metering and other traffic management decisions. The scheduler algorithm has been evolving through an iterative process involving operational data analysis and feedback from field users. The design and performance of the scheduling algorithm are found in [28,30,31].

C. Collaborative Tactical Surface Metering

The goal of surface metering is to reduce taxi-out time of aircraft by shifting some of the taxi time from the departure queue to gates while engines are off, thus reducing both fuel burn and engine emissions, and allowing more time for passenger boarding and baggage loading. The Surface Metering function of the ATD-2 IADS system generates target times for both off-block (i.e., pushback) and entry into the movement area. These target times are provided as advisories to the ramp controllers on their display. The target off-block time (TOBT) is calculated according to the delay propagation formula:

$$TOBT = \max\{\, EOBT \; or \; CurrentTime,\; TTOT - UTT - Y \,\} \quad (1)$$

where UTT is the undelayed transit time from gate to runway, and Y is the target excess taxi-out time. Table I shows the surface metering parameters set by the user to control the amount of gate holding. In addition, the user sets the condition to display metering advisories triggered to 'on' or 'off'. Display of surface metering advisories is automatically triggered when the scheduler assesses that the excess taxi-out time of an aircraft taxiing on the surface is predicted to exceed the target excess taxi-out time *(Y)* and that an aircraft at gate predicted to push back in the next 10 minutes is predicted to experience excess taxi-out time greater than the upper threshold *(UT)*. The metering advisory display will be triggered 'off' if no aircraft at the gate within 10 minutes of pushback is predicted to have an excess taxi-out time greater than the lower threshold *(LT)*. As indicated in (1), the larger the Y value is set the less the gate holding is advised, and vice versa. Also, the target off-block time (TOBT) is always greater than or equal to EOBT, meaning that under a metering situation an aircraft that is ready earlier than its EOBT will likely need to wait for a pushback clearance until its EOBT, which emphasizes the importance of accuracy of EOBT supplied by the flight operator.

TABLE I. TACTICAL SURFACE METERING PARAMETERS

Parameters	Description
Target Excess Taxi-Out Time (*Y*, min)	Excess taxi-out time allowed for aircraft in departure queue (e.g., 10 min)
Upper Threshold (*UT*, min)	Excess taxi-out time above which display of metering advisory is triggered on (e.g., 12 min)
Lower Threshold (*LT*, min)	Excess taxi-out time below which display of metering advisory is triggered off (e.g., 5 min)

The ATD-2 Phase 1 Baseline IADS demonstration is focused on tactical surface metering, where the prediction of surface demand-capacity imbalance is made in a tactical timeframe (e.g., 10 minutes into future) and TOBTs are updated every 10 seconds reflecting traffic situation on the surface and EOBT updates. Once an aircraft's pilot calls in ready for pushback, its TOBT becomes frozen and the ramp controller is advised to release the aircraft at its TOBT. The IADS system generates a prediction of excess taxi-out time and displays it on the Surface Metering Display (SMD) to help the ramp traffic manager set the metering parameters and decide when to set the surface metering condition to 'on' in close collaboration with ATCT TMC.

The Target Movement Area entry Time (TMAT) generated by the surface metering algorithm is the target time that the aircraft is expected to cross its designated spot and enter the AMA. The metering advisory for the ramp controller includes both TOBT and TMAT. TMAT is calculated by the scheduler by adding the undelayed ramp transit time from gate to the spot to TOBT, such that if TOBT compliance (e.g., within ±2 min) is met by the ramp controller, then TMAT compliance (e.g., within ±5 min) is also expected to be met in normal situations.

Although the objective of surface metering is to reduce the departure runway queue length during busy periods by holding aircraft at their gates, the runway throughput should not be negatively affected by metering, nor the arrival ON-time performance of departures at their destination airports. These are important metrics that must be examined in addition to the key surface metering performance/benefits metrics, such as taxi-out/taxi-in times, gate hold times, fuel savings, and emissions reduction. A detailed description of the ATD-2 surface metering concept and design is found in [28,31,32].

D. *Tactical Departure Scheduling for Overhead Stream Insertion*

ATD-2 Tactical Departure Scheduling is the capability that facilitates automated coordination between ATCT and the related Center for the release time of the departures subject to APREQ restrictions for overhead stream insertion. For the Phase 1 demonstration, the ATD-2 IADS system was integrated with FAA's TBFM/IDAC (Integrated Departure Arrival Capability) to schedule flights departing from CLT into Washington Center's (ZDC) airspace. These departures are bound to ZDC's adjacent facilities, such as the Potomac Consolidated TRACON (PCT), the New York TRACON (N90), and the Philadelphia TRACON (PHL), and are subject to flow restrictions that require the flights to meet miles-in-trail (MIT) restrictions over constrained meter points. The ZDC Center TMC will typically schedule the departure's crossing time at the meter points to meet the MIT restriction, which is passed back to CLT.

ATD-2 Tactical Departure Scheduling enables non-verbal coordination of release times at CLT through the interface embedded in STBO Client's timeline. Prior to pushback from gate, the surface scheduler estimates the earliest feasible takeoff times (EFTTs) of APREQ flights by which the aircraft will reach the runway with a high confidence. These times are displayed on the timeline of Tower TMC. When the APREQ aircraft is selected on the timeline, TBFM/IDAC searches for the window(s) of release time that would allow the aircraft to be inserted in the available slots in the overhead stream over the constrained meter point. TBFM/IDAC calculates a runway release time based on the flight's EFTT and returns it to the Tower. If the 'Select Slot on Timeline' option is chosen the Center sends a release time that is either the same time as requested or a different time depending on slot availability. Detailed information regarding ATD-2's automated APREQ coordination procedures are found in [32,33].

The improved prediction accuracy of takeoff time by the ATD-2 surface scheduler enables Tower TMC to coordinate release times with the Center while aircraft are still at the gate with engines off. The surface scheduler calculates target pushback time (TOBT) from the negotiated release time. This would allow the aircraft to be held at the gate until its TOBT, but reach the runway and take off within the compliance window, i.e., from two minutes earlier to one minute later than the release time. The gate holding due to scheduling prior to pushback saves fuel burn that would otherwise have been spent on the airport surface. Also, the electronic coordination procedure makes the re-negotiation process easier and faster in cases when STBO Client timeline indicates that the aircraft is predicted to arrive at the runway earlier or later than the release time [34]. The re-negotiation would allow the aircraft to take an earlier slot in the overhead stream, thus resulting in an earlier runway release time.

IV. PHASE 1 FIELD EVALUATION RESULTS

NASA deployed the Phase 1 Baseline IADS system in CLT facilities for operational field evaluation in late September 2017. The Phase 1 capabilities, installations, and associated users who participated in the field evaluation are shown in Table II. The displays listed in the table are the main interfaces that allow the users to interact with the system, provide additional situational awareness, and help reduce the amount of verbal communication.

This section presents the selected results of the Phase 1 field evaluation conducted at CLT through the end of September 2018. The data generated by the ATD-2 operational system and recorded in the database for analysis include: input data from external sources such as TBFM/TFMS/TFDM SWIM and American Airlines data feed, user inputs made through STBO Client and Ramp Traffic Console (RTC)/Ramp Manager Traffic Console (RMTC), outputs from the surface modeler and scheduler, and outputs from surface metering.

TABLE II. ATD-2 PHASE 1 BASELINE IADS CAPABILITIES AND USERS

Facility	User	Display/Capability
CLT Tower	Tower TMC	• STBO Client display • APREQ coordination with Center • RMTC (observer mode)
CLT TRACON	TMU	• STBO Client display • RMTC (observer mode)
ZDC Center	TMU	• STBO Client display • APREQ coordination with Tower
AAL Ramp Tower	Ramp controller	• RTC • Surface metering
	Ramp traffic manager	• RMTC • Surface metering

A. *Collaborative Surface Metering*

CLT is a major hub airport for AAL flight operations with nine traffic banks of departures and arrivals throughout the day. Each bank has a surge of departures pushing back from gates, overlapped by arrivals coming in about a half hour into the bank (see Fig. 4), which causes heavy traffic congestions in both Ramp and AMA, resulting in long departure queues and increased controller workloads.

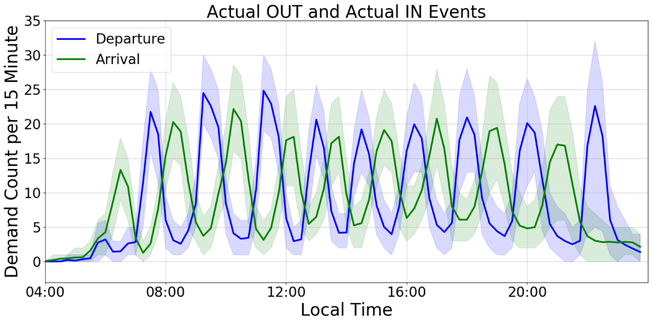


Figure 4. Aircraft count for gate arrival (IN) and gate departure (OUT) events averaged for Oct 2017 – Sept 2018. The shaded area represents the range between 10th and 90th percentiles.

In late November 2017, tactical surface metering was enabled during the second bank of CLT operations initially (typically starting around 9am local time) and extended into the third bank in February 2018. Fig. 5 depicts the CLT airport diagram, where three parallel runways (18L/36R, 18C/36C, 18R/36L) and one diagonal runway (5/23) are shown. With exceptions, runways 18R/36L and 23 are used for arrivals only;

18C/36C for departures only; and 18L/36R for both arrivals and departures. There are three major flow configurations utilized for runway operations depending on the airport conditions, such as wind direction and traffic demand: 'South Converging' configuration uses three parallel runways (18L, 18C, 18R) and the diagonal runway (23), achieving maximum capacity; 'South Simultaneous' configuration uses three south parallel runways; and 'North' configuration uses three north parallel runways (36L, 36C, 36R). Runway configuration governs the traffic pattern, such as spot/runway assignments and taxi route/distance. Runway configuration is the dominant factor considered in setting surface metering parameters, and the dynamics of surface traffic and performance of surface metering are influenced by these parameters.

Surface metering was used during bank 2 for 258 days out of 303 days (85.1% from Nov 29, 2017 through Sept 30, 2018); and during bank 3 for 170 out of 223 days (76.2% from Feb 19 through Sept 30, 2018). Surface metering was not used when traffic demand was not high enough or during irregular operations caused by weather, such as de-icing and hurricane. Fig. 6 shows the distribution of runway configurations used during banks 2 and 3, and the average number of departures and arrivals during surface metering days. As can be seen in the figure, North flow was the dominant configuration during this period. The numbers of departures were similar between the two banks, whereas there were less arrivals during bank 3 than bank 2.

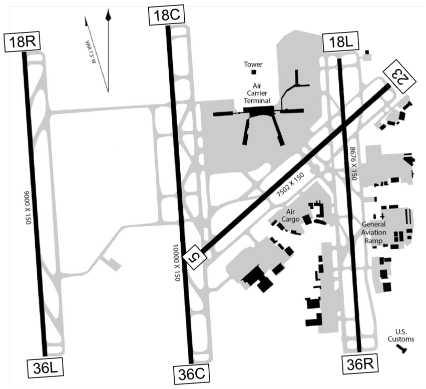


Figure 5. CLT airport diagram.

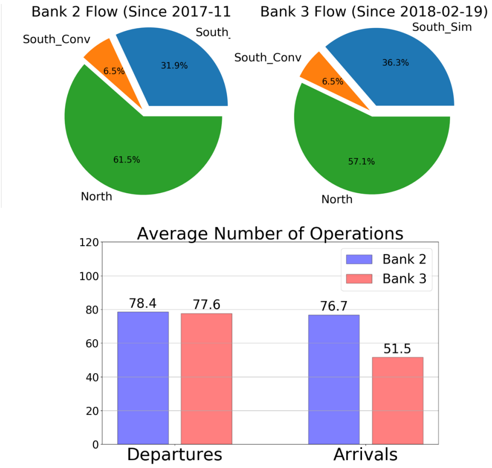


Figure 6. Runway configuration (upper) and average number of operations (lower) during surface metering.

A.1 Metered Flights and Gate Hold Times

Fig. 7 shows the average number of departures subject to surface metering (orange), number of aircraft that were assigned a gate hold advisory (green), and number of departures actually held at their gates by the ramp controller (red) during bank 2 and bank 3, separated by runway configuration. The aircraft subject to surface metering are the ones for which metering advisories are displayed to the ramp controller either by a hold time in 'mm:ss' or 'PUSH' if no further hold is advised. It was observed that metering generally triggers approximately 15 minutes into the bank when the scheduler detects a physical queue existing in the AMA and estimated gate hold time exceeds the threshold, so that gate holding is warranted. Of those aircraft subject to metering, a small number of aircraft did not need any gate holding (indicated by the difference between orange and green bars). This was primarily the case where TOBT was the same as the current time because its EOBT was in the past, see (1). The RTC displays pushback advisories in minutes next to the flight strip and a countdown timer starts as the aircraft is put on hold by the ramp controller after the pilot calls in ready to depart. The surface metering procedure was developed such that the ramp controllers are allowed to push back aircraft if the hold time, either initial or remaining, is less than 2 minutes. The difference between green and red bars in Fig. 7 are aircraft that controllers were able to and did push immediately due to initial gate hold advisories less than 2 minutes.

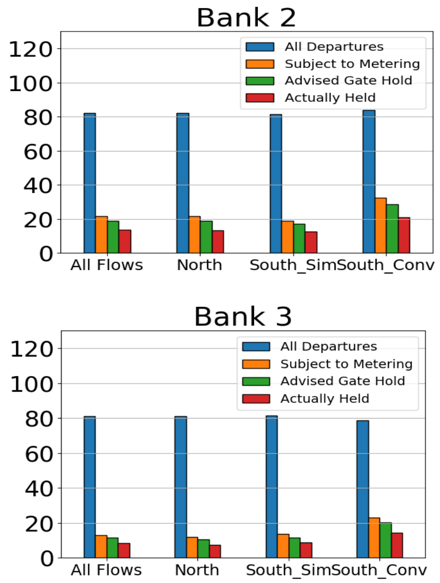


Figure 7. Metering statistics: all departures (blue); subject to metering (orange); with non-zero hold advisories (green); actually held (red).

In Fig. 8, box plots show the comparison of the distribution of gate hold times between advisories and actual hold during each metering period. The actual gate hold times are shorter than hold advisories in all quartiles in both banks, which indicates that the ramp controllers tend to hold departures less than they are advised by the scheduler (the mean values of advisories vs. actual hold times are 6.2 min and 3.5 min, respectively, for bank 2; and 6.3 min and 3.6 min, respectively, for bank 3).

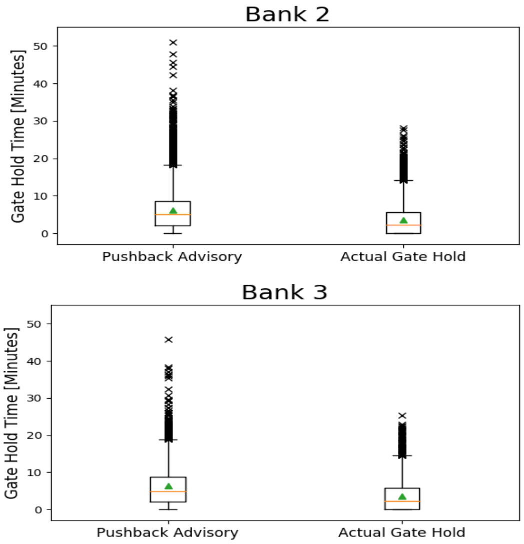
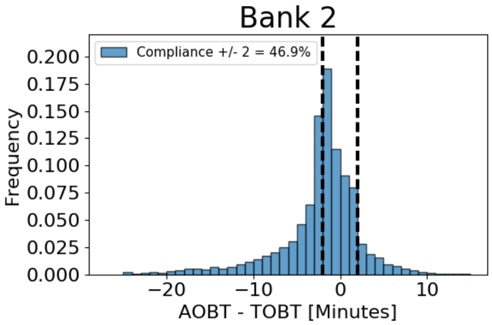


Figure 8. Pushback advisories vs. actual gate hold times. (Horizontal bars show median, 25th, and 75th percentile; vertical whiskers show 1.5 IQR; triangles show the mean.)

Fig. 9 shows the distribution of the difference between target off-block times (TOBTs) and actual off-block times (AOBTs), which indicates the compliance of pushback advisory by the ramp controller. The ramp controllers were advised to release the aircraft within ±2 minutes of its TOBT (vertical dashed lines) in order to maintain scheduler integrity and thus achieve the performance objectives of surface metering. The results show that the ramp controllers met the compliance window for 46.9% and 45.9% of flights for bank 2 and bank 3, respectively. In addition, the result is skewed towards negative compliance, indicating that the ramp controllers tend to release aircraft earlier than TOBTs. The plot also reveals that there are cases with large deviations from the advisories, which may be due to either potential gate conflicts with arrivals (earlier pushback) or pushback being blocked by other aircraft (delayed pushback) among other reasons.



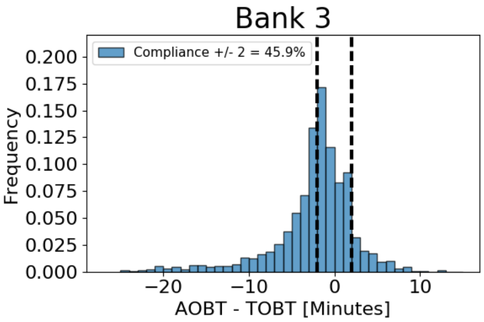


Figure 9. Compliance of pushback advisory (dashed lines show the ±2 min compliance window of TOBT).

A.2 Surface Metering Performance and Benefits

a) Excess taxi-out time: First, excess taxi-out time was examined to assess the effect of gate holding on surface congestion. Excess taxi-out time is defined as the difference between actual taxi-out time (from gate pushback to start of takeoff roll) and undelayed taxi-out time. The gate pushback event of a departure aircraft is recorded when the ramp controller makes a mouse click on RTC as he/she issues a pushback clearance. This pushback clearance time is used for taxi-out time calculation as a surrogate for actual pushback time due to the difficulty in detecting physical motion of aircraft pushback. Both AMA and ramp excess taxi-out times were analyzed from operational data. Fig. 10 shows the comparison of AMA excess taxi-out time of departures between pre- and post-metering periods for bank 2 under the North flow configuration, which was the prevailing configuration. The excess taxi-out time plot shows that both the average and standard deviation for the post-metering period are less than those from the pre-metering period (i.e., by 1.5 minutes per aircraft), indicating less congestion on the surface and shorter queue lengths under metering conditions. Although not reported here, no significant difference was noticed in ramp excess taxi-out time.

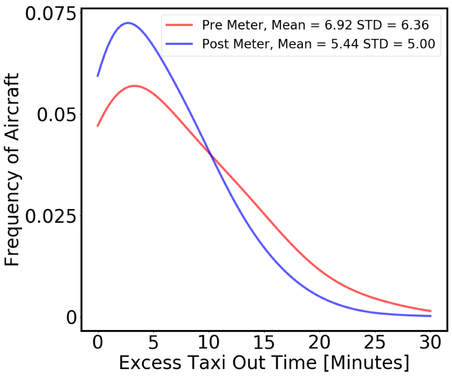


Figure 10. AMA excess taxi-out time of all departures during bank 2 under the North configuration. Data includes 14 days of pre-meter operations (11/1 – 11/28/2017) and 46 days of post-meter operations (12/1/2017 – 2/1/208).

b) Fuel burn and engine emissions: Fuel burn savings and emissions reduction due to surface metering were estimated. The actual gate hold time of individual aircraft was used to estimate fuel burn and emissions savings that would otherwise have been spent (or emitted) while taxiing on the surface if there was no metering. These calculations are based on engine emission certification data from the International Civil Aviation Organization (ICAO) [35]. The specific engine type matching with aircraft's tail number was located from the FAA Registry [36] and the percentages of aircraft with single engine taxi operations obtained from the flight operator were applied. Table III shows the estimates of total fuel and emissions savings during banks 2 and 3, accumulated since implementing surface metering. The total gate hold time during this period was 553.7 hours. The reduction in CO_2 emissions is equivalent to planting 22,017 urban trees according to the formula developed by the Energy Department [37].

TABLE III. PHASE 1 ESTIMATES OF FUEL AND EMISSIONS SAVINGS DUE TO SURFACE METERING (NOV 2017 – SEPT 2018)

Fuel (kg)	**CO_2 (kg)**	**HC (kg)**	**CO (kg)**	**NO_x (kg)**
278,786.45	858,662.29	463.01	6,489.61	1,276.10

c) ON-time arrival performance: The ATD-2 surface metering concept states that delay in a departutre flight's pushback due to gate holding should not adversely affect the flight's takeoff time and, thus, arrival time at its destination airport should not be affected [32]. The comparison of ON-time performance between pre- and post-metering is challenging because it requires sufficient data under similar operational conditions, such as traffic demand, weather, and TMI restrictions, in both periods. Instead, ATD-2 ON-time performance analysis used FAA's Aviation System Performance Metrics (ASPM) database [38], which is widely used by the aviation community for this type of analysis.

ASPM's arrival times of CLT departures at their destination airports were extracted for the period between January and September in 2017 (pre-metering) and the same preiod in 2018 (post-metering). The industry standard ON-time performance metrics, so called A0 (i.e., the flight has arrived at the gate on or earlier than its scheduled arrival time), were compared. In Fig. 11, the upper graph shows the comparison of A0 metric across all banks and the lower plot shows the comparison in banks 2 and 3. In both views, the results do not indicate any noticeable differences.

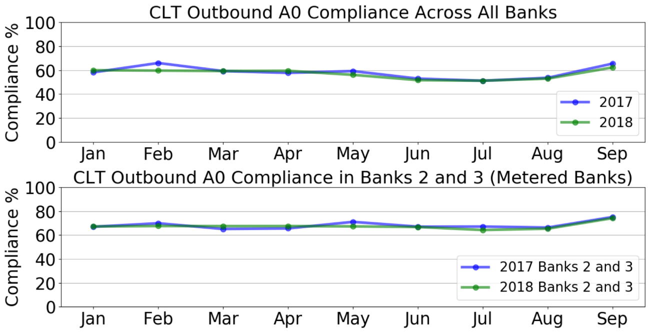


Figure 11. CLT outbound ON-time performance (A0).

Table IV shows the comparison of the same performance metric by 9-month average. The average compliance data across all banks shows a 1.1% of year-over-year decrease in the post-metering period, whereas the average compliance in banks 2 and 3 shows 0.8% decrease in the post-metering period. These small decreases suggest that surface metering did not adversely affect arrival ON-time performance.

TABLE IV. CLT OUTBOUND ON-TIME PERFORMANCE (A0) - AVERAGES

Bank	**Jan - Sept 2017 (pre-metering)**	**Jan - Sept 2018 (post-metering)**	**YoY Change**
All banks	58.0%	56.9%	-1.1%
Bank 2 & 3	58.2%	57.4%	-0.8%

Similarly, ON-time performance of inbound aircraft arriving at CLT was investigated in order to assess whether gate hold of departures due to surface metering would adversely affect arrival flights' ON-time performance. As seen in Table V, the results showed that surface metering had no negative impact on ON-time performance of inbound arrival flights. The average ON-time performance during banks 2 and 3 showed a slight improvement over the same period in the previous year (+4.0%) that surpasses the change in the year-to-year average (+2.9%).

TABLE V. CLT INBOUND ON-TIME PERFORMANCE (A0) - AVERAGES

Bank	**Jan - Sept 2017 (pre-metering)**	**Jan - Sept 2018 (post-metering)**	**YoY Change**
All banks	61.0%	63.9%	+2.9%
Bank 2 & 3	67.9%	71.9%	+4.0%

B. Scheduling of APREQ flights into Overhead Stream

Departure scheduling of overhead stream insertion of APREQ flights started in October 2017. The surface scheduler's improved prediction accuracy of takeoff times of APREQ flights enables earlier coordination of release time with the Center prior to gate pushback. The gate hold advisories for APREQ flights generated by the scheduler are displayed on RTC to assist the ramp controller. In Phase 1, the coordination process for APREQ flights going through Washington Center (ZDC) airspace was automated through electronic negotiation between ATD-2 STBO and ZDC TBFM/IDAC, which entirely eliminates verbal communication between Tower TMC and Center TMU.

The benefits from ATD-2 departure scheduling into overhead streams are measured in two parts: 1) the amount of fuel and emissions savings due to gate hold that would otherwise have been spent taxiing if the coordination of release time had happened after pushback, which was the case pre-ATD-2, and 2) the amount of fuel and emissions savings due to re-negotiation of release time to earlier times while aircraft are taxiing (as described in Section III.D). In this case, the difference between old and revised release times is regarded as taxi-time savings and translated into fuel and emissions savings. Table VI shows the amounts of taxi time reduced, fuel savings and reduction in CO_2 emissions, and equivalent urban tree planting due to departure scheduling of APREQ flights into overhead streams.

TABLE VI. PHASE 1 ESTIMATES OF ENVIRONMENTAL BENEFITS DUE TO DEPARTURE SCHEDULING INTO OVERHEAD STREAM (OCT 2017 – SEPT 2018)

Benefit mechanism	Est. taxi time savings (hr)	Fuel (kg)	CO_2 (kg)	Urban trees
Gate Hold	298.52 (12,865[a])	201,002.08	619,086.41	15,874
Re-negotiation	92.59 (658[a])	59,126.64	182,110.05	4,669
Total	391.11	260,128.72	801,194.46	20,543

a. Number of flights affected.

V. CONCLUDING REMARKS AND FUTURE WORK

This paper describes the main capabilities and benefits of the ATD-2 Phase 1 Baseline IADS system that was deployed in CLT and surrounding air traffic management facilities for field evaluation. Throughout a year-long field evaluation, the ATD-2 system, built upon integration of the existing technologies developed by both NASA and FAA, has demonstrated its Phase 1 objectives: common situational awareness through data exchange and integration; reduced taxi-out time and surface congestion via tactical collaborative surface metering based on FAA's Surface CDM ConOps; and efficient tactical departure scheduling for overhead stream insertion of APREQ flights through automated coordination between Tower and Center.

The ATD-2 system has been developed and tested in collaboration with field evaluation partners, including the FAA, Surface CDM Team, ATC controllers and managers, AAL Ramp, flight operators, and pilots. The usability and performance of ATD-2 system have been continually enhanced during Phase 1 through extensive use by the field users. The system performance was assessed in terms of operational efficiency gain. The results showed that tactical surface metering has reduced the excess taxi-out time, and therefore, surface congestion, by holding gate pushback of departures through surface metering. In addition to general surface metering, the gate holds of APREQ flights prior to pushback as well as re-negotiation of release time while taxiing through tactical departure scheduling have also reduced excess taxi-out time. The total savings in fuel burn and CO_2 emissions for the Phase 1 field evaluation were estimated as 538,915.18 kilograms and 1,659.85 metric tons, respectively, by adding up savings from each individual benefit mechanism. The total CO_2 emissions savings are estimated as equivalent to planting 42,560 urban trees. The total engine run time savings were estimated as 944.81 hours due to both gate hold and APREQ re-negotiation. Arrival ON-time performance of departures subject to surface metering was also investigated using ASPM data and it is assessed that gate holding does not adversely affect gate arrival time at destination airports. Similarly, gate hold of departures due to surface metering does not indicate any negative impact on ON-time performance of inbound aircraft arriving at CLT.

Aside from APREQ flights, similar benefits can be achieved for the flights under Ground Delay Program (GDP) or Ground Stop (GS) restrictions. These restrictions are part of strategic TMIs managed by the Air Traffic Control System Command Center (ATCSCC) to mitigate NAS-wide demand-capacity imbalances [39]. ATD-2 receives the Expect Departure Clearnace Time (EDCT) for the flights subject to GDP, and detailed information regarding GS restriction through SWIM data feed in real-time and transmits to the ramp user for situational awareness. The benefit mechanism for these flights through ATD-2 surface scheduling and calculation of the actual benefits in terms of fuel burn and emissions savings are currently under investigation.

Considering future improvements of the ATD-2 IADS system, accurate predictions of EOBT and aircraft trajectory in the presence of uncertainties have been identified as one of the biggest challenges for achieving robust surface scheduling and metering advisories. The availability of accurate EOBTs is also considered as the key element for scheduling release times of APREQ flights prior to pushback, and thus enabling fuel and emissions savings. Refinement of surface scheduling and metering algorithms, and departure scheduling for TMI flights will continue in subsequent phases of the project. Automated coordination of APREQ flights departing for Atlanta International Airport via Atlanta Center (ZTL) TBFM in advance of EOBTs has already been implemented in the field. In addition, the development of new capabilities, including strategic surface metering called Surface Metering Program (SMP), a two-way integration of Advanced Electronic Flight Strips (AEFS) with the ATD-2 system, and Terminal TFDM Publications (TTP) for sharing information with external users via SWIM, have been completed and deployed Phase 2 IADS demonstration, and field evaluation by the users is currently underway.

ACKNOWLEDGMENT

The successful field demonstration of ATD-2 Phase 1 Baseline IADS system would not have been possible without support from field evaluation partners. The authors are grateful for their fervent engagement and willingness to provide valuable feedback for development and testing. Many thanks must go to ATC and Ramp controllers and managers who made every effort in the evaluation of the tool in their daily operations. Special thanks go to Mr. Pete Slattery, the National Air Traffic Controllers Association (NACA) representative for ATD-2, Dr. Tim Niznik, Mr. Mike Bryant, and Mr. Bernie Davis from American Airlines, Messrs. Kerry Face, Mike Smith, and Jeff Condo at CLT AAL Ramp, and Ms. Susan Passmore and Mr. Ben Marple from the FAA Technology Development and Prototyping Division (ANG-C5), and the members of Surface CDM Team for their enthusiasm and collaboration.

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