Simulation-based Benefits and Costs Assessment of NASA's Airspace Technology Demonstration-2

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Abstract*—This paper estimates the benefits and costs for an integrated arrival, departure, surface traffic management technology currently under operational evaluation at Charlotte Douglas International Airport. The technology under study is NASA's Airspace Technology Demonstration 2 (ATD-2) system. Using high-fidelity fast-time simulations of current-day operations (including modeling of current-day operational shortfalls) and future ATD-2 operations (including the modeling of associated ATD-2 benefit mechanisms), ATD-2 benefits were projected for three major U.S. airports. Individual airport benefits were then annualized (extrapolated to full year benefits) and nationalized (extrapolated to Core-30 FAA airports), to compute total projected monetary benefits per year. FAA-recommended cost assessment approaches were applied to compute projected ATD-2 implementation costs. Finally, costs were compared against National Airspace System (NAS)-wide benefits, and a projected return on investment was calculated. Our results estimate that the ATD-2 system can provide $2.6 billion in monetary benefits nationwide over the lifecycle of the program due to significant reduction in taxi delay as well as shifting of the delays from taxi to gate. The projected ATD-2 benefits significantly outweigh the projected implementation costs. Incorporation of ATD-2 into the FAA's planned Terminal Flight Data Manager (TFDM) system deployments is estimated to improve the benefit-cost ratio of the TFDM program from an earlier estimated 1.09 to 1.89 over the lifecycle of the program.

***Keywords*—integrated arrival departure surface traffic management departure metering, ATD-2, benefit cost analysis, fast-time simulation**

I. INTRODUCTION

The current-day practices for managing departure flights taking off from the airport surface, then traveling through the terminal airspace, and eventually merging into overhead en route traffic streams lead to multiple operational shortfalls.

These shortfalls include:

• Identical ticketed departure times, a pushback-when-ready operational paradigm, and reactive first-come-first-served (FCFS) management of clearances at ramp transition spots lead to inefficient departure sequences, causing taxi inefficiency (stop-and-go) and throughput loss.

• Lack of predictability in the departure process forces tower controllers to impose buffers (e.g., excess runway separation) to ensure safety and forces the receiving Terminal Radar Approach Control (TRACON) facility and Centers to impose inefficient departure restrictions, e.g., excess miles-in-trail (MIT) or approval requests (APREQs) on airports, to make space for airborne merging.

• Lack of predictability causes airlines to set excessively large scheduled block times, which limits fleet utilization and increases operating costs including personnel and fuel costs.

Under the Airspace Technology Demonstration-2 (ATD-2) subproject, NASA has started addressing these shortfalls by developing Integrated Arrival, Departure, Surface (IADS) technologies and transitioning them to field implementation. These technologies aim to increase the predictability, efficiency, and throughput of metroplex operations while meeting future air traffic demand [1]. The operational environment for the ATD-2 system consists of a local metroplex airspace overlying multiple proximate airports. Within this operational environment, departures from proximate airports may share departure fixes on the TRACON boundary and merge into busy en route traffic streams in the Center airspace. In many cases, departures are subject to multiple restrictions including APREQs for specific destination-bound flights, MIT restrictions at en route merge points and departure fixes, Expected Departure Clearance Times (EDCTs) from Ground Delay Programs (GDPs), and weather-imposed departure fix/gate closures. The ATD-2 system computes time-based departure schedules for departures from all airports in the local metroplex while accounting for local, regional and national departure restrictions listed above.

At the core of the ATD-2 system is a traffic scheduling algorithm that aims to balance traffic demand with capacity for key metroplex resources (e.g., runways, departure-fixes, overhead traffic stream merge points) while minimizing taxi and airborne delays by allocating hold times at the gates for departure flights (at well-equipped, busy airports) and/or controlled runway takeoff times (at less-equipped satellite airports and busy airports, as well). Further, the ATD-2 system includes a collaborative, strategic planning function that enables the airlines, airport traffic control towers (ATCTs) and TRACONs to collaboratively determine scheduling parameters and metering start/end times. Furthermore, the ATD-2 system enables electronic two-way data-exchange between the airline operator and relevant FAA systems. This data exchange includes dissemination of flight operator information regarding

aircraft pushback readiness and company priorities as well as early dissemination of departure restriction data and controlled gate/movement area entry/runway takeoff times to the flight operators.

ATD-2's data-exchange, collaborative decision making and scheduling capabilities are expected to provide significant benefits by saving taxi delays, fuel, passenger time and airline direct operating costs (ADOC), as well as provide beneficial environmental impacts by reducing greenhouse gas emissions. Quantification of these benefits needs detailed analysis and modeling of the operational shortfalls that ATD-2 can address, the associated benefit mechanisms, and relevant benefits metrics. The research work described in this paper fulfills this need by generating high-fidelity benefit and cost estimates of implementing NASA's ATD-2 system at major airports in the NAS.

Research described in this paper took a fast-time simulation-based approach for estimating ATD-2 benefits. To support this approach, we developed a high-fidelity fast-time simulation environment for simulating aircraft trajectories in both the surface and airspace subsystems of the ATD-2 system, under current-day ATM procedures, as well as under ATD-2 procedures. Before beginning the simulation environment development, we undertook a rigorous analysis of current-day operational shortfalls that ATD-2 can address, the associated ATD-2 benefit mechanisms and the relevant benefit metrics. This analysis, published in [11], helped us in modeling all the relevant features required for modeling the current-day as well as ATD-2 operations in the simulation environment. Our approach compared performance metrics obtained by simulating airport and airspace operations under these two procedures (current-day and ATD-2) on multiple simulation days, and properly apportioned the performance metrics differences to benefits provided by the ATD-2 system. Simulations were conducted at a small number of airport sites and simulation scenarios. Three airport sites—Charlotte Douglas International Airport (CLT), Dallas Fort Worth International Airport (DFW) and Newark Liberty International Airport (EWR)—were selected based on an analysis of historical operational data [12]. Results from simulations at these airports using selected scenarios were extrapolated to annualized and nationwide scale using extrapolation approaches. FAA-recommended cost assessment approaches were applied to compute the cost associated with implementing the ATD-2 system at major U.S. airports. Finally, costs were compared against NAS-wide benefits, and a return on investment was calculated.

The rest of the paper is organized as follows. Section II describes the combined airport surface-terminal airspace fast-time simulation platform that was used for benefits estimation. Section III describes the fast-time simulation experiments and outlines their results. Section IV discusses benefits extrapolation and monetization. Section V presents results from the benefits and cost analysis. The paper ends with a discussion of the conclusions in Section VII.

II. FAST-TIME SIMULATION ENVIRONMENT

Our technical approach for ATD-2 benefits estimation involved developing and utilizing a high-fidelity simulation environment for simulating aircraft trajectories in both the surface and airspace subsystems of the ATD-2 system, under current-day ATC procedures as well as under ATD-2 procedures. Our modeling simulated all the key constraints faced by departure flights along their path from departure gate to overhead en route traffic stream merge. These constraints include traffic congestion in the ramp area and on movement area taxiways at the departure airport, capacity constraints on the runway system, capacity constraints at departure-fixes where flights from multiple TRACON airports merge, and miles-in-trail spacing constraints at entry points to overhead en route traffic streams. We generated a high-fidelity simulation environment for simulating operations at three airport sites: CLT, EWR, and DFW. Next, we describe the integrated airport surface and airspace simulation environment that we developed and used for our simulations.

A. Integration of Surface and Airspace Simulations

The core of our simulation environment is NASA's high-fidelity Surface Operations Simulator and Scheduler (SOSS) platform [2]. SOSS simulates departure and arrival flight trajectories on the airport surface. SOSS has been validated against operational data [3,4] and has been used in airport simulation studies [5,6]. We integrated SOSS with the ATAC Airspace Operations Simulator and Scheduler (AOSS). The AOSS has three components. The first component, Airspace Simulation, is a MATLAB-based queuing simulation that simulates aircraft trajectories along a network of frequently-flown airspace routes in the TRACON and en route airspaces. The second component simulates the Surface Traffic Flow Management control actions implemented by the ground and local controllers in order to ensure adherence to APREQ, EDCT and MIT traffic management initiatives (TMIs). The third component simulates the coordination between the airport tower and receiving Center Traffic Flow Management, which involves fitting APREQ departure flights into time-slots on the Center meter arc timelines in accordance with the estimated runway takeoff times provided by the ATCT, and sending back runway release time constraints. ATAC's AOSS was developed on this project and has undergone validation against historical airspace operations data [13].

Figure 1 shows the interconnected SOSS-AOSS system. As shown in the figure, SOSS transfers over the simulation-control of a departure flight to the airspace simulation component of AOSS when the departure flight takes off, i.e., at the simulated Actual Takeoff Time (ATOT). AOSS's airspace simulation component then simulates the movement of the departure flight along its airborne route from takeoff runway to departure fix and then on to an en route stream merge point. Along this route, we also simulate the transit through individual en route sectors in the flight's path. AOSS includes queuing-based airspace delay models for the departure-fix merge process, as well as the en route stream merge process. These models space the flights at the departure-fix or the meter arc based on the actual historical miles-in-trail restrictions that were active for

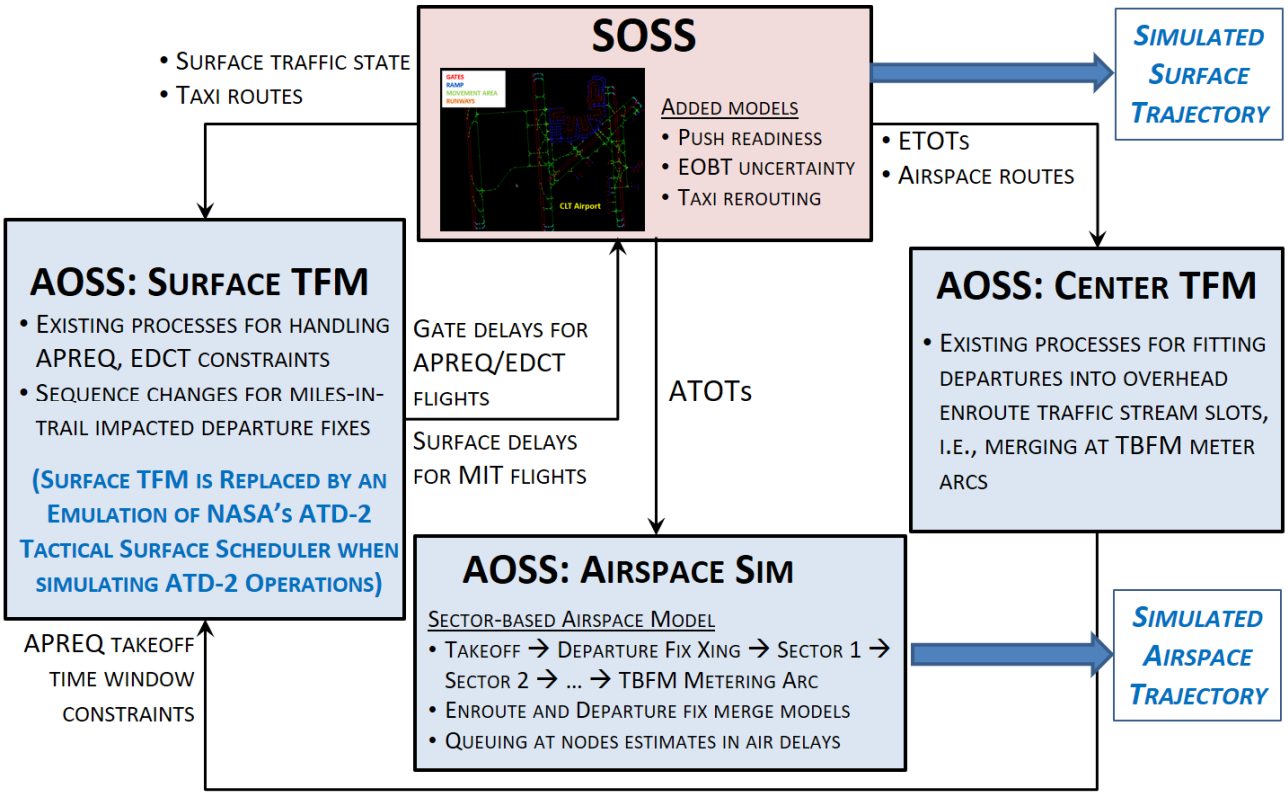


Figure 1. Integrated Surface Airspace Simulation Environment

those specific NAS elements on the simulated day of operations.

In addition to the focus ATD-2 airport (e.g., CLT) departures, AOSS's airspace simulation also includes departures from satellite airports within the same TRACON Some of these satellite departures merge with the focus airport departure flights at the departure-fixes. It also includes departures from NAS-wide airports that merge with the focus ATD-2 airport's departures in the en route airspace. (In the simulation these flights take up time-slots on timelines at the TBFM-defined en route meter arcs where they merge with the focus ATD-2 airport departures). Runway takeoff times, simulation entry times, airspace routes and departure-fix/meter arc crossing times for these "other" flights (non-focus airport departures) are derived from historical end-to-end merged radar track data obtained from NASA's Sherlock ATM data warehouse [7]. As shown in Figure 1, at the end of the simulation we were able to extract the simulated surface flight trajectories from SOSS and the simulated airspace flight trajectories from AOSS. Next, we describe how we modeled the ATD-2 benefit mechanisms and associated current-day shortfalls in our simulation environment.

B. Modeling of key operational shortfalls and associated ATD-2 benefit mechanisms

As discussed in Section I, we performed a rigorous identification of operational shortfalls and associated ATD-2 benefit mechanisms [11]. The identified shortfalls and benefit mechanisms were modeled in the simulation platform, primarily using the Surface Traffic Flow Management (S-TFM) and Center TFM (C-TFM) components of AOSS shown in Figure 1. In addition, we also developed an emulation of NASA's ATD-2 Tactical Surface Scheduler, which models the time-based scheduling and surface metering benefit mechanisms.

Modeling of Current-day Operations and Associated Shortfalls: A key benefit of ATD-2 is that it brings about significant improvement in current-day practices for coordinating multiple TMIs impacting departure flights (e.g., APREQs, EDCTs, MITs). As a result, we gave emphasis to accurately modeling current-day TMI implementation procedures and shortfalls in our current-day operations models.

The current-day management of APREQ-impacted flights consists of the following steps: **(1)** In real-operations, when an APREQ-impacted departure flight is ready for pushback, the ATCT estimates its runway takeoff time using a rough estimate of taxi-out time and sends the estimate to the Center Traffic Management Unit (TMU). **(2)** Next, the Center TMU uses the TBFM system to compute the flight's estimated time to key TBFM metering arcs and finds a time-slot on the metering arc timeline for the flight. In finding the time-slot the TBFM system finds a gap in the sequence of estimated meter arc crossings, which consist of flights originating from NAS-wide airports and going to the destination airports served by a specific TBFM metering arc. **(3)** Next, the Center TMU sends a Controlled Runway Takeoff Time back to the ATCT. This controlled time is back-computed from the allocated meter-arc time-slot using the estimate of the time from takeoff to meter arc crossing. **(4)** Finally, the Controlled Runway Takeoff Time is communicated to the pilot. The pilot uses a rough estimate of taxi-out time to decide when to pushback from the gate and requests gate pushback from the ramp controller at the

appropriately determined pushback time. In today's operations, inaccurate runway takeoff time estimates communicated to the Center TMU lead to the allocation of invalid metering arc time-slots, and subsequent back-computation of erroneous pushback times. Consequently, many APREQ-impacted flights reach the head of the departure queue outside the APREQ permitted window of -2/+1 minutes around the Controlled Runway Takeoff Time. In these instances, the local controller either renegotiates a new takeoff clearance from the Center TMU, which wastes time, or the flight departs outside its APREQ window leading to subsequent airborne delays.

The S-TFM and C-TFM components simulate the following four steps to model current-day procedures (and associated shortfalls) for handling APREQ-impacted flights. **(1)** In real operations, when an APREQ-impacted departure flight is ready for pushback, the ATCT estimates its runway takeoff time using a rough estimate of taxi-out time and sends the estimate to the Center Traffic Management Unit (TMU). In the simulation, the S-TFM component performs this estimation using averages derived from historical operational data and sends the estimate to the C-TFM component. **(2)** Next, in real operations, when the Center receives the runway takeoff time estimate for an APREQ-impacted flight from the ATCT, the Center TMU uses Time Based Flow Management (TBFM) system to compute the flight's estimated time to key TBFM metering arcs and finds a time-slot on the metering arc timeline for the flight. In the simulation, the C-TFM module emulates these Center TMU actions. C-TFM uses historical airspace transit time data to estimate the meter arc crossing times for APREQ-impacted flights. In addition to the focus airport departure flights, C-TFM also has data on all other NAS flights that merge at the meter arcs. C-TFM estimates the meter arc crossing times for these other departures also. Then, C-TFM spaces these flights at the meter arc according to the published miles-in-trail restriction active for that meter arc on the actual day of operations that was simulated, and computes an acceptable time-slot in the meter arc timeline for the APREQ-impacted flight from the focus airport. **(3)** Next in the traffic management sequence, in real operations the Center TMU sends back a Controlled Runway Takeoff Time back to the ATCT. This controlled time is back-computed from the allocated meter-arc time-slot using the estimate of the time from takeoff to meter-arc crossing. In the simulation, the C-TFM performs this back-computation and sends back the Controlled Runway Takeoff Time to the S-TFM component. **(4)** Next in the traffic management sequence, in real operations this Controlled Runway Takeoff Time is communicated to the pilot. The pilot uses a rough estimate of taxi-out time to decide when to pushback from the gate and requests gate pushback from the ramp controller at the appropriately determined pushback time. In the simulation, S-TFM computes an estimate of the flight's taxi-out time, which is different from the ATCT estimate computed in step 1 (to emulate the difference between the pilot's and ATCT's taxi-out time estimates) and uses this other taxi-out time estimate to back-compute an appropriate gate pushback time for the APREQ-impacted flight.

In addition to APREQ-impacted flights, the simulation also models real-world procedures for managing EDCT-impacted and MIT-impacted flights. For EDCT-impacted flights, the S-TFM component adds a gate-hold delay for the respective GDP being simulated to the flight's Scheduled Off Block Time to compute the actual pushback time. The gate-hold delay is set equal to the average ground delay published in the historical GDP advisory, which is obtained from a Traffic Flow Management Initiatives database. For MIT-impacted flights, STFM emulates the current-day ground controller sequencing actions for avoiding consecutive flights going to the same departure-fix before they merge onto the final active movement area (AMA) taxiway that takes them to the departure runway. Different merge-locations are simulated for different airports and runway configurations.

Furthermore, in today's operations non TMI-impacted flights are pushed back whenever they are ready, which leads to congestion on the airport surface and results in excess taxi times and loss of throughput. Our current-day simulation platform simulated this "pushback when ready" operational paradigm by not imposing any gate delays on departure flights.

Modeling of ATD-2 Operations and Associated Benefit Mechanisms: In the case of ATD-2 operations simulation, the APREQ-related modules of the STFM component are replaced with an emulation of the ATD-2 Tactical Surface Scheduler. The ATD-2 Tactical Scheduler computes more accurate taxi-out time estimates for APREQ-impacted flights and sends them to the CTFM component. This models the data exchange benefit mechanism of ATD-2. CTFM computes the controlled runway takeoff time by fitting the new departure into a time-slot on the TBFM metering arc timeline. This models the electronic APREQ data exchange benefit mechanism. The ATD-2 Tactical Surface Scheduler also back-computes the Target Off-Block Time (TOBT) from the runway release time for APREQ flights. A major feature of the ATD-2 Tactical Surface Scheduler is the holding of flights (all flights, including non TMI-impacted flights) at the gates to lessen surface congestion, reduce emissions, and reduce taxi times. The scheduler emulates the scheduling steps in NASA's Tactical Surface Scheduler to apply gate delays to all (even non TMI-impacted) flights based on demand-capacity imbalances observed/estimated. This models the time-based scheduling and surface metering benefit mechanisms. The STFM modules that perform EDCT implementation and sequencing for departure-fix interleaving of flights are retained in the ATD-2 operations simulations.

In summary, the airspace simulation, STFM and CTFM components of the AOSS together enable high-fidelity modeling of key ATD-2 benefit mechanisms and thereby enable reliable benefits estimation.

III. Simulation Experiment Design & Results

High-fidelity fast-time simulations of airport and airspace operations under current-day procedures as well as ATD-2 procedures were conducted at the three chosen airport sites, using the simulation environment described above. In order to perform a credible benefits analysis it was important to select simulation scenarios that were sufficiently different from each other and that covered the entire range of operational characteristics observed across an entire year. To fulfill this

objective we undertook a careful scenario selection task as described below.

A. *Simulation Scenario Selection*

We performed a comparative analysis of historical local and nationwide weather patterns, traffic demand-vs-capacity metrics and TMI impact data, to identify a set of simulation days for each airport. After this step, we further analyzed the actual airport surface traffic on the selected days and down-selected timeframes for simulation on each of the selected days. We considered the following factors when selecting the simulation timeframes: (1) We wanted to keep a balanced mix of runway configurations (top two configurations simulated per airport) in the selected simulation timeframes; (2) The start of a simulation timeframe had to match with a time-period in actual operations when there were only a small number of departure flights on the airport surface. This factor enabled us to provide each of our simulations with a realistic "initial condition," rather than starting the simulation in the middle of a busy operational period on the actual historical day; (3) We wanted to keep the total number of simulation days to a manageable level (maximum 6 days per airport). With these factors in mind, we down-selected to a simulation matrix consisting of six simulation days for each of CLT and DFW, and four simulation days for EWR. This simulation matrix required us to design and conduct a total of 32 simulation experiments.

B. *Simulation Configuration and Execution*

Simulations were conducted using a networked combination of two computers: a Linux laptop running NASA's SOSS simulation platform, and a Windows laptop running the MATLAB-based AOSS platform. AOSS acted as an external scheduler for SOSS, with SOSS periodically (every 30 seconds of simulation time) calling AOSS and waiting for AOSS to send back airport surface delay advisories. The following steps were followed for executing each individual simulation:

1. First, a SOSS surface traffic demand set was generated using a combination of OAG schedules, Flightaware data (for gate allocation and scheduled gate departure time data) and ASDE-X data (for runway allocation, taxi route allocation, etc.), from the historical day that was selected for simulation

2. A corresponding airspace traffic demand set was generated by applying a number of ATAC track processing scripts to end-to-end merged track data, which was obtained from the NASA's Sherlock ATM data warehouse [7]

3. The APREQ, GDP and MIT advisories that were active during the same historical day were obtained by parsing the National Traffic Management Log (NTML) database as well as from the FAA system command center website (https://www.fly.faa.gov/adv/advADB.jsp). Restriction start and end times, restriction sizes, and impacted NAS elements were entered into the AOSS simulation platform for reliable simulation of these departure restrictions.

Figure 2 shows the different TMI restrictions modeled from historical TMI databases and input as restrictions for each simulation scenario, using CLT as an example (the same inputs apply to DFW and EWR simulations).

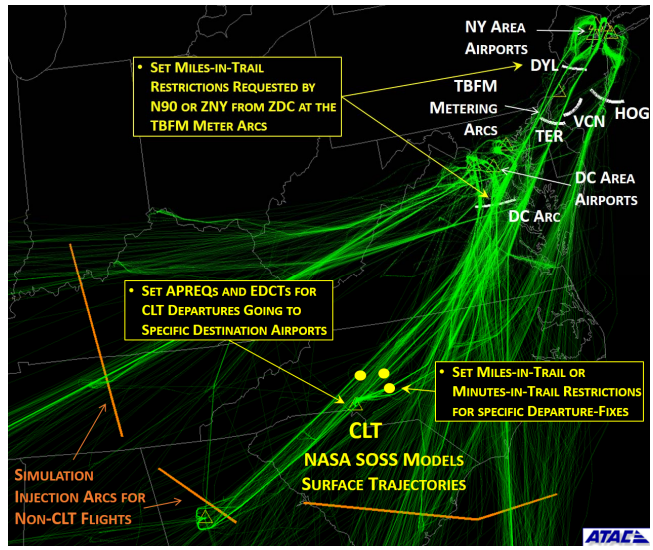


Figure 2. Different TMI restrictions modeled from historical data, and input for each simulation scenario. Restriction input options shown in yellow boxes; flight tracks in green, airports/meter-arcs in white and simulation injection points in orange)

4. The simulation was started by running SOSS and AOSS in tandem

5. After the simulation finished, surface trajectory data were saved from the SOSS platform and airspace trajectory data were saved from the AOSS platform, for further analysis

6. Post-processing scripts were then applied to compute performance metrics from the simulation output data

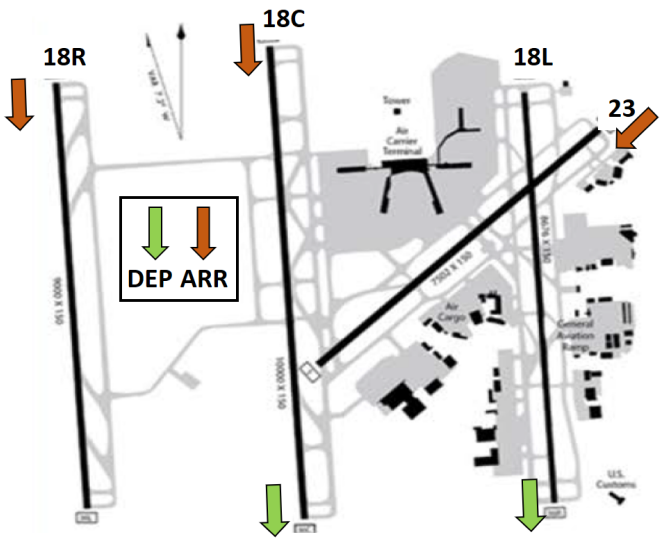
7. The same procedure was repeated for two settings per day – one a baseline (current-day) operations simulation and one an ATD-2 operations simulation

C. *High-fidelity Simulation Results – Estimates of ATD-2 Benefits at CLT, DFW, and EWR*

This section outlines the results from high-fidelity fast-time simulations. We present results showing a comparison of airport operation performance between the baseline (current-day procedures) simulation and the ATD-2 (departure metering procedures) simulation. We present detailed results for one CLT scenario in Section III-A to provide a comprehensive picture of the types of simulation analyses we performed and the benefit metrics we computed. Following that, we summarize the high-level benefits estimated for each of the simulation scenarios we simulated for the three chosen airport sites, in Section III-B.

1) *Detailed Simulation Results for one Example Scenario*

The scenario we describe in detail involved the simulation of CLT airport arrival and departure traffic on 06/15/2016 during the 1000-1600 UTC timeframe. Out of the nine departure banks that occur daily at CLT, this simulation timeframe covered CLT departure banks # 2, 3 and 4. CLT was under the South-Flow runway configuration during the selected simulation time-period, with departures operating on runways 18C and 18L, and arrivals operating on runways 23, 18C and 18R, as shown in 0Figure 3. Runway 18C was operating in a mixed-use mode. We also simulated the APREQ and MIT traffic management initiatives that were active during the 1000-1600 UTC timeframe on the actual 06/15/2016 day.



0Figure 3. CLT South Flow Config Runway Usage

Taxi Time Savings Results. Our simulation results for this scenario showed that the ATD-2 system saved 10% of the total taxi-out time over all the departures, as shown in Figure 4. Higher levels of taxi-out time savings were seen in the active

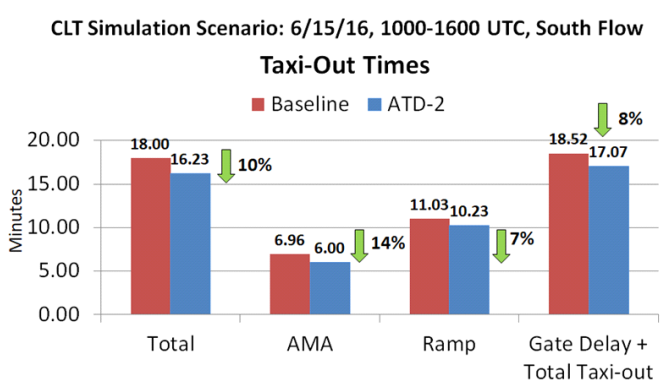


Figure 4. Taxi-Out Time Savings Benefits Estimated for the 06/15/2016 1000-1600 UTC simulation scenario

movement area (AMA) taxi-out times as compared to the ramp taxi times. Further, we also computed the total transit time for each departure consisting of the excess time spent at the gate in the ATD-2 simulation (i.e., ATD-2 system-imposed gate delay) and the taxi transit from gate pushback to runway takeoff. This total transit time metric is the fourth pair of bars shown in Figure 4. (Note that APREQ-impacted flights experienced gate holds even in the baseline simulation, which is the reason why the fourth blue bar is taller than the first blue bar). As seen from the figure, with the ATD-2 system we observed an 8% drop in the total transit time metric on an average.

We also analyzed the impact of ATD-2 departure metering on arrival taxi-in times. Our simulations did not show a significant negative or positive impact of ATD-2 scheduling on taxi-in times.

Impact on Airport's On-Time Performance. An important consideration for user-acceptance of the ATD-2 system is whether the ATD-2 gate delays have a negative impact on the overall on-time performance of the airport, in terms of late or early runway takeoff times. In relation to this aspect, we compared the simulated takeoff times of departure flights with the scheduled takeoff times. Scheduled takeoff times were computed as Scheduled Gate OUT Time + Airline Taxi-out Time Budget. The takeoff delay was computed as the Simulated Takeoff Time – Scheduled Takeoff Time. Figure 5 shows the histograms of this Takeoff Delay metric, with the data for baseline simulation shown in the top-half (red bars) and the data for the ATD-2 simulation shown in the bottom half (blue bars).

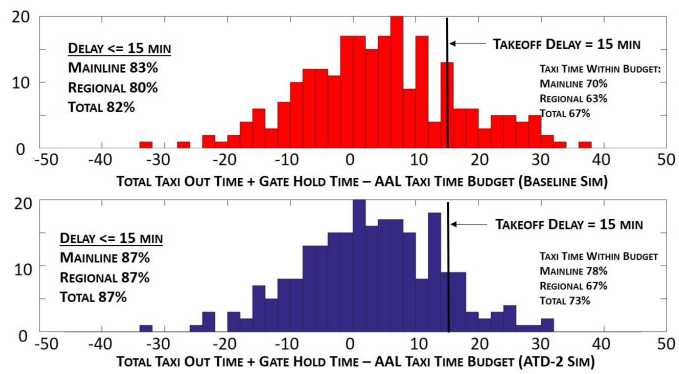


Figure 5. ATD-2 system had a beneficial impact on the airport's on-time performance as per an analysis of Total Taxi-out Times as compared to Taxi-Out Time budgets

Our computations show that in the baseline simulation around 83% of the mainline and 80% of the regional flights took off with a delay of less than 15 minutes with respect to the Scheduled OFF time, whereas in the case of ATD-2 operations these numbers were higher 87% and 87%, respectively. Moreover, the percentage of mainline and regional flights that had shorter taxi-out times than the budgeted taxi-out times was also higher in the ATD-2 simulations as compared to baseline (see figure for the percentages). These data indicate that the ATD-2 system had a beneficial impact on the airlines' on-time performance in the simulations. This is primarily because of better handling of APREQ/EDCT/MIT-impacted flights, which reduces instances when TMI delays for these flights block the departure runway queue.

Impact on Airport's Departure Throughput. The ATD-2 system did not significantly impact the overall airport throughput in our simulations. Figure 6 shows the cumulative airport throughput (i.e., the number of departures that have already taken off at time 't') throughout the simulation timeframe. As seen from the figure, the baseline cumulative airport throughput line (red dashed line) falls either on or below the ATD-2 cumulative airport throughput line (blue solid line) for most of the simulation timeframe, with only a few places where it goes above the blue line by 1-2 departure aircraft.

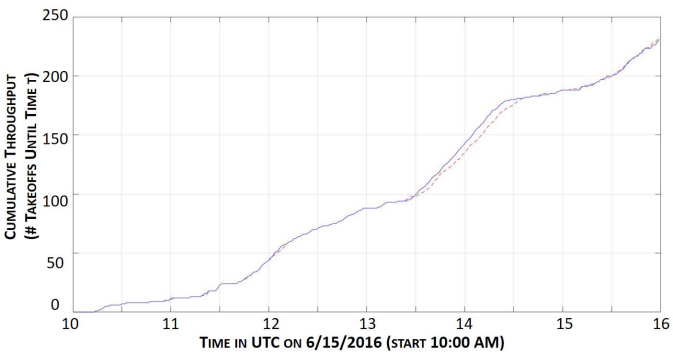


Figure 6. Cumulative airport throughput (baseline sim: red dashed line; ATD-2 sim: blue solid line) shows very little impact of ATD-2 gate holds on departure throughput

As seen from the discussion in this section, we performed rigorous analysis of simulation output results to apportion the benefits to operations in terms of taxi time savings, as well as verified that the ATD-2 system does not have a negative impact on important metrics such as on-time performance and throughput. Next, we summarize the benefits estimates obtained from all the simulation scenarios that we simulated.

2) Summary of Simulation Results from all Simulated Scenarios

The key performance metric from the benefits computation perspective was the amount of taxi-out time savings provided by ATD-2 for each simulation scenario. Table 1 shows the summary taxi-out time savings per scenario in terms of the percentage savings over the average taxi-out time in the baseline simulation, observed over the duration of the simulation timeframe. Since we simulated only a part of each selected simulation day, we applied a full day multiplier to extrapolate part-day benefits to full-day benefits. This full-day multiplier was computed by assessing the traffic demand, available capacity and observed delays in the real, historical operations data during the simulation timeframe in comparison to the same metrics over the entire duration of the day. The last column of the table shows the full-day benefits.

As seen from the table, on average, the ATD-2 system provided around two minutes of taxi-out time savings per departure at CLT and DFW. For EWR, the benefit was slightly higher than two minutes per departure flight. These benefits were used in the annualization computations, which we discuss next in Section IV.

Table 1. Summary Taxi-Out Time Savings Results

Air-port	Simulation Day	Rwy Config	Taxi-Out Time Savings During Sim Time (%, min)	Full Day Benefits (min)
CLT	6/15/2016	South	9.82, 422	1346
CLT	5/17/2016	South	5.71, 325	702
CLT	6/1/2016	North	8.97, 368	1847
CLT	6/2/2016	South	5.85, 324	1217
CLT	5/6/2016	North	15.13, 708	1579
CLT	5/31/2016	North	3.8, 155	541
CLT AVG SAVINGS PER DEPARTURE FLIGHT = 1.72 MIN				
DFW	5/12/2016	East	8.16, 551	1322
DFW	6/4/2016	East	14, 869	2207
DFW	6/3/2016	West	8.38, 626	2091
DFW	7/5/2016	West	10.6, 728	1871
DFW	7/17/2016	West	10.7, 511	1559
DFW	7/28/2016	West	6.39, 289	1202
DFW AVG SAVINGS PER DEPARTURE FLIGHT = 1.89 MIN				
EWR	5/6/2016	North	9.7, 249	1307
EWR	7/21/2016	South	6.55, 319	887
EWR	7/29/2016	North	7.24, 295	917
EWR	7/3/2016	South	21.69, 761	2230
EWR AVG SAVINGS PER DEPARTURE FLIGHT = 2.34 MIN				

IV. Benefits Extrapolation and Monetization

The next step after obtaining high-fidelity estimates of ATD-2 benefits at the three chosen airports was to extrapolate the benefit estimates to an annualized scale (annualization) as well as to extrapolate them to the FAA Core-30 airports (nationalization), and then monetize the extrapolated benefit estimates. We first discuss the nationalization approach and results.

A. Benefits Extrapolation to Nationwide Airports

The generalization to a wider range of airports involved the development of medium-fidelity queuing network models for the major airports in the U.S. These models focused on modeling the aggregate queuing behavior at the runway thresholds and, when needed, the ramp areas. These models considered major flows/configurations and the number of departure runway servers needed. We also implemented the ATD-2 logic within the queueing network simulation environments. A key advantage of the medium-fidelity queueing network models is that they enable fast-time simulations of operations on a large number of days and at a larger number of airports in a short time. In order to compare medium-fidelity simulation results with high-fidelity SOSS-AOSS simulations, we developed and ran models for CLT, DFW, and EWR, first. Figure 7 compares the taxi-out time

distributions at CLT, with and without ATD-2. The benefits of ATD-2 are apparent from the leftward shift of the taxi-out time distributions, indicating a decrease in the number/ proportion of flights with long taxi-out times.

Unlike the high-fidelity SOSS simulations, the queuing network models do not model benefit mechanisms such as APREQ/MIT management, data-exchange, and improved

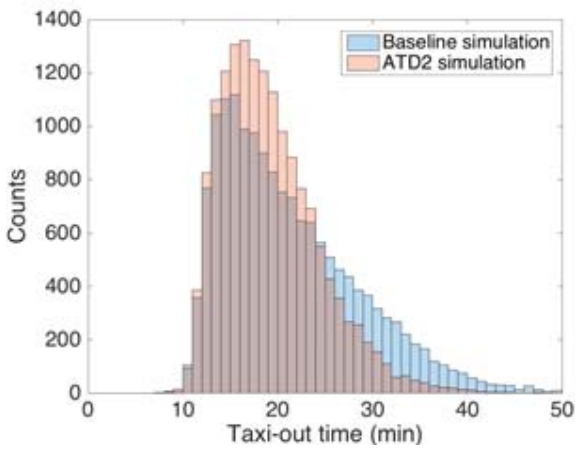


Figure 7. Estimated impact of ATD-2 on taxi-out time distributions at CLT in North Flow Configuration, as computed by medium-fidelity simulations

merges into the overhead stream, but model only the purely ground-based benefits of departure metering. Therefore, simulations of the same day (and underlying conditions) using the two different models can result in different estimates of taxi-time reduction. Upon comparison of the percentage reduction in taxi-out time estimated by the two approaches, for the same set of days (and adopting the median scaling factor in order to minimize the impact of outliers), it appears that a factor of 1.9 may be used to approximate the taxi-out time benefits of a SOSS-AOSS simulation, given those of a queuing model simulation, i.e., SOSS-AOSS estimates were 1.9 times bigger on average than the queuing model estimates.

To estimate benefits of ATD-2 at other Core-30 FAA airports, we leverage prior analysis of airport congestion that was developed in [8] to evaluate the pool of benefits from aggregate departure metering strategies such as N-Control [9]. Reference [8] determined the number of flights that departed when an airport was saturated (i.e., in congestion), the taxi-out times of flights in congestion, and the typical taxi-out times experienced by flights when the airport was at the saturation point. The difference between the aforementioned taxi-out times is a reflection of the potential taxi-out time reduction that may be achieved by operating the airport at close to the saturation point (thereby maintaining runway utilization). Reference [8] performed this analysis for JFK, PHL, BOS and EWR, providing us good benefits estimates for three additional airports. For other Core-30 FAA airports, results from the FAA's analysis of TFDM benefits at these airports [10] were used as proxy estimates for ATD-2 benefits.

For JFK, BOS, and PHL, the benefits estimates obtained via queueing network models were corrected by a factor of 1.9 (computed above) to estimate the benefits of ATD-2. For the other Core-30 FAA airports, we computed their TFDM benefits estimate relative to EWR, e.g., the ATD-2 benefit for PHX was estimated as follows:

PHX ATD-2 benefit estimate =
(PHX TFDM benefit estimate ÷ EWR TFDM benefit estimate) × EWR ATD-2 benefit estimate

In this way, the ATD-2 benefits from the three focus airports were extrapolated to the FAA Core-30 airports.

B. Extrapolation to Annualized Benefits

In extrapolating the daily benefits to a full year (2016 in this case), the following method was applied: As discussed in Section III.A, the selected simulation dates were chosen because weather and other factors indicated a fair number of "similar" days. For example, 5/6/2016 at CLT was similar to 6 NAS days and 6/15/16 is similar to 16 days. This allows extrapolation to the similar days by simple multiplication with the number of similar days. One can then extrapolate to annualized benefits by the simple expedient of multiplying the daily benefits on simulated dates by 365/n where n is the number of equivalent dates.

C. Benefits Monetization

After the benefits estimates were nationalized and annualized, total monetary benefits per year were computed by monetizing the results using the standard methods provided by the FAA (economic factors) [10] which include Airline Direct Operating Costs (ADOC), Passenger Value of Time (PVT) and fuel costs. The ATD-2 system is expected to move taxi-out delay to the gate resulting in fuel savings, while any increase in throughput is also expected to translate into delay reduction (measured by change in Off-Time). Thus, ATD-2 is expected to provide benefits in fuel savings as well as in ADOC and PVT.

In order to calculate the fuel savings vs early takeoff time benefits the following equation was applied to the results:

$$C_i = \{\min(t^0_{off}, t^i_{off}) - t^i_{out}\} * F_r + (t^i_{off} - t^0_{off}) * (A + P)$$

The cost C is an estimate of the cost for an ATD2 flight. The baseline would have no ADOC (A) or PVT (P). F_r is the cost of fuel/minute. Note that the computation uses a takeoff time value, which is relative to the minimum of the two "off" times (Baseline vs ATD-2). This is due to the occasions where ATD-2 has a later off-time and we want to avoid double counting (ADOC contains fuel as a subset). This cost is then subtracted from the baseline cost (Off – Out)* F_r to yield the net savings. To provide a more detailed context, the following is an example of the benefits calculation for a single CLT simulation output.

Baseline Flight: Taxi-Out Ready/Actual Out = 12:30 UTC

Off-Time = 12:52

Thus, Taxi-Out time = 22 minutes

ATD-2 Flight: Taxi-Out Ready = 12:30

Actual Out =12:40

Off-Time=12:50

Thus, Taxi-Time = 10 minutes

And, Early Off-Time by = 2 minutes

Cost for fuel in Baseline = 22 minutes*$10.09/min = $222

Cost for fuel in ATD-2 = 10*$10.09=$101

Cost savings for early off = Early off-time * (PVT+ADOC)

= 2 minutes*($64.08/min+$29.14/min) =$186

ATD-2 Savings = $222-101+186 = Net change of $307

Figure 8 shows the monetized benefits for each SOSS-AOSS simulated airport. Note that CLT and DFW each have six simulated days and EWR four. There are three components to the benefits: ADOC, PVT, and Fuel. In these results, only CLT was observed to realize significant benefit in all three categories, while DFW had little delay savings and EWR a smaller percentage. This chart shows the total across all the days simulated and extrapolated to a full day. Using methods explained in Section IV-A to extrapolate benefits to nationwide airports, overall, we estimate that the ATD-2 system will provide $2.6 billion in monetary benefits nationwide over the entire lifecycle of the program, due to significant reduction in delay as well as shift in delay from taxi to gate. Since ATD-2 is expected to be incorporated into the TFDM system, the lifecycle was assumed to be FY16-FY48 (end date was set to be 20 years following the latest TFDM airport deployment). Next, we discuss the comparison of computed ATD-2 benefits against implementation costs.

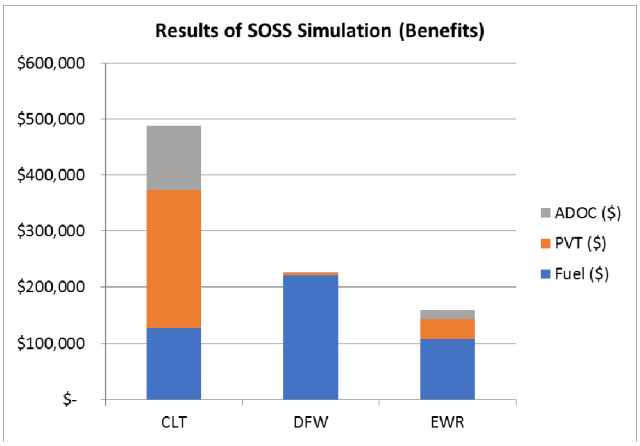


Figure 8. Monetized Simulated Benefits Estimates

V. Benefits Costs Analysis

Our benefits costs analysis approach aimed to quantify the benefits and costs impact of ATD-2 research and development activities on the FAA's Terminal Flight Data Manager (TFDM) program. There was a two-fold influence. First, we estimated that ATD-2 provides additional benefits by enabling supplementary benefit mechanisms that were not considered in earlier TFDM benefits estimates. Second, we estimated that ATD-2 could reduce TFDM implementation costs by reducing the cost uncertainty related to the implementation of specific TFDM work breakdown structure elements.

Our benefits estimate, discussed in previous sections, puts the estimated benefit of implementing the ATD-2 system NAS-wide at $2.6 B over the full life-cycle, which is 77% higher (1.77 times) than the benefit estimated for the FAA's TFDM program [10] (earlier benefit estimate only assumed surface metering benefit mechanism). Note that the earlier benefit estimate in [10] assumed a TFDM program without the additional scheduling and TMI-coordination capabilities added by NASA's ATD-2 system. The earlier estimates in [10] also relied exclusively on simulations conducted using medium-fidelity queuing models. Hence, the increase in estimated benefits can be allocated to the addition of scheduling and TMI-coordination capabilities as well as a more detailed simulation modeling-based benefits quantification methodology.

We next estimated the cost impact of ATD-2 on the ongoing FAA TFDM program. For this analysis, the ATD-2 system was assumed to influence the existing TFDM program that has been baselined, but not implemented. The TFDM program was baselined in June-2016 after extensive cost analyses. The TFDM cost estimates were based on a combination of proposals from vendors and estimates based on size and type of the problem (e.g., Software lines of code (SLOC) and cost/SLOC). In addition, the cost had uncertainty applied to various parameters to capture the lack of certainty in the values (e.g., salaries of software engineers, number of SLOC). The uncertainty was evaluated using Monte-Carlo techniques and then the output was created at a "high-confidence" level. High-Confidence at the FAA is generally an 80% confidence that the costs will be less-than the estimate 80% of the time. This is often called "Risk-Adjusted Cost" and is done to be conservative and ensure success without the need for additional funds a majority of the time.

In estimating the impact of ATD-2 on the baselined TFDM program, two factors were assumed: 1) ATD-2 research and development done by NASA would reduce the parametric uncertainty in the cost estimate and 2) NASA's ATD-2 research would guide the way to a lower point estimate (e.g., mean or mode of the risk distribution). Thus, the technique was to reduce the variance and mode of the risk distributions assigned to the dominant work breakdown structure elements. The amount of change was based on discussions with cost and operational SMEs. In the end, the relative max and min of the typically assigned triangular distribution were set to 5% lower, and the point/mode of the distribution to 2.5% lower. Overall the effect was to reduce the cost estimate by 3.5%. The TFDM cost was estimated at $1.3B in risk-adjusted Then Year dollars (TY$), thus the modified costs due to ATD-2 would be $1.25B. Note that this approach was applied only to the Capital Facilities and Equipment (F&E) portion of the cost. No impact on the operating costs was assumed.

The business case metrics—Benefit-to-Cost (B/C) ratio and Net Present Value (NPV)—were computed next and compared to earlier TFDM results. B/C can be calculated by using simple multipliers that adjust the numerator (benefits) by a factor of 1.77 (as per the 77% increase in benefits estimated) and the denominator (costs) by a factor of 0.965 (as per the 3.5% drop in implementation costs estimated), which results in an increase of 83%. The B/C ratio for TFDM was estimated at

1.03 by the earlier effort [10], a barely breakeven estimate. With ATD-2 analysis, this improved to a solid 1.9. Similarly, the NPV increases from a minimal $17M to nearly $500M.

VI. CONCLUSIONS

This paper presented the technical approach for and results from a simulation-based benefit/cost analysis of implementing NASA's ATD-2 system at airports nationwide. Results from high-fidelity simulations of current-day and ATD-2 procedures at three busy U.S. airports were annualized (extrapolated to full year benefits) and nationalized (extrapolated to Core-30 FAA airports), to compute total monetary benefits per year. Results suggest that the ATD-2 system will offer significant taxi-out time savings benefits at congested airports in the NAS, with no adverse impact on taxi-in times, OFF-time performance or airport throughput. The ATD-2 system is estimated to provide $2.6 billion in monetary benefits nationwide over the lifecycle of the TFDM program by significantly reducing delay as well as shifting delay from taxi to gate. The three primary simulated airports (CLT, DFW, EWR) had an annual total of 3.5 million minutes of reduced taxi-time and nearly 400,000 minutes of early off times (delay savings). The projected ATD-2 benefits significantly outweigh the projected implementation costs. Incorporation of ATD-2 into the FAA's planned TFDM system deployments is estimated to improve the benefit/cost ratio of the TFDM program from an earlier estimated 1.03 to 1.89 over the lifecycle of the program.

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