Benefit Opportunities for Integrated Surface and Airspace Departure Scheduling

A Study of Operations at Charlotte-Douglas International Airport

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Abstract— **NASA is collaborating with the FAA and aviation industry to develop and demonstrate new capabilities that integrate arrival, departure, and surface air-traffic operations. The concept relies on trajectory-based departure scheduling and collaborative decision making to reduce delays and uncertainties in taxi and climb operations. The paper describes the concept and benefit mechanisms aimed at improving flight efficiency and predictability while maintaining or improving operational throughput. The potential impact of the technology is studied and discussed through a quantitative analysis of relevant shortfalls at the site identified for initial deployment and demonstration in 2017: Charlotte-Douglas International Airport. Results from trajectory analysis indicate substantial opportunity to reduce taxi delays for both departures and arrivals by metering departures at the gate in a manner that maximizes throughput while adhering to takeoff restrictions due mostly to airspace constraints. Substantial taxi-out delay reduction is shown for flights subject to departure restrictions stemming from traffic-flow management initiatives. Opportunities to improve the predictability of taxi, takeoff, and climb operations are examined and their potential impact on airline scheduling decisions and air-traffic forecasting is discussed. In addition, the potential to improve throughput with departure scheduling that maximizes use of available runway and airspace capacity is analyzed.**

Keywords—air-traffic; surface; airspace; departure operations; integrated operations; shortfalls and benefits

I. INTRODUCTION

Improving the flow of operations into and out of the airport environment when demand exceeds capacity remains a key objective of the Next Generation Air Transportation System (NextGen). Whereas trajectory-based concepts and technologies have been developed for specific phases of flight and control facilities, their integration across surface and airspace domains to more fully optimize traffic flow remains a considerable challenge. Nowhere is the need for integrated solutions greater than in metroplex terminal environments where traffic to and from multiple airports compete for limited airspace resources. In these environments, flight trajectories must be coordinated in a manner that de-conflicts traffic flows and balances demand and capacity by adhering to a multitude of surface and airspace flow and separation constraints.

To address the Integrated Arrival, Departure, and Surface (IADS) challenge, NASA is developing and demonstrating trajectory-based departure automation under a collaborative effort with the FAA and industry known Airspace Technology Demonstration 2 (ATD-2). ATD-2 builds upon and integrates previous NASA research capabilities that include the Spot and Runway Departure Advisor (SARDA) [1–2], the Precision Departure Release Capability (PDRC) [3], and the Terminal Sequencing and Spacing (TSAS) capability [4].

Reference [5] provides a qualitative description of shortfalls targeted by ATD-2 and discusses how stakeholder feedback was used to establish the high-level performance goals of improving operational efficiency and predictability while maintaining or improving throughput. Many of the shortfalls in today's airport operations can be traced to reactive handling of departures, based primarily on the order in which pilots first call the tower for services. Without automation to coordinate aircraft movements from the gate, large queues and other forms of congestion can develop on ramps and taxiways causing delays that waste fuel and generate excess emissions. Furthermore, surface congestion creates physical constraints that limit a controller's options for re-sequencing flights for maximum throughput and compliance with Traffic-flow Management Initiatives (TMIs). Inadequate compliance with TMIs at takeoff increases the chances that costly and unpredictable tactical maneuvers will be required once airborne to satisfy airspace constraints.

The purpose of this paper is to provide a quantitative assessment of operational shortfalls relevant to ATD-2 efficiency, predictability, and throughput objectives. The study is also intended to identify key performance metrics needed to measure the benefits-related impact of ATD-2 in upcoming simulations and field demonstrations. Analyses were performed for operations at Charlotte Douglas International Airport (CLT), which is the site selected for the initial field demonstrations of ATD-2 that start in 2017.

The paper first provides background on the ATD-2 concept and operational characteristics at CLT. Benefit mechanisms and metrics are then described followed by the approach to the quantitative shortfalls analyses. A broad sample of benefit opportunities identified by the analyses is then provided and discussed.

II. BACKGROUND

A. *Concept Overview*

The ATD-2 concept centers on departure scheduling that allows aircraft to taxi and climb with minimal interruption. A key principle is to allow aircraft to absorb required delay at the gate prior to engine start in order to reduce fuel burn and emissions.

ATD-2 manages traffic volume on the surface while accounting for takeoff constraints and flight priorities. Scheduling solutions rely on trajectory-based taxi and climb predictions that incorporate airline flight readiness information and account for individual flight routing between allocated gates, runways, and airspace fixes. Whenever possible, scheduling accommodates airline priorities and preferences by invoking the principles of Collaborative Decision Making (CDM) [7].

Takeoff constraints factored into scheduling include wake-vortex separation criteria and takeoff restrictions due to strategic and local TMIs. Strategic TMIs produce specific takeoff-time restrictions in the form of Expected Departure Clearance Times (EDCTs) used mostly to control the flow of traffic to destinations impacted by weather. Local TMIs include takeoff times negotiated between Tower and Center controllers through an Approval-Request (APREQ) process. As shown in Fig. 1, local TMIs help facilitate the insertion of departures into overhead streams, prevent imbalances between en-route airspace demand and capacity, and help meter departures into arrival streams at their destination. Local TMIs can also result in Miles-in-Trail (MIT) restrictions for flights transitioning from terminal to en-route airspace. These in-trail restrictions are typically enforced at departure meter points located near the terminal boundary, as shown in Fig. 1. Such constraints are intended to prevent overloading downstream airspace and help regulate departure flows from multiple airports within a metroplex terminal environment.

ATD-2 scheduling results in target times at potential control points along an aircraft's departure trajectory, which include for pushback from the gate, entry into the Airport Movement Area (AMA) at the *spot*, takeoff, and departure-fix crossing. Yellow ovals in Fig. 1 depict control points on the surface, while blue ovals depict control points in the airspace. The takeoff point is shown by a by a yellow and blue oval as it represents the key control point for surface and airspace integration. In the initial implementation at CLT, schedule conformance is managed primarily through the metering of pushback events from the gate by Ramp controllers and conformance with takeoff restrictions due to TMIs at the runway by Tower controllers. Although only departures are directly controlled through ATD-2 automation, arrival predictions (represented by the red trajectory in Fig. 1) are factored into scheduling to minimize surface congestion. Arrivals therefore stand to benefit indirectly through less-impeded taxi trajectories from runways to gates.

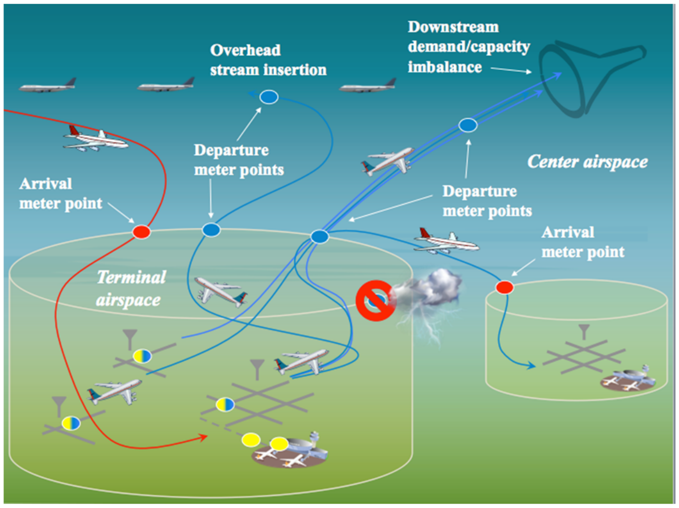


Fig. 1. ATD-2 end-state concept environment

B. *CLT Operations Overview*

As the initial site for ATD-2, CLT provides an opportunity to demonstrate the capabilities and benefits of integrated surface and airspace departure scheduling. With approximately 1,600 operations per day, CLT is the sixth busiest airport in the nation in terms of operations and the second busiest on the East Coast behind Atlanta (ATL) [6]. CLT is a hub for American Airlines, which together with its regional carriers operates about 90% of commercial flights at the airport. The remaining 10% of operations is comprised of other regional carriers, mainline flights operated by Southwest, Delta, United and Jet Blue, military flights, business and general aviation, and air cargo. As the dominant carrier, American manages all ramp operations at the airport.

Located midway between ATL and the Washington D.C metroplex, CLT lies beneath one of the busiest air corridors in the U.S. This location, and the fact that many flights from CLT are destined to constrained airspace and airports on the East Coast, results in departures being frequently subjected to TMIs, particularly APREQs for managing overhead stream insertion for flights headed to airports within the New York and Washington DC metroplexes. The prevalence of such TMIs make CLT a suitable site for demonstrating the airspace integration benefits of ATD-2 prior to adapting the technology to multi-airport metroplex environments.

Without predictive automation to assist controllers in meeting TMIs in today's operations, departures must often absorb delay on the airport surface. This can add to existing surface congestion due to traffic volume that often exceeds available gate, ramp, taxiway, and runway capacity. Such congestion is mostly a consequence of traffic growth at CLT in recent years, which has nearly doubled in the past decade. Surface congestion in the ramp area is further exacerbated by limited gate availability, single-direction taxiways, and limited options for holding flights off the gate. In response, CLT is currently undergoing a major airport expansion effort that will add gates, a new tower, and a fourth parallel runway [8].

As shown in Fig. 2, CLT currently operates with three north/south parallel runways and one diagonal runway. Triple simultaneous instrument approach procedures are authorized for the parallel runways. In south-flow configurations, aircraft typically arrive on runways 18R, 18C, and 23 and depart on runways 18C and 18L. In north-flow, aircraft typically arrive on all three parallel runways – 36L, 36C, and 36R – and depart on dual-use runways 36C and 36R. Runway 05/23 is used mostly for arrivals in south-flow and often as a relief taxiway in north-flow. In the south-flow configuration where the diagonal runway is used for arrivals, departures from 18C are restricted by recent FAA rules for converging but non-intersecting runways. At nighttime, Runway 05/23 is used by both arrivals and departures for noise abatement. Noise abatement procedures also require jet traffic from 18C and 18L to fly runway heading for 2 miles prior to turning on course.

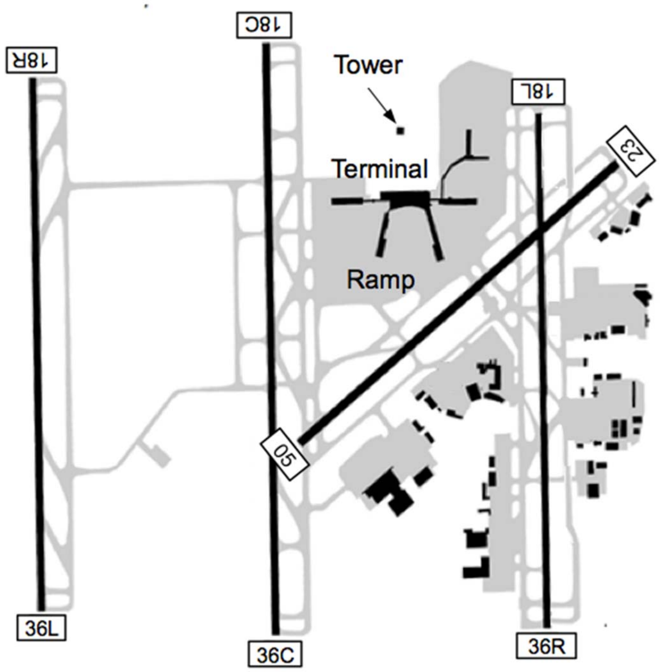


Fig. 2. CLT airport plan view

III. BENEFIT MECHANISMS AND METRICS

A. *Efficiency*

Efficiency goals pertain to more expedient trajectories during taxi and climb that consume less fuel and reduce emissions. ATD-2 offers to improve efficiency through coordinated scheduling that prevents surface congestion and assists controllers in managing TMIs. The bulk of any required delay is taken at the gate, thereby reducing fuel consumption. Following pushback, aircraft can taxi with minimal interruption, forming short takeoff queues only as necessary to keep pressure on runways for maximum throughput during peak traffic periods. Once airborne, aircraft can fly optimal profile climbs along area-navigation (RNAV) departure routes, with guidance and control aided by flight-deck automation. With improved TMI conformance on the ground, fewer airborne control actions involving path, speed, and altitude changes are potentially required. In this way, ATD-2 can provide a means for transferring required delay to flight phases where it is more efficient to absorb, i.e., from the airspace domain to the airport surface, and ultimately to the gate. Less tactical maneuvering once flights are underway can also potentially reduce workload and radio frequency congestion.

ATD-2 metrics for assessing efficiency include taxi-out and taxi-in durations as well as transit times to departure meter points in the airspace. To examine efficiency independent of flight routing, transit delays can be computed by comparing actual and unimpeded times along the same taxi and departure routes.

B. *Predictability*

Predictability goals pertain to reducing the variance in actual transit times as well as improving the prediction of future aircraft locations and events. For ATD-2, this involves reducing the variance of taxi-out and climb durations for departures and the variation of taxi-in times for arrivals. For individual flights, key trajectory points in need of greater predictive accuracy are pushback from the gate and takeoff.

ATD-2 aims to improve predictability through the scheduling of departures from the gate to decrease surface congestion and conform indirectly to any takeoff restrictions. Even without scheduling, ATD-2 offers to improve nominal (non-metered) trajectory prediction accuracy through the use of machine-learning methods and the incorporation of flight readiness information from airline operators [9].

On an individual flight basis, better trajectory predictions can improve awareness of aircraft state and intent, leading to improved tactical decisions by controllers and flight operators. On an aggregate flight basis, improved predictions can result in better forecasting of traffic demand, leading to more efficient management of airport and airspace resources. Controllers can make more informed decisions regarding airport configuration changes, TMIs, and weather-mitigation routes; and airlines can make better decisions to avoid missed connections and preserve network integrity.

Furthermore, sustained predictability improvements could allow airlines to confidently reduce scheduled block times – i.e., the gate-to-gate times in published flight schedules. These times have trended upwards in recent years as airlines strive to maintain on-time performance in the presence of increasing air-traffic uncertainty. Smaller scheduled block times can reduce operating costs and decrease the probability that flights arrive early and add to surface congestion as they compete with departures for gate resources.

ATD-2 metrics for assessing predictability improvements are focused on the variance of transit times for taxi-out, climb, and taxi-in phases of flight and the degree to which aircraft comply with takeoff-time restrictions derived from TMIs.

C. *Throughput*

Throughput objectives pertain to the number of departure and arrival operations using runways and the airport as a whole. Throughput can also be examined from an airspace perspective by considering the number of flights crossing a given fix or boundary. ATD-2 aims to increase, or at least maintain, departure throughput with scheduling that keeps pressure on runways and maximizes use of available airport and airspace capacity. Key ATD-2 throughput metrics for benefit and shortfall assessments include runway and departure rates and excess in-trail spacing at constrained departure fixes as possible indicator of wasted airspace capacity.

IV. DATA SOURCES AND GENERAL METHOD

Shortfalls were analyzed using flight-specific data obtained from a variety of government and industry data sources over a time period ranging from January 1, 2014 to April 30, 2015. Surface analysis was supported with data provided by American Airlines from their Aerobhan traffic display and management system. These data contained surface track and event data for all mainline and regional airlines operating at CLT. Aerobahn track data are obtained from the Airport Surface Detection Equipment, Model X (ASDE-X) surveillance system in place at CLT. ASDE-X provides aircraft position updates at 1 Hz in the AMA and limited locations in the ramp area, obtained by combining surveillance from a variety of sensors that include surface radar, muti-lateration sensors, and Automatic Dependent Surveillance - Broadcast (ADS-B). Aerobahn data were used to obtain taxi times specific to each gate, spot and runway combination. To further support surface analysis, the Surface Operations Data Analysis and Adaptation (SODAA) tool was used.

Airspace operations analysis was performed using aircraft track and flight-plan data obtained through NASA's research version of the Center-TRACON Automation System (CTAS). Archived CTAS data files were processed for input into NASA's TCSim Route Analyzer/Constructor (TRAC) tool, which was used to perform flight time and distance analysis, identify tactical airspace maneuvers, and evaluate in-trail spacing across fixes and boundaries. For use in both surface and airspace analyses, TMI restrictions were obtained from the FAA's National Traffic Flow Management Log (NTML) and Time-Based Flow Management (TBFM) system.

Data were examined to reveal shortfalls in current operations that ATD-2 aims to address through departure scheduling automation. The following results are categorized by efficiency, predictability, and throughput shortfalls to align with ATD-2 benefit objectives. Within each category, findings are further divided between surface and airspace domains.

V. RESULTS: EFFICIENCY ANALYSIS

A. *Surface Efficiency*

1) Taxi-out time, fuel, and emissions

To estimate inefficiencies on the airport surface for aircraft taxiing for departure, taxi-out times were calculated by subtracting pushback (OUT) times from takeoff (OFF) times. For all flights in 2014, mean taxi-out time was found to be 18.8 min with 33% of flights experiencing taxi-out times greater than 20 min. As seen in Fig. 3, taxi-out times were similarly distributed between the ramp area (gate to spot) and AMA (spot to runway). On average, however, aircraft spent more taxi-out time in the ramp area (10.2 min) than in the AMA (8.8 min). Time spent in the AMA was generally lower in south-flow configurations, because the terminal complex is located at the north end of the field.

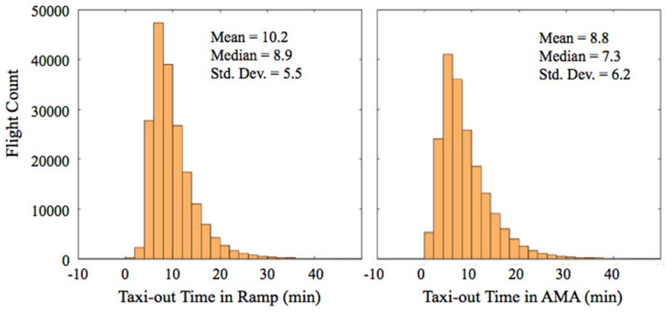


Fig. 3. Distribution of taxi-out time in ramp area and AMA for all departures in 2014

To compute delays during movement, estimates of unimpeded taxi times were subtracted from actual taxi times for the same gate, spot, and runway combinations. Unimpeded times were calculated as the 10th percentile of observed taxi-out times. The resulting distribution of excess taxi-out time (referred to here as taxi-out delay) is shown in Fig. 4. Here, the mean taxi-out delay was found to be 7.2 min for all flights in 2014, with 11.2% of flights experiencing delays of 15 minutes or more.

Excess fuel burn and emissions associated with taxi-out delays were estimated using fuel-flow rate and emission coefficients obtained from the ICAO Aircraft Emissions Databank [10]. These coefficients were obtained for specific aircraft types and engine fits under standard atmospheric conditions, assuming an all-engine taxi at idle-thrust (7% total available thrust). Emission compounds – computed as a ratio to fuel burned using the ICAO coefficients – included carbon dioxide along with gas compounds that contribute to air pollution and are sensitive to engine type and thrust settings, specifically unburned hydrocarbons (H_xC_x), nitrogen oxides (NO_x), and carbon monoxide (CO). Total excess fuel burn was estimated at 20,400 metric tons (83 kg per flight). Estimated excess emissions, averaged for each flight due to excess fuel combustion, are shown in Table I. Total excess carbon dioxide emissions for all taxiing departures were estimated at 62,800 metric tons.

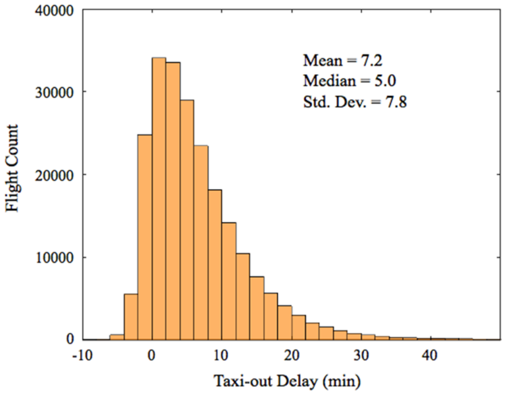


Fig. 4. Distribution of taxi-out delay distribution for all departures in 2014

TABLE I. EXCESS TAXI-OUT FUEL AND EMISSIONS PER FLIGHT

	Fuel (kg)	**CO_2 (kg)**	**H_xC_x (g)**	**CO (g)**	**NO_x (g)**
Mean	83.3	256.6	199.8	1999.1	362.5
Median	57.1	175.9	88.3	1412.0	240.1
Std. Dev.	96.3	296.6	434.1	2336.3	432.6

These findings suggest considerable opportunity for ATD-2 to improve taxi-out efficiency through departure metering that holds flights at the gate prior to engine start in order to manage traffic volume and satisfy airspace flow constraints. Even with ATD-2, however, it is recognized not all flights can be expected to execute an unimpeded taxi to the runway. Indeed, the ATD-2 scheduler will work to feed enough aircraft into the AMA to keep pressure on runways for maximum throughput during peak periods. Prior simulations of departure metering with SARDA, from which ATD-2 borrows much of its tactical surface-scheduling algorithm, show taxi-out delay reductions of 60% during heavy traffic conditions [11].

2) *Taxi-out efficiency factors*

To gain further insight into the causes of taxi-out delays in current operations, stopping and queuing on the airport surface is now examined along with unregulated demand and the effect of TMI constraints

a) Demand exceeding capacity:

A root cause of surface congestion is an excess number of departures competing for taxi and takeoff services beyond what the airport and surrounding airspace can accommodate. Contributing to this phenomenon is the peaking of airline schedules in hub-and-spoke operations and published departure times that tend to fall at the top of the hour, or at the half hour, for customer convenience and ticket sales [5].

Taxi demand based on airline-published departure times was examined by counting the number of flights scheduled to push back within 10-minute, non-overlapping time windows. Fig. 5 (lower) shows a time history of taxi demand versus actual taxi operations as a function of local time-of-day, compiled by averaging the demand in each 10-minute window across the entire year 2014. The difference between airline-scheduled and actual pushback demand reflects actions taken by Ramp controllers to meter demand in an effort to prevent surface congestion. These actions involved holding company-owned flights for up to 10 minutes whenever more than 15 aircraft were away from their gates and headed for the same departure runway. Fig. 5 (lower) shows that departure demand based on airline schedules often exceeded more than 20 flights competing for taxi services from the gate within a 10-minute period.

To examine unregulated demand from a runway perspective, takeoff times projected from published pushback times were obtained from Aerobahn. Fig. 5 (upper) shows this *airline-scheduled* takeoff demand in comparison with actual takeoff events. The difference reflects delays that had to be absorbed on the airport surface, contributing to congestion and excess fuel burn.

In the ATD-2 concept, a combination of strategic and tactical surface scheduling will be used to meter departures from the gate in order to spread out demand with the aim of preventing volume-related surface congestion. Perturbations to airline-published departure times will be limited, however, in order to preserve on-time arrival performance and ensure that flight networks remain intact.

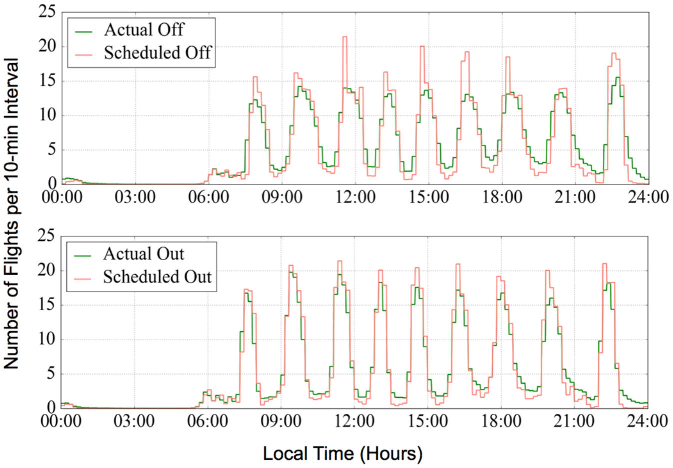


Fig. 5. Departure demand vesus actual operations, averaged over 2014 as a function of local time

b) Stopping and Queuing:

Stopping on the airport surface was examined using ASDE-X surveillance data and filtering algorithms available through SODAA. For this analysis, stopping was defined by an aircraft's speed falling to zero for multiple sequential points in its trajectory time-history, followed by a sustained, non-zero velocity segment. Using this method, it was found that aircraft stopped an average of 4.5 times between gates and runways with an average stop duration of 4.1 minutes, including stopping at the spot and at designated holding areas.

Some of the detected stops were the result of aircraft progressing in queues to runways. The maximum queue size experienced by each flight was approximated by counting the number of aircraft already in the AMA and headed for the same runway at the time the flight left its gate. Fig. 6 shows the resulting histogram of maximum departure queue size experienced by flights in 2014 operations. Whereas it was still common for departing flights to experience more than 15 aircraft ahead of them destined for the same runway, these larger queues occurred with less frequency, likely a result of American's departure management procedure previously described.

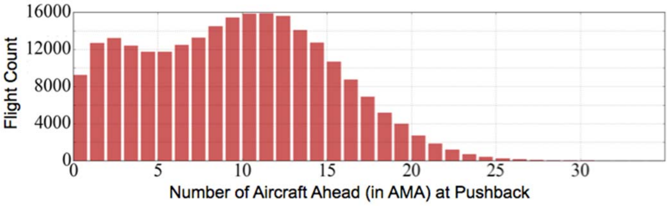


Fig. 6. Distribution of departure queue size experienced at pushback for all departures in 2014

c) Effect of TMIs on Taxi-Out Time

Of considerable relevance to ATD-2 is the impact of TMIs on taxi-out delay and congestion. To examine this, flights subjected to EDCT and APREQ takeoff-time constraints and MIT spacing restrictions at departure fixes were identified. Flights subjected to combinations of these TMIs were also examined. Fig. 7 shows the effect of TMIs on taxi-out delay between gates and runways. It can be seen that flights with no restrictions experienced the least amount of taxi-out delay. Considering TMI categories independently, APREQ and MIT constraints had a similar effect on mean taxi-out delay, while EDCT constraints resulted in somewhat larger delays. In general, flights subjected to multiple constraints, although far fewer in number experienced substantially larger delays than those subjected to just one constraint type. Flights with multiple constraints where one constraint was an EDCT had the largest delays, with flights subjected to both EDCT and MIT constraints experiencing a median of more than 15 minutes of delay on the surface relative to an unimpeded transit. Analysis of stopping on the surface, using the method previously described, revealed that flights with MIT constraints stopped more frequently, but flights with EDCTs, especially when also subjected to MIT constraints, stopped longer. Flights with EDCTs stopped for an average of 7.2 minutes compared to 4.0 minutes for flights with no TMI restrictions. Those flights subjected to both EDCT and MIT experienced an average stop time of 10.8 min.

With departure metering that considers TMI restrictions, ATD-2 aims to reduce the need for controllers to maneuver and hold aircraft away from the gate to meet required takeoff times. It is important to note, however, that the ability to hold aircraft at the gate is limited at CLT because demand for gates often exceeds their availability. Even with ATD-2, controllers may at times have to push departures earlier than advised in order to free up gates for arrivals, thus requiring some delay to be absorbed either in the ramp area or AMA.

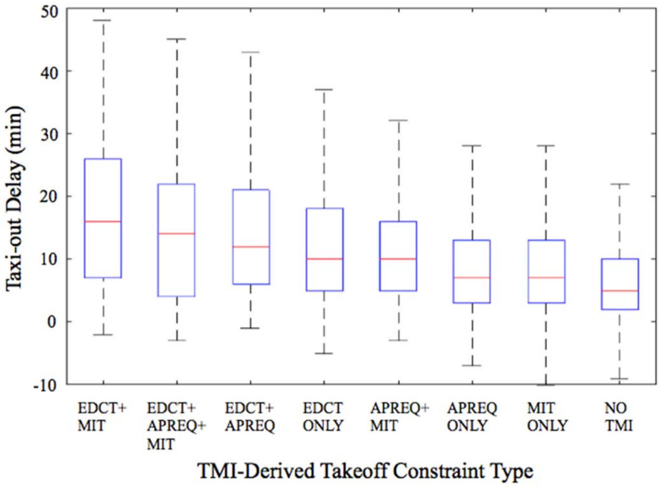


Fig. 7. Effect of TMIs on taxi-out delay for all departures in 2014

3) Taxi-in time, fuel, and emissions

Taxi delays for arrivals were computed using the same process previously described for departures. Mean taxi-in delay for all arrivals was 4.97 minutes, with somewhat larger mean delays in the ramp area than in the AMA (3.4 minutes vs. 2.5 minutes). Considerably higher mean taxi-in delays were found for those aircraft that had gate conflicts upon landing, presumably as they waited for gates to be vacated by departures. Mean taxi-in delay for arrivals with gate conflicts was 12.9 minutes with a standard deviation of 9.3 minutes. Flights with gate conflicts upon landing represented 6.9% of all arrivals. This number is likely low, however, since situations where gates were reassigned after landing to resolve a conflict were not discernable from the data.

Total excess fuel burn due to taxi-in delays for all operations in 2014 was estimated at 16,551 metric tons, corresponding to average of 62 kg per aircraft. Using the method described previously for departures, excess taxi-in fuel burn was found to result in a total CO_2 excess of 50,977 metric tons, with an average per-flight excess in CO_2, CO, NO_x, and H_xC_x of 191 kg, 1.6 kg, 0.27 kg, and 0.22 kg, respectively.

B. Airspace Efficiency

Climb efficiency was examined in terminal airspace to observe the maneuvering of flights off their nominal departure routing between runways and departure fixes. Through more accurate compliance with controlled takeoff times, ATD-2 aims to reduce the need for maneuvering in the airspace to satisfy TMI constraints pertaining to in-trail spacing at departure fixes and en-route meter points.

For this initial analysis, which focused on terminal airspace, the most relevant TMIs were MIT spacing requirements associated with RNAV departure fixes but enforced by controllers at fixes slightly upstream along the TRACON boundary, as shown by the blue triangles in Fig. 8. Due to the complexity of generating unimpeded times, which are dependent on aircraft type and atmospheric conditions, excess along-path distance was used as a surrogate for airborne delay. For this, nominal path distance along the filed RNAV Standard Instrument Departure (SID) route was used as a datum. This simplification assumes that the majority of maneuvering to satisfy MIT requirements is accomplished through vectoring, which has been affirmed by Subject Matter Experts (SMEs).

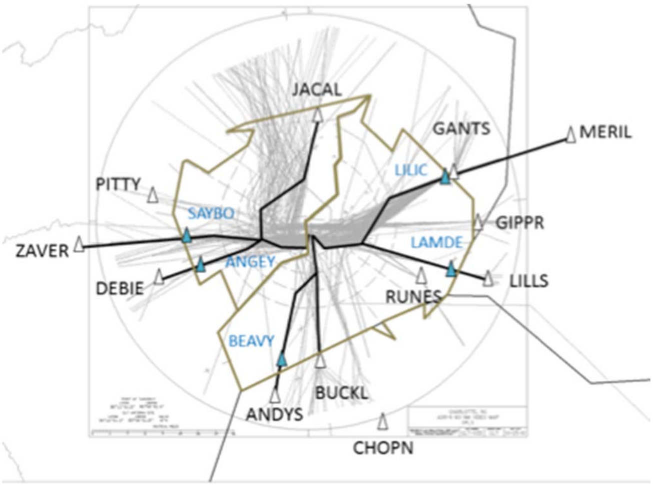


Fig. 8. Terminal airspace fixes and tracks, March 31, 2015

The resulting distribution of excess path distance for all departures filing RNAV SIDs between May 2014 and April 2015 is shown in Fig. 9. Here, negative values indicate that flown distances were shorter than those associated with RNAV routes. Mean excess path distance for all flights was -2.8 nmi. Path stretching in terminal airspace was evident in only 11% of departure operations. Far more common was the shortcutting of routes by controllers to provide more direct flight paths. This was most common for departures destined for fixes in the opposite direction to their runway heading. For instance, when departures took off in a north-flow configuration destined for ANDYS or BUCKL (south of CLT), the controller often vectored flights directly to these fixes, resulting in sharper turns than had these flights otherwise remained on their RNAV routes. SMEs suggested that the shortcutting of routes was motivated, in part, by sub-optimal RNAV route designs.

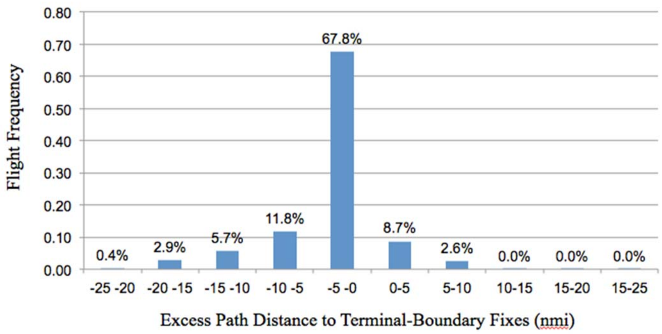


Fig. 9. Distribution of excess path distance flown in terminal airspace for all departures on RNAV routes from May 2014 through April 2015

A closer examination of airspace maneuvering revealed that 50% of flights with evidence of path stretching flew along-track distances that were within 2 nmi of those associated with their nominal RNAV routes. Excluding these flights left only 6% of all departures with deliberate path stretching in terminal airspace. Flights routed through MERIL, which is the departure fix most commonly associated with MIT restrictions, were most frequently path stretched. MERIL flights represented 54% of all path-stretch cases. The mean excess path distance in these cases was 4.3 nmi, which was two to three times greater than for flights routed through other departure fixes.

For the same period, a search for tactical level-offs and decelerations was conducted to find further evidence of maneuvering for delay absorption in terminal airspace. For this purpose, tactical level-offs were defined as those lasting for more than one minute, not associated with procedural level-offs for segregating arrival and departure flows or managing controller handoffs. Deceleration events were defined by non-procedural ground-speed reductions greater than 20 knots, sustained for at least one minute. Results indicated that both types of maneuvering were rare, with tactical level-offs occurring in only 2% of departures and speed reductions occurring in only 0.4% of departures.

VI. RESULTS: PREDICTABILITY ANALYSIS

A. *Surface Predicability*

1) *Takeoff time prediction*

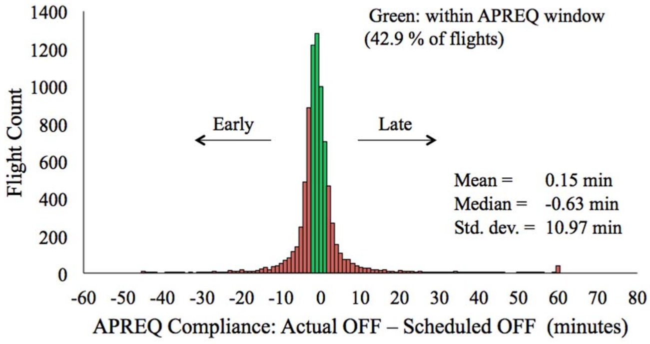
An important aspect of increasing predictability with ATD-2 is improving the accuracy and precision of takeoff predictions prior to aircraft leaving the gate. From an automation standpoint, such predictions are required not only as input to ATD-2 internal scheduling but also for external TBFM departure and arrival scheduling with which ATD-2 will interface. For 2014 operations, takeoff predictions were obtained from Aerobahn just prior to aircraft leaving the gate and compared against actual takeoff times. In current operations, takeoff predictions used for airline flight planning rely on published departure times (adjusted for flight-plan changes) together with a nominal taxi-out time assumption. In current practice, this nominal taxi time is typically a constant value that is adjusted for season but does not account for assigned gate and runway end points.

Results revealed a mean airline takeoff prediction error of 6.3 min with a standard deviation of 21.4 min. The large variance is due in part to uncertainty in actual taxi-out times, which, in 2014 operations at CLT, had a standard deviation of 8.7 min. ATD-2 aims to reduce the variance of taxi-out time predictions using machine-learning algorithms, trained with historical data. Applying such algorithms to 2014 CLT data reduced the mean taxi-out prediction error to nearly zero and the standard deviation to 5 minutes [9].

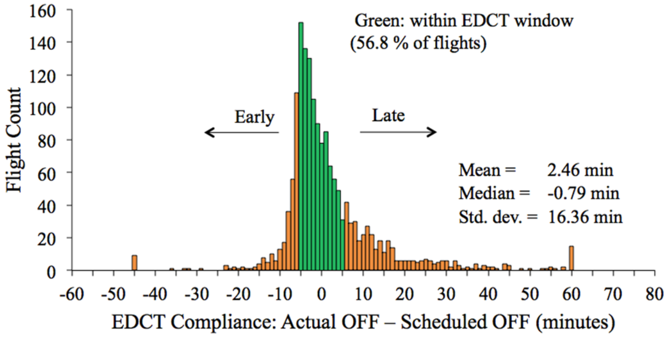
2) *Compliance with TMI takeoff-time constraints*

For departures with EDCT and APREQ constraints, climb predictability is governed primarily by the degree to which flights comply with target takeoff times. FAA regulations set performance objectives for controllers that specify a 10-minute compliance window for EDCT flights (-5 to +5 minutes of EDCT) and a 3-minute compliance window for APREQ flights (-2 to +1 minutes of APREQ time). For APREQ flights, the window is biased towards early takeoff times since it is easier for controllers to further delay flights if needed once airborne than to advance them. EDCT has a larger compliance window because it is typically used to manage demand and capacity imbalances further downstream, most often at destination airports subject to FAA Ground-Delay Programs.

Compliance was examined for 29 airports in the NAS with more than 10,000 APREQ operations in 2014. It was found that an average of 46.9% of flights complied with their EDCT window, and 54.4% of flights complied with their APREQ window. For CLT, the percentage of flights departing within their EDCT and APREQ windows was 56.8% and 42.9%, respectively. The corresponding distributions of compliance errors are shown in the histograms in Fig. 10. For the small number of flights subjected to both EDCT and APREQ restrictions (a total of 517 in 2014), the percentage of APREQ compliant flights was largely unchanged, whereas EDCT compliance dropped to 52%. This is consistent with SME feedback indicating that for flights with both types of constraints APREQ compliance is given higher priority.



b) APREQ Compliance



a) EDCT Compliance

Fig. 10. Distribution of compliance with takeoff-ttme restrictions for all departures in 2014

B. *Airspace Predicability*

1) Variance of terminal climb time

By helping controllers comply with airspace restrictions while flights are still on the ground, ATD-2 aims to reduce the need for maneuvering during climb, thus reducing the variance of flight time in terminal and en-route transition airspace. Variation of flight time to the CLT TRACON boundary was investigated for departures filing RNAV SIDs over a 12-month period from May 2014 to April 2015. Flight-time variance was examined for the most common combinations of departure runways (18C, 18L, 36C, and 36R) and departure fixes (ANDYS, BUCKL, DEBIE, JACAL, LILLS, MERIL, and ZAVER). Standard deviations across these combinations – expressed as a percentage of mean flight time – ranged from 4.4% to 11.3%. Greater variation relative to mean flight time was seen in combinations where flights departed in the opposite direction to their filed departure fix, e.g., flights departing 18L headed for the northern fix JACAL. This is consistent with the earlier finding that controllers often shortcut routes for flights with opposite runway-fix pairings. Such shortcutting performed on an ad-hoc basis would result in greater terminal flight time variance.

2) Conformace with MIT spacing constraints

Further insight into the predictability of current operations in terminal airspace can be gained by examining conformance to MIT spacing requirements. For this analysis, differences between actual in-trail spacing at terminal fixes and those stipulated by MIT constraints were examined for departures from April through December 2014. The distribution of these spacing differences for all terminal-fix MIT constraints is shown in Fig. 11. It was found that only 33% of flights conformed to their MIT requirements within +/- 5 nmi and that 22% of flights crossed into en-route airspace with less than their target spacing. Flights crossing with less spacing than required is considered a shortfall, since MITs are imposed to limit the number of aircraft entering downstream airspace. ATD-2 aims to address such a shortfall through tactical scheduling that takes MIT restrictions into account. In the majority of cases, however, flights crossed into en-route airspace with excess spacing. This may or may not indicate a shortfall, depending on whether the departure demand from the airport was sufficient to saturate at the maximum throughput implied by the MIT value. This issue is explored further in the throughput analysis that follows.

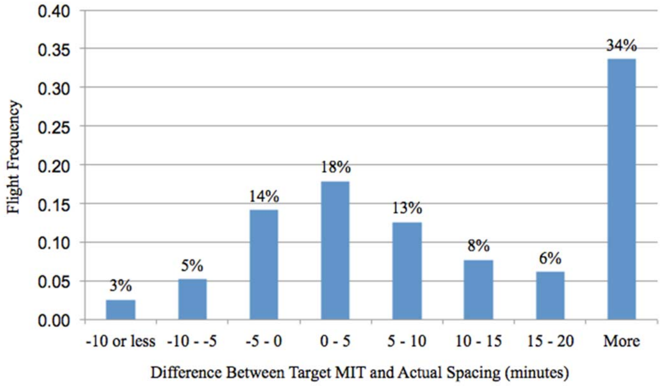


Fig. 11. Distribution of compliance with MIT constraints at terminal boundary for all departures from April through December, 2014

VII. RESULTS: THROUGHPUT ANALYSIS

A. *Runway Throughput*

While ATD-2 is not expected to increase arrival runway throughput, departure runway throughput can potentially be increased through tactical surface scheduling and sequencing that maximizes the use of available runway capacity. To examine opportunities for increasing throughput at CLT, analysis was performed using 2014 track data from SODAA and Aerobahn to search for unused runway slots where aircraft could have theoretically departed. Only periods where departure demand exceeded the actual departure rate were used in the analysis. Departure opportunities were identified by looking for gaps in runway occupancy between combinations of departing, landing, and runway-crossing flight pairs. Analysis was performed on each runway, accounting for wake-vortex separation and runway configuration. Also taken into account was the converging runway procedure that constrained departures on runway 18C when runway 23 was in use for arrivals.

Fig. 12 shows the resulting increase in takeoff opportunities (departure slots) possible through optimized scheduling and sequencing on the surface. Results show additional takeoff opportunities between existing departing, landing, and runway-crossing flight pairs as a function of the three most common runway configurations: 1) north-flow using the three parallel runways, south-flow using the three parallel runways, and south-flow using all four runways (including the diagonal runway). In south-flow configurations, the greatest number of extra takeoff opportunities was found between departing and crossing flights. In north-flow, extra takeoff opportunities were greatest between departing and landing flights. In total, analysis suggests that 9.4% of excess takeoff demand could potentially be absorbed through optimized scheduling and sequencing, corresponding to a total departure-throughput increase of 1.4%.

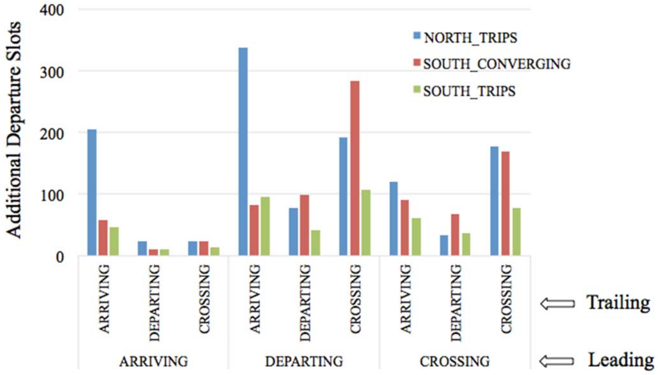


Fig. 12. Potential increase in takeoff opportunities between aircraft in 2014

B. *Airspace Throughput*

Opportunities to increase throughput between terminal and en-route airspace were examined by searching for unused capacity when MIT restrictions enforced at the terminal boundary were in effect. Such restrictions are often put in place to manage the flow of departures during peak traffic periods or when downstream capacity is limited due to weather. In 2014, there were a total of 588 unique MIT restrictions affecting CLT departures. The departure fix most affected was MERIL, which is used predominantly by flights bound for capacity-constrained airspace and airports in the northeast corridor. MIT restrictions for MERIL are enforced at the terminal fix LILIC. In searching for unused capacity, it was important to ensure that uncontrolled departure demand would have resulted in a meaningful portion of flights crossing into en-route airspace with less than the desired spacing, i.e., that the original departure demand was sufficient to overload the fix. To investigate this, times at which flights were predicted to arrive at terminal fixes were computed based on their published gate departures times, nominal taxi-out times, and unimpeded climb times (based on the 10th percentile of observed climb time to the fix from the given departure runway). It was found that LILIC had the largest percentage of flights (45%) that would have crossed with less than the required MIT spacing without control over demand. MIT requirements at LILIC ranged from 10 nmi to 30 nmi.

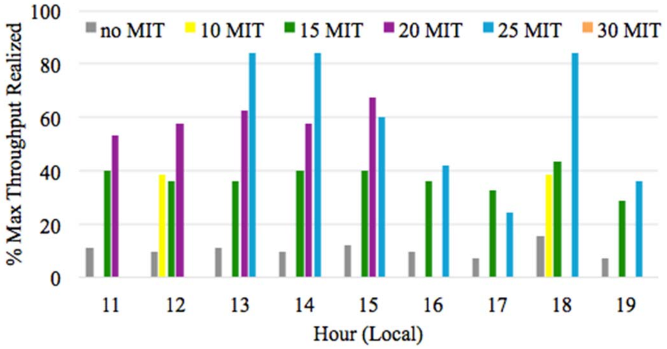


Fig. 13. Saturation of LILIC departure fix when subject to MIT constraints for all departures in April 2015

Traffic loading at LILIC when MIT restrictions were in place was examined over the month of April 2015. Fig. 13 shows actual throughput as a percentage of the capacity based on MIT restrictions. It can be seen that the saturation level at LILIC generally increases as the MIT increases, a finding consistent with a NAS-wide study of MIT restrictions found in [12]. This is somewhat intuitive, since uncontrolled traffic demand relative to fix capacity increases with increasing MIT, potentially making it easier for controllers to more fully saturate fixes. For the more common in-trail spacing restrictions of 15 and 20 MIT, LILIC was less than 70% saturated on average for each time of day. Moreover, for the most common restriction of 15 MIT, LILIC was less than 45% saturated.

Such findings suggest opportunities for ATD-2 to increase throughput by scheduling departures to meet MIT restrictions with minimal excess spacing when sufficient demand exists to saturate fixes under MIT constraints. In the further term, ATD-2 aims to facilitate less conservative airspace constraints by improving departure demand predictions, thus leading to further potential increases in capacity and throughput.

VIII. CONCLUSIONS

Operations at Charlotte-Douglas International Airport were examined to identify benefit opportunities for departure scheduling automation that accommodates both surface and airspace constraints. The automation, planned for initial deployment at CLT in 2017, relies on trajectory-based taxi and climb predictions that incorporate updated airline departure intent data. Analysis identified shortfalls in recent operations relevant to efficiency, predictability, and throughput objectives. Although opportunities for improving efficiency at CLT were found mostly on the airport surface rather than in the airspace directly, the largest taxi-out delays were experienced by flights subject to traffic-flow management initiatives. Across all departure operations in 2014, the average taxi-out delay was 7.2 minutes. Average taxi-out delay for flights subject to TMIs, however, ranged between 7 and 15 minutes, with the largest delays experienced by flights subject to multiple TMIs. Delays were associated with sizable taxi queues with frequent and prolonged stopping on the airport surface. Delays were associated with departure demand that often exceeded runway capacity. Annual excess fuel consumption resulting from both departure and arrival taxi delays was estimated at 36,950 metric tons. Automation offers to reduce taxi delays with scheduling that balances demand and capacity while helping controllers to comply with takeoff restrictions. Opportunities to improve predictability were identified by comparing current airline taxi-time predications with those based on machine-learning methods. Opportunities to further improve predictability were revealed by examining TMI compliance at runways and departure fixes. Finally, analysis suggests opportunities to increase throughput with coordinated departure scheduling that maximizes use of available airport and airspace capacity. Together, these analyses provide quantitative insight for bounding ATD-2 benefit expectations and selecting key performance metrics for upcoming field evaluations.

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