Strategic Surface Metering at Charlotte Douglas International Airport

Isaac Robeson
Mosaic ATM, Inc.
Leesburg, VA
irobeson@mosaicatm.com

William J Coupe, Hanbong Lee, Yoon Jung
NASA Ames Research Center
Moffett Field, CA
william.j.coupe@nasa.gov
hanbong.lee@nasa.gov
yoon.c.jung@nasa.gov

Liang Chen
Moffett Technologies, Inc.
Mountain View, CA
liang.chen@nasa.gov

Leonard Bagasol
Universities Space Research Association
Mountain View, CA
leonard.n.bagasol@nasa.gov

Bob Staudenmeier
Cavan Solutions
Frederick, MD
bob.staudenmeier@cavansolutions.com

Pete Slattery
Cavan Solutions
Charlotte, NC
pete.slattery@cavansolutions.com

***Abstract*— NASA is conducting a field test of the Airspace Technology Demonstration 2 (ATD-2) to evaluate an Integrated Arrival, Departure, and Surface (IADS) traffic management system. The IADS system was deployed to Charlotte Douglas International Airport (CLT) in 2017 for a three-year field evaluation. The Phase 1 field evaluation included tactical surface metering, which manages departure excess taxi time by tactically assigning gate holds. Phase 2 built upon the lessons learned from Phase 1 to extend surface metering into the strategic metering timeframes. In this paper, we describe the strategic metering capabilities of the ATD-2 IADS system and the operational results from CLT.**

Keywords— Airspace Technology Demonstration 2; Integrated Arrival, Departure, and Surface Scheduling; Operational Field Evaluation; Surface Metering

I. Introduction

NASA is developing and testing a suite of decision support capabilities for integrated arrival, departure, and surface (IADS) operations. The effort consists of three phases, under NASA's Airspace Technology Demonstration 2 (ATD-2) sub-project, through a close partnership with the Federal Aviation Administration (FAA), National Air Traffic Controllers Association (NATCA), air carriers, airport, and general aviation community. The Phase 1 and 2 IADS capabilities provide enhanced operational efficiency and predictability of flight operations through data exchange and integration, surface metering, and automated coordination of release time of controlled flights for overhead stream insertion. Phases 1 and 2 have been demonstrated at Charlotte Douglas International Airport (CLT) starting in 2017. The users of the IADS system include the personnel at the American Airlines ramp tower, CLT air traffic control tower (ATCT), CLT terminal radar approach control (TRACON), and Atlanta and Washington Air Route Traffic Control Center (ARTCC) [1][2]. Phase 1 and Phase 2 include departure surface metering, whereby flights are held at the gate to manage situations where departure demand exceeds runway capacity, resulting in longer taxi times and runway queues. Holding flights at the gate reduces fuel burn and emissions by transferring time that would be spent in queue with engines on to the gate, where the engines can be left off. From the analysis of operations data, it is estimated that 2.9 million pounds of fuel savings, and CO_2 emission reductions equivalent to planting 66,000 urban trees were achieved between October 2017 and April 2020 as a result of surface metering during the ATD-2 field evaluation [3]. The results have also shown that the use of surface metering had no negative impact on on-time arrival performance of both outbound and inbound flights [4].

In the Phase 3 demonstration, the focus has shifted to a metroplex environment where departures from multiple airports in a terminal airspace operate under various restrictions within the terminal boundary at the Dallas-Fort Worth TRACON (D10) metroplex environment [5]. The ATD-2 surface metering capabilities have not been exercised in the D10 metroplex.

During Phase 1, surface metering was activated and deactivated tactically by the ATD-2 scheduler, a component of the ATD-2 IADS system, once the metering capability had been enabled by CLT users. Surface metering was triggered based on the predicted excess taxi time for departures that had already pushed back from the gate and flights about to push back from the gate [6]. Excess taxi time is defined as the difference between predicted total taxi time and unimpeded taxi time. When metering is triggered, gate holds are assigned to flights departing off the metered runway in the form of Target Off Block Times (TOBTs). In Phase 1, a flight's TOBT was frozen only once the pilot had called ready for pushback.

In Phase 2, the ATD-2 IADS system was expanded to predict when the tactical metering triggers would be met and then inform local stakeholders of upcoming Surface Metering Programs (SMPs). Users at CLT are given the option to affirm or reject the upcoming SMP. Users have chosen to have the system automatically affirm upcoming SMPs. The ATD-2 automation computes the assigned TOBTs in advance and freezes TOBTs when they fall within a configurable look ahead time called the Static Time Horizon (STH). The SMP start time is also frozen when it falls within the STH. These capabilities provide stability and predictability, but also reduce the ability to respond to tactical changes at the airport, such as runway changes or flight delays. If the runway demand is predicted to drop during an SMP within the STH, ATD-2 will compress flights within the STH to mitigate the risk of wasting runway capacity by holding flights too long and thereby causing the runway queue to become empty during metering.

This paper focuses on the Phase 2 strategic surface metering capabilities at CLT that were added to the Phase 1 tactical surface metering capabilities. The strategic metering capabilities were added to provide advance notice of metering and additional stability to the assigned gate holds. Additionally, the added strategic metering capabilities align more closely with the metering capabilities of the FAA's Terminal Flight Data Manager (TFDM) system. CLT is the key site for the TFDM surface metering capabilities [7]. The ATD-2 team provided a technology transfer of lessons learned from the Phase 1 and 2 field demonstration at CLT to the FAA's TFDM team. The FAA plans to maintain the ATD-2 IADS system with the Phase 1 and 2 capabilities in use at CLT until TFDM is deployed.

This paper provides details on the strategic metering algorithms, as well as results regarding the ATD-2 scheduler's ability to predict SMPs up to one hour in advance of start time. The paper also reports on the effects of the strategic metering capabilities on the ability to manage the departure queues and examines the causes and frequency of the need for SMP compressions. These results can inform decisions made during the deployment of TFDM's surface metering capabilities.

II. Background

Airlines and airport authorities have long had an interest in departure surface metering to manage surface congestion at airports and thereby reduce fuel burn and emissions. There have been numerous studies conducted on the use of gate holds to manage surface metering in the US and abroad. In 2009, through the RTCA NextGen Mid-Term Implementation Task Force, the US aviation community recommended that surface operations be a priority for the FAA's NextGen program. The FAA responded in 2010 by agreeing to work with the Surface Collaborative Decision Making (CDM) Team (SCT), a group consisting of FAA and industry representatives, on ways to improve surface operations [8]. The SCT developed the Surface CDM Concept of Operations, which included surface metering capabilities [9]. This concept of operations incorporated lessons learned from EUROCONTROL's Airport CDM (A-CDM) concept and implementations, which include pre-departure sequencing [10]. The SCT also considered lessons learned from departure metering programs at John F. Kennedy International Airport (JFK), Memphis International Airport (MEM), and Boston Logan International Airport (BOS). JFK has been using departure metering since 2010 due to a runway construction project that significantly limited departure capacity. The metering programs at JFK continued after the runway project in response to positive feedback from local stakeholders [11]. The FAA also conducted a series of trials at MEM, exploring Collaborative Departure Queue Management (CDQM) as part of the Surface Trajectory Based Operations (STBO) project. The CDQM system managed departure queues at MEM by assigning slots to flights in different bins [12]. Around the same time, BOS experimented with pushback rate control (N-Control) to manage the number of aircraft taxiing on the airport surface [13].

In response to the industry's interest in improving surface operations through shared situational awareness and surface metering, the FAA agreed to incorporate the Surface CDM concept into the Terminal Flight Data Manager (TFDM) program. The aviation industry recommended that the FAA conduct a feasibility assessment of the TFDM departure management capability prior to the implementation of TFDM [14]. The FAA and NASA collaborated on the ATD-2 project to test surface metering capabilities operationally. The ATD-2 project was built upon the research NASA had conducted as part of the Spot and Runway Departure Advisor (SARDA) project [15] and incorporated strategic metering concepts from TFDM. CLT airport was selected as the ATD-2 demonstration site to implement surface metering. At the time, CLT had been managing surface congestion with a capability called departure sequencing. Flights were held on the gate based on the number of flights in the Airport Movement Area (AMA), but specific pushback times were not assigned.

A. ATD-2 Surface Metering Overview

Building upon these concepts and areas of previous research, the ATD-2 scheduler updates takeoff and landing predictions and evaluates the need for surface metering to reduce surface congestion at regular intervals. The ATD-2 IADS system uses the latest information provided from the airlines and Air Traffic Control (ATC) to make these predictions and metering decisions. Airlines provide flight information, including two key data elements: gate assignments and Earliest Off Block Times (EOBTs), which is the earliest time that the flight will be ready for pushback in the absence of any external constraints. The EOBT is the best prediction of pushback time when a flight is not assigned a gate hold due to surface metering. In cases when the EOBT is not provided, the ATD-2 IADS system falls back on a hierarchy of other pushback time estimates provided by the airlines. ATC provides information about the airport configuration and Traffic Management Initiatives (TMIs). Flights that are a part of certain types of TMIs are assigned controlled times of departure that the flight is expected to comply with: either an Expect Departure Clearance Time (EDCT) or an Approval Request (APREQ) release time. The ATD-2 surface model uses this information to predict the departure runway, Undelayed Off Block Time (UOBT), the undelayed taxi time from gate to runway, and Undelayed Take Off Time (UTOT) for all departures. The UOBT is the later of the best available estimated pushback time and current time.

The ATD-2 scheduler uses these data elements to compute a Target Take Off Time (TTOT) for all flights, the best prediction of takeoff time considering runway spacing constraints. The scheduler also computes the predicted excess taxi time for all departures. Excess taxi time is calculated as TTOT minus UTOT. Flights predicted to exceed a set excess taxi time threshold indicate a potential need for surface metering.

When metering is needed, the ATD-2 scheduler assigns TOBTs and Target Movement Area entry Times (TMATs) to departures to reduce excess taxi times. The TMAT is the time the flight should enter the AMA to be in compliance with the metering program, and the TOBT is the recommended time at which the flight should push back to comply with the TMAT. The scheduler computes the TOBT and TMAT so that a flight takes a gate hold for some of the time that it would have been waiting in the queue if not for metering.

The focus at CLT has been on complying with the TOBT to within plus or minus two minutes. After pushback, ramp controllers do not try to comply with the TMATs except in cases where the flight was holding off the gate in the ramp due to an EDCT or release time. The ATD-2 team conducted two Human-In-The-Loop (HITL) simulations, one using CLT [16] and the other, Dallas/Fort Worth International Airport (DFW), which showed that the TMAT compliance rates were in the 85% range at both CLT and DFW when ramp controllers were asked to comply with gate hold advisories based on TOBTs. The DFW simulation also included a TMAT-only advisory condition and compliance was in this same 85% range. However, there is evidence that this would not be the case at CLT. Both simulations had a condition where both TOBT and TMAT advisories were displayed to the ramp controllers at the gate. There was a much lower TMAT compliance rate at CLT (69%) compared to DFW (91%), indicating that a TMAT advisory alone at the gate might not work in the more constricted and complex ramp at CLT.

Ramp controllers see the TOBT and TMAT for flights on the Ramp Traffic Console (RTC) [19]. Ramp managers view the information on a similar display, the Ramp Manager Traffic Console (RMTC), which contains additional functionality. These displays have been the primary tools used by the ramp controllers and ramp managers during the ATD-2 field evaluation. On the RTC, the TOBT is shown in the form of an assigned gate hold countdown timer that counts down to the TOBT when metering is active. When a pilot calls ready for pushback, the ramp controller puts the flight on hold in the RTC and communicates the assigned gate hold to the pilot. Then when the gate hold countdown reaches the desired hold time, the ramp controller receives a "Push" advisory. The ramp controller is asked to aim for pushback within a plus or minus two-minute window of this hold time when operationally feasible and then marks the flight as cleared to push back on the RTC.

B. Tactical Surface Metering

The ATD-2 Phase 1 demonstration tested tactical surface metering capabilities at CLT starting in November 2017. Local stakeholders had the ability to enable and disable the surface metering capabilities. When disabled, surface metering would never be triggered and no gate holds would be assigned. When enabled, the ATD-2 scheduler would check for the need for surface metering at 10-second intervals by comparing predictions of excess taxi time to configurable thresholds. The three configurable thresholds used to determine when to hold flights at the gate were the Upper Threshold, the Target Excess Taxi Time, and the Lower Threshold.

Tactical surface metering would be triggered when both parts of a two-fold check were simultaneously met. The first check was that at least one departure predicted to push back from the gate within the next 10 minutes had a predicted excess taxi time greater than the Upper Threshold. The second check was that at least one departure off the gate had a predicted excess taxi time greater than the Target Excess Taxi Time. These checks excluded flights with a lower level of certainty regarding their pushback time and flights that had an external constraint due to an EDCT or APREQ release time. The second check was added during Phase 1 to prevent surface metering from triggering too early when there was not a need for surface metering [6].

Once metering was triggered on, flights would be assigned gate holds to manage their excess taxi time. The assigned gate hold is calculated as the difference between the predicted and target excess taxi times. The assigned gate hold would be updated every 10 seconds based on the latest information. The assigned gate hold would be frozen only after a flight had called ready for pushback and been placed on hold via the RTC.

Metering would remain on until the tactical metering off triggers were met. The off threshold was also a two-fold check requiring both checks to be met simultaneously. The first check was that no departure off the gate had a predicted excess taxi time greater than the Lower Threshold. The second was that no flights predicted to push back from the gate within the next 10 minutes had an excess taxi time greater than the Lower Threshold. When both conditions were met, metering would be turned off and all assigned gate holds removed.

The tactical nature of the metering on and off triggers, along with the frequent updates of the assigned gate holds, helped to ensure that surface metering advisories provided by the ATD-2 IADS system did not adversely affect CLT airport operations. The assigned gate holds could be updated until just before the pilot calls ready for pushback. This worked well for ramp controllers because they needed to know the gate holds only in time to communicate times to pilots and to manage pushbacks. However, the tactical nature did not afford the opportunity for users to plan strategically for surface metering.

C. Strategic Surface Metering

After gaining positive results and confidence in the performance of the system during Phase 1, the Phase 2 demonstration added strategic surface metering capabilities to allow decision makers to plan for surface metering prior to gate holds being applied. These capabilities were added to align more closely with the FAA's TFDM system. The first capability added was to predict when surface metering would be needed, recommend an SMP, and provide decision makers with the opportunity to decide whether to implement the SMP. The second capability added was the ability to freeze TOBTs and TMATs in advance of the pilot's calling in ready. The SMP start time was also frozen in advance. Finally, the ATD-2 scheduler could reduce gate holds of frozen flights if certain conditions were met to utilize excess capacity at the runway. These capabilities will be discussed in detail in the following sections.

The Phase 2 field evaluation provided an opportunity to test these strategic surface metering capabilities prior to the implementation of the TFDM system in an effort to smooth the transition at CLT from the ATD-2 IADS system to the TFDM system. The strategic surface metering capabilities were also added to assess the potential of leveraging surface metering to pass additional benefits to the flying public. If a long gate hold is known far enough in advance of a flight's expected pushback with enough certainty, airlines would have the ability to act on the assigned gate hold before the pilot calls ready to push back from the gate. For example, an airline could apply this knowledge and decide to hold the aircraft doors open longer for part of the gate hold to allow passengers that otherwise would have missed the flight to make it onboard. The plan was to test these types of benefit mechanisms in the spring of 2020, but these plans have been put on hold due to COVID-19.

D. Procedures for Strategic Surface Metering

Consistent with the goal to ease the transition from IADS to the TFDM system, as part of Phase 2, the surface metering decision making capabilities were officially transferred from the ramp tower manager to the ATCT traffic management unit (TMU), which will be responsible for managing SMPs using TFDM. In Phase 1, the ramp managers enabled the metering capabilities and set the metering threshold. CLT is a banked airport with nine departure banks a day as shown in Fig. 1. At the beginning of Phase 2, the procedure was modified so that the ATCT TMU would enable the metering capability prior to bank 2 and take action on any SMPs recommended during bank 2 and bank 3, the two banks regularly metered during Phase 1. After bank 3, the ramp manager would assume responsibility to manage metering for any additional banks that they wished to meter. The ramp manager would disable the metering capability when they no longer wished to meter. As it became standard to meter more banks, the procedures transitioned until the point where they are today. The metering capability is now enabled by default all day at CLT and the ATCT TMU has requested that recommended SMPs be automatically affirmed without requiring user action.

The metering thresholds were calibrated in Phase 1 and the Phase 1 values were carried over to Phase 2. If a change is ever needed, the changes are verbally coordinated over the phone between the ramp manager and ATCT TMU. The new strategic parameters that are discussed in the coming sections were set and changed in collaboration with NASA researchers, airline personnel, and ATCT personnel.

III. Strategic Surface Metering Programs

The ATD-2 IADS system first predicts the need for an SMP and then manages the state of the predicted SMP until the system detects that the SMP is no longer needed. The ATD-2 system uses a set of SMP parameters to determine when an SMP is needed and how to assign TOBTs once the need for an SMP is determined.

A. SMP Detection

The ATD-2 scheduler detects the need for an SMP by predicting when the tactical metering triggers will be met. The scheduler first predicts take off times and the associated excess taxi times for all flights over the prediction horizon. The scheduler computes the number of flights predicted to meet each of the tactical triggers at one-minute intervals. This creates four time series, as shown in the top chart of Fig. 2: (1) flights predicted to be at the gate and above the Upper Threshold, (2) flights predicted to be off the gate and above the Target Excess Taxi Time, (3) flights predicted to be at the gate and above the Lower Threshold, and (4) flights predicted to be off the gate and above the Lower Threshold. For a flight to be considered at the gate at a set point in time, the flight must have a UOBT greater than the timestamp and less than the timestamp plus 10 minutes. For a flight to be considered off the gate at a point in time, the flight must have a TTOT greater than the timestamp and either

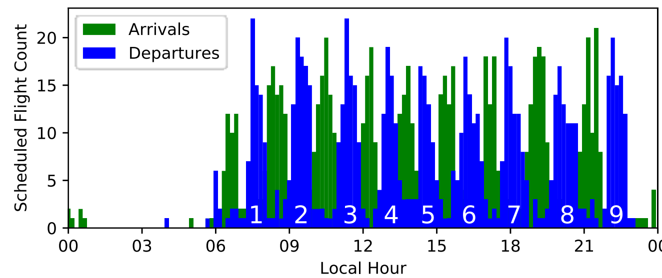

Fig. 1. Scheduled arrival and departure banks on 2018-10-10.

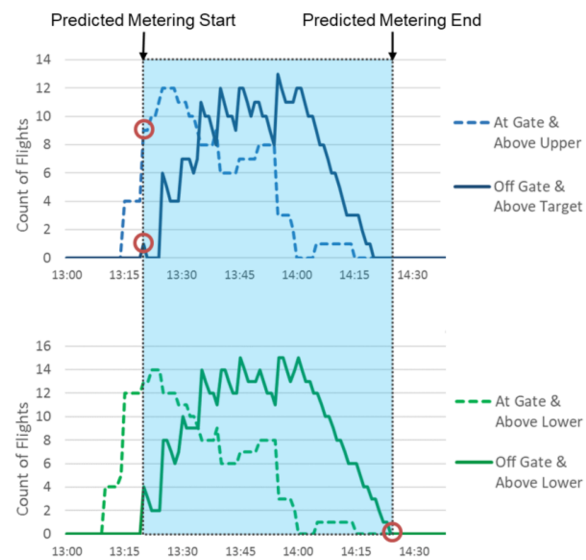

Fig. 2. SMP prediction using predicted excess taxi times.

already be off the gate or have a UOBT less than or equal to the timestamp.

Once all four time series have been computed, the scheduler starts with the first two and begins iterating through them until a time is reached at which both time series have a value greater than one, indicated by the red circles in Fig. 2. The scheduler predicts metering will be on at that point in time. Then the scheduler begins iterating over the last two time series to predict when metering will turn off. Once both of these times series are equal to zero at the same point in time, then the metering period is predicted to end. In the example shown in Fig. 2, the metering period is predicted to start at 13:20Z and end at 14:24Z.

Each time the scheduler runs, it will predict the metering periods throughout the entire scheduler prediction horizon, which is currently set to 8 hours. The scheduler then checks to see if any of the predicted metering periods have a start time less than the current time plus a configurable SMP Lead Time and have a predicted duration greater than an adapted value (5 minutes). If so, the scheduler will publish the metering period as a recommended SMP. The scheduler continues to update the start and end times of the SMP each time the scheduler runs.

During Phase 2, the SMP Lead Time has been set to 60 minutes. This value was set so that the SMP for the next departure bank at CLT is recommended shortly after the previous bank ends. This prevents users from being distracted with SMPs for a future bank while managing operations in the

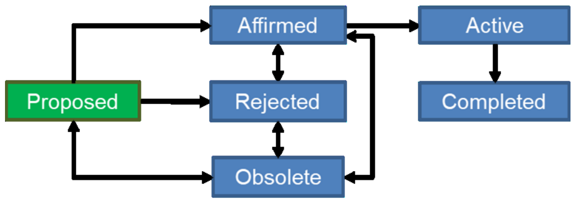

Fig. 3. SMP state changes.

current bank. Once the current bank is over and CLT is in the lull between banks, users can evaluate the SMP for the upcoming departure bank. For each SMP, the scheduler computes the number of flights predicted to be a part of the SMP, along with the average and maximum gate hold of flights in the SMP.

B. SMP State Transitions

Once an SMP has been recommended, it transitions between a series of states based on user actions and scheduler updates. These states are based on the TFDM SMP states, but they are not identical to the TFDM SMP state transitions. The ATD-2 SMP state transitions are summarized in Fig. 3.

When the scheduler first recommends an SMP, the SMP starts in a proposed state. The SMP information is displayed to users in the ATD-2 Surface Metering Display (SMD) [20]. The SMD shows a list of SMPs with associated statistics and allows users to take action on the SMPs.

Once an SMP has been proposed, the users can either affirm or reject the SMP if the system is not configured to automatically affirm the SMP. If the SMP is affirmed, whether automatically or by a user, TOBTs and TMATs are assigned to all flights in the SMP. An affirmed SMP will transition to the active state once the SMP start time is reached. When an SMP becomes active, the gate holds are shown to ramp controllers on the ATD-2 RTC display and flights are held at the gate. An active SMP is completed once the end time is reached. The transition from proposed to affirmed to active to completed represents the standard progress of SMP states.

A user can reject a proposed or affirmed SMP. When an SMP is rejected, TOBTs and TMATs for flights in the SMP are cleared. A rejected SMP will never become active. A user can affirm a rejected SMP, at which point TOBTs and TMATs are assigned to the flights and the SMP can become active. A user can also cancel an active SMP early. When this happens, the end time is set equal to current time and the SMP transitions to a completed state. The option to reject an SMP has been very rarely used at CLT.

If the scheduler no longer predicts the need for an SMP in the proposed, affirmed or rejected SMP, then the scheduler will put the SMP into an obsolete state and remove the TOBTs and TMATs from all affected flights. If the start time of an obsolete SMP is reached, the scheduler continuously updates the start time to match the current time. The scheduler continues to evaluate the need for metering during the time period of an obsolete SMP. If the need for metering is predicted again, the scheduler will transition the SMP back to the previous state – either proposed, affirmed, or rejected. If the scheduler was hovering an obsolete SMP's start time at current time when it transitions the SMP back to affirmed, the scheduler will immediately move the SMP to the active state.

Shortly after the start of Phase 2, the ATCT TMU and ramp managers identified the need for auto-affirmation of SMPs. Some SMPs were right on the edge of being needed and as a result, they were toggling back and forth between the proposed and obsolete states very frequently – in some instances as frequently as once every 10 seconds, which is the scheduler update interval. In other cases, the SMP would become obsolete for long periods of time before the users had a chance to affirm the SMP due to changes in the SMP state. While in the obsolete state, the option to affirm or reject is disabled. Due to workload, the users were not able to continue monitoring the SMP status; consequently, in some cases, a desired SMP was never affirmed. As a result, ATD-2 added an auto-affirm capability. When this capability is enabled, SMPs skip the proposed state and begin in the affirmed state. The auto-affirm capability has been enabled for the majority of Phase 2 operations at CLT.

IV. Strategic Freeze Capabilities

Another important capability added as a part of Phase 2 was freezing assigned gate holds and SMP start times earlier to provide an opportunity for airlines to plan with more certainty.

A. Freezing Assigned Gate Holds

For an airline to be able to leverage surface metering by passing benefits on to passengers, the airline needs to have confidence that gate holds will not change significantly. Prior to Phase 2, the assigned gate hold was only frozen when the pilot called ready to push back and the ramp controller put the flight hold in RTC. As a result, there was uncertainty about the expected gate hold until the pilot and gate crew were ready to push the flight back from the gate. At that point, it is too late for an airline to take any other action on the flight.

To move the freeze earlier in the lifecycle of the flight, ATD-2 Phase 2 metering capabilities freeze TOBTs and TMATs based on the Static Time Horizon (STH). The STH is a rolling window extending out from the current time. A flight's TOBT and TMAT are frozen when the TOBT is less than the current time plus the STH. The TOBT was chosen as the freeze point in the ATD-2 because the TOBT has been the focus of operations throughout the ATD-2 field evaluations. While the TFDM system uses similar logic for the TOBT and TMAT freeze, the freeze point in the TFDM system is the TMAT because the TMAT is the time at which compliance is measured in the TFDM system. Additionally, in the ATD-2 IADS system, the TOBT and TMAT can still be frozen if a flight happens to be put on hold in RTC prior to the flight being frozen by the STH.

ATD-2 began Phase 2 with the STH set to 0 minutes, which effectively continued the Phase 1 freeze capabilities. Over the course of Phase 2, the STH has been incrementally increased to 15 minutes. The plan was to continue to increase the STH as high as practical, but those plans have been put on hold due to COVID-19. One risk to extending the STH is that the highest quality EOBTs start to be received around 30 minutes prior to pushback once the boarding process has started. Extending the STH beyond 30 minutes risks freezing based on lower-quality EOBTs.

The ATD-2 IADS system does contain some exceptions to the STH freeze. Flights that have an EDCT or APREQ release time are assigned a TOBT and TMAT based specifically on the EDCT or APREQ release time. The TOBT and TMAT are assigned so that the flight can hold at the gate until it needs to push back to be able to reach the runway shortly before it has to take off in order to comply with the EDCT or APREQ release time. Because the TOBT and TMAT are based on the EDCT and APREQ release time, any change to these times will result in a change to the TOBT and TMAT.

Another exception to the STH are flights that are delayed by the airline past their TOBTs. The airline communicates this delay by updating the flight's EOBT. If the EOBT is ever greater than the TOBT, the TOBT is no longer considered feasible and the ATD-2 scheduler updates the TOBT to be equal to the EOBT and updates the TMAT to equal EOBT plus ramp transit time. If the TOBT is still within the STH after the update, the TOBT refreezes. However, if the TOBT is outside of the STH, the flight will be unfrozen until it reenters the STH. A third exception to the STH are flights that change runways. When a flight changes runway, it is assigned a new TOBT and TMAT for the SMP on the new runway if an SMP exists for that runway.

A fourth exception to the STH is prioritization of flights by the airline. This exception was added at the request of the airline users and to align with TFDM, which allows substitution of flights within the STH. In the ATD-2 IADS system, the airlines have the ability at any point in time to mark flights as a priority. This action has two effects on the system. First, the flight is highlighted on ramp displays so that all ramp controllers are aware that the flight is a priority. Secondly, if the flight is frozen and metered, the ATD-2 scheduler will automatically perform substitutions with other frozen metered flights from the airline to move the priority flight as early as possible given the constraint that the priority flight must be able to make it to the runway in time to meet the TOBT plus transit time of the flight it is substituting with. This process will result in changes to the TOBT and TMAT for both the priority flight and the other flights that it is substituted with.

B. *Freezing SMP Start Time*

In addition to freezing assigned gate holds earlier during Phase 2, the start times of affirmed SMPs are also frozen in advance in Phase 2. This provides certainty as to which flights will be a part of the SMP and are expected to hold. The ATD-2 scheduler freezes the start time of an affirmed SMP when the SMP start time is within the STH. If the STH is set to zero, the SMP start time is frozen only when the SMP becomes active, as was the case in Phase 1. In this situation, the tactical metering on triggers are used to determine when the SMP should become active. Over the course of Phase 2, the goal was to freeze both assigned gate holds and SMP start times earlier to allow for a longer, strategic outlook.

An additional reason for freezing SMP start times during Phase 2 was to align with the capabilities of the TFDM system, which will effectively freeze the start time when the SMP is affirmed. Adding the SMP start time freeze capability to the ATD-2 IADS system allowed the team to measure the effects of freezing the start time on the performance of SMPs.

Freezing of SMP start time does increase the risk of starting metering too early. One of the lessons learned from Phase 1 was to make sure metering is not started too early by waiting to start metering until a point in time when there was already a flight off the gate that is predicted to have an excess taxi time greater than the target. Prior to that check being added, the only check needed to trigger metering was that there be a flight predicted to push back in the next 10 minutes that was predicted to exceed the Upper Threshold. This sole check caused metering to start too early because metering would trigger when the triggering flight was still 10 minutes in the future. The second cause of metering too early is that the EOBT is only an estimate; thus, some flights will be ready for pushback prior to EOBT and others later, making the predictions subject to error.

When freezing the start time of an SMP, the SMP algorithms mitigate the first risk by predicting the time when the second tactical trigger – a departure off the gate with an excess taxi time greater than the target – will be met. However, the freeze is still subject to the second risk of EOBT uncertainty. To mitigate the risk of starting metering too early and doing harm by wasting runway capacity, the ramp managers monitor the queues and number of departures currently taxiing to the runway at the start of metering. If there are few departures actively taxiing, the ramp manager will instruct the ramp controllers to ignore gate holds until the number of active flights have built up to an acceptable level.

V. SMP Compressions

After adding the TOBT freeze and associated SMP start time freeze, the ATD-2 team and partners observed occasions where the runway queue was very short during metering. A number of these cases happened due to last minute arrival and departure runway changes. To mitigate this risk, ATD-2 implemented the concept of SMP compressions.

A. *Runway Changes*

Prior to pushback, ATD-2 predicts departure runways based on the airport configuration and runway utilization scenario entered into the ATD-2 IADS system by the CLT ATCT. The ATD-2 IADS system has a set of runway rules associated with each runway utilization scenario that are used to predict the assigned runways for flights. For arrivals, ATD-2 heavily relies on a modified research version of the FAA's Time Based Flow Management (TBFM) system run by NASA as part of the ATD-2 IADS system. The research TBFM system predicts arrival runways based on the airport configuration entered into the ATD-2 IADS system and receives scratch pad entries from the TRACON that update the assigned runways. Using these sources of runway predictions, ATD-2 has been able to achieve a high level of prediction accuracy. On most days, the departure runway prediction accuracy at pushback is between 94% and 98%. Arrival prediction accuracy at the arrival fix is typically between 89% and 93%.

Based on these runway assignments, the ATD-2 scheduler creates SMPs for each runway and assigns TOBTs and TMATs. Although the prediction accuracy is normally high, there are cases where last minute runway changes can affect the runway assignment of flights within the STH. For departures, pilots may request to depart off the longer center runway rather than the shorter east runway due to weight and balance issues. This request is communicated to the ramp controller when the pilot calls for pushback approval. The ramp tower enters that information into the ATD-2 IADS system, which updates the runway assignment. Fig. 4 shows the number of departures per day that changed runways for reasons of operational necessity, along with a rolling 15-day average. The frequency of changes increases over the summer due to the warmer weather, which reduces engine performance, thus requiring longer take off rolls. For arrivals, the TRACON will frequently off-load arrivals from the east runway to the center runway if there is low departure demand on the center runway.

Both sets of changes reduce demand for the east runway, which would normally result in less gate hold being assigned to the departures that remain on the east runway. For example, three departures moving from the east runway to the center runway could result in up to six minutes of reduced gate hold for all subsequent departures, because the east runway is mixed use resulting in a separation of approximately 2 minutes per departure. However, the scheduler was restricted from changing the TOBTs of flights within the STH. As a result, flights were holding on the gate longer than needed.

B. SMP Compressions within the Static Time Horizon

The concept of SMP compressions comes from the TFDM design to mitigate these and other risk factors, such as delayed flights, that affect flights within the STH. Unlike the ATD-2 IADS system, which updates TOBTs and TMATs outside of the STH every time the scheduler runs, the TFDM system only updates TOBTs and TMATs through the use of SMP adjustments that are triggered when the metered queue is predicted to go outside of the Upper and Lower Threshold bounds. One of the types of TDFM adjustments is an SMP compression, which reduces the gate holds on flights, including flights within the STH. SMP compressions reduce the gate hold only if the gate hold reduction is greater than a set Minimum TMAT Adjustment Time (MTAT) parameter.

The ATD-2 IADS system adopted this concept from the TFDM system for flights within the STH. The ATD-2 scheduler will compress flights within the STH if it predicts that the excess queue time for these flights is below the Lower Threshold. If this condition is detected, the scheduler will reduce the gate holds of flights within the STH to bring their predicted excess taxi time back up to the Target Excess Taxi Time. The ATD-2 scheduler will reduce the gate hold only if the change will be more than

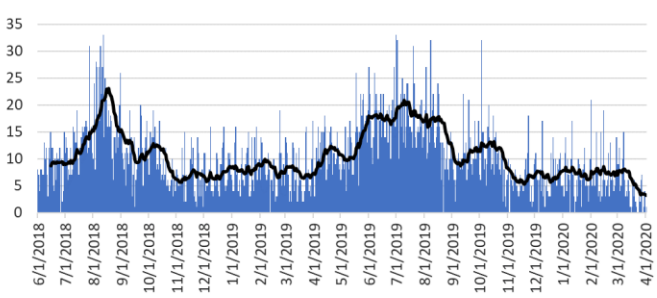

Fig. 4. Count of departures per day requesting a runway change for operationally necessary purposes.

the MTAT. The MTAT prevents very minor changes to TOBT and has been set to 2 minutes to align with the guidance to ramp controllers that they can push back flights on hold once the flight is within plus or minus 2 minutes of the TOBT.

The ATD-2 system compresses flights only within an active SMP, whereas the TFDM system can compress flights within an affirmed, but not yet active SMP. One unexpected outcome of implementing compressions in combination with freezing SMP start times in the ATD-2 system was the early termination of SMPs. TFDM has another type of SMP adjustment called an SMP Termination, which will end an SMP early if the need for an SMP is no longer detected. This termination capability was an inadvertent side effect of using SMP compressions and freezing SMP start times in the ATD-2 system.

In some cases, compression of flights would occur in the same ATD-2 scheduler cycle that the metering off conditions were also met. This would often happen as soon as the SMP starts if the SMP start time was set too early and frozen. The SMP compression logic would trigger the first scheduler run after the start of the SMP and the SMP would be terminated in that first cycle. Often a second SMP would be created 10 or 15 minutes in the future as the ATD-2 scheduler would detect the need for an SMP later in the bank. This inadvertent side effect mitigates the risk of starting an SMP too early. However, these events reduce the strategic aspect of SMP and reduce the ability to plan to an SMP.

VI. Results

The strategic metering capabilities described in the previous section have been deployed over the course of Phase 2 operations that started in the fall of 2018. A timeline of the deployment of these capabilities is provided in Table I.

Over the course of ATD-2 Phase 2, the number of metered flights per day has grown, as seen in Fig. 5, which shows the count of flights per day that were held at the gate due to surface

TABLE I. Timeline of Key Metering Events

Event	Date
Tactical Metering Go-Live (Phase 1)	November 30, 2017
Strategic SMP Go-Live	October 10, 2018
SMP Auto-Affirm enabled	November 27, 2018
Static Time Horizon = 5 minutes	March 6, 2019
Static Time Horizon = 10 minutes	April 16, 2019
Static Time Horizon = 15 minutes	June 20, 2019
Static Time Horizon = 10 minutes	June 26, 2019 (due to adaptation error)
Static Time Horizon = 15 minutes	July 2, 2019
SMP start time freeze enabled	October 3, 2019
SMP Compressions enabled	December 19, 2019
Prioritizaiton allowed within the STH	January 31, 2020
CLT Ramp Tower ceased usage of RTC due to COVID-19 relocation	April 4, 2020
CLT Ramp Tower resumed usage of RTC after installed in a new location	June 10, 2020

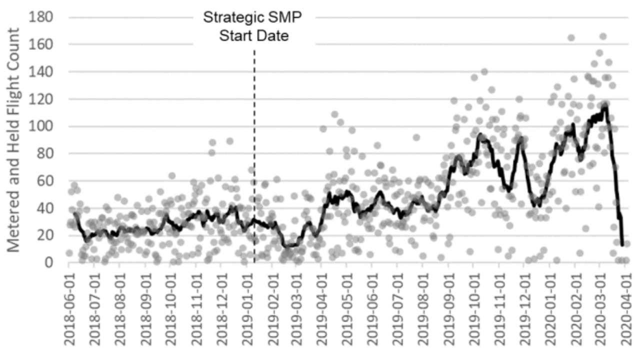

Fig. 5. Count of held metered flights per day.

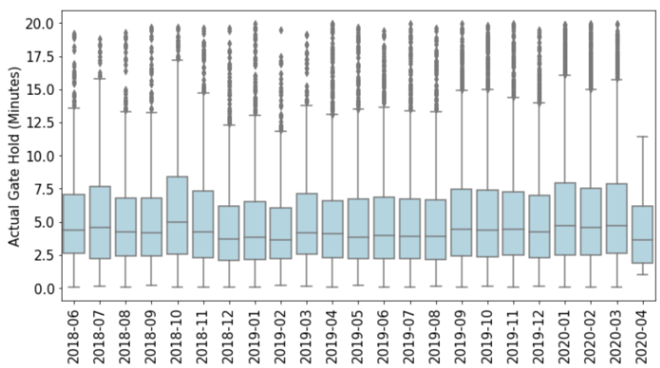

Fig. 6. Actual gate hold distribution per month.

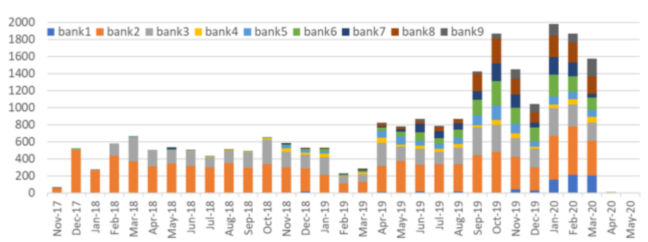

Fig. 7. Count of metered flights held per month per departure bank

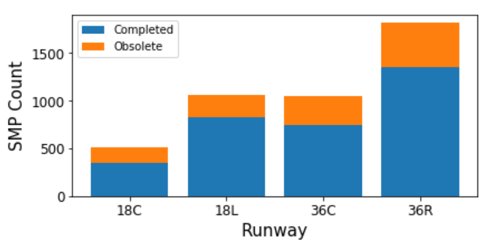

Fig. 8. Final SMP status by runway (2018-10-10 through 2020-04-04).

metering along with a 15-day moving average. In early 2020, it was not unusual to have over 100 flights per day that were held for metering, up from 20 to 40 flights per day in 2018.

These increases have come with only minor increases in the amount of total time that flights are held at the gate, as seen in Fig. 6. The median gate hold time has remained around 5 minutes and the 75th percentile around 7 to 8 minutes throughout the ATD-2 field evaluation, with only a slight increase starting around September 2019.

The increase in metered flights has been driven largely by metering later into the day. CLT typically has nine departure banks a day. At the start of ATD-2, only bank 2 was metered. Then metering was extended into bank 3 at the end of Phase 1. Over the course of Phase 2, metering has been extended to all banks, as seen in Fig. 7. There also have been some schedule changes at CLT starting in September of 2019 that have resulted in the later banks needing to be metered more frequently.

A. SMP Statistics

There was a total of 4,425 SMPs from October 10, 2018, when strategic SMPs were first turned on, through April 4, 2020, when the ramp controllers temporarily ceased using RTC due to COVID-19. Runway 36R has had the highest total number of SMPs regardless of final state, as seen in Fig. 8. In general, the east runway (18L/36R) has had more SMPs than the center runway (18C/36C). The two north flow departure runways (36R and 36C) are used more heavily as north flow is the preferred configuration at CLT; as a result, both have more SMPs than their corresponding south flow runways.

The center runway is used primarily for departures, whereas the east runway is mixed use with arrivals and departures. Thus, the center runway has a higher departure rate and can clear a queue of flights faster. Therefore, the peaks during the bank tend to be shorter and there is less need for metering on that runway.

During ATD-2 Phase 2, the SMP Lead Time parameter has been set equal to 60 minutes, which caps the timeframe in which an SMP can be recommended. However, if the need for an SMP is not predicted 60 minutes out, an SMP may be proposed with less lead time. Fig. 9 shows the cumulative distribution of lead times for SMPs measured as the difference between the SMP creation time and the first predicted start time. Only 15% to 30% of SMPs are proposed with a 60-minute lead time. SMPs on the east runway have a higher likelihood of being proposed earlier. With a lead time of 30 minutes, only about 30% of SMPs on the center runway have been proposed, whereas over 60% of SMPs on the east runway have been proposed. A side effect of the higher throughput rate and shorter peaks on the center runway is that it is harder to predict when an SMP will be needed. The predicted excess taxi times often stay just below the Target Excess Time and Upper Threshold until shortly before the bank starts. As a result, many SMPs on the center runway occur with shorter lead times.

B. TOBT Freeze Results

Fig. 10 shows the distribution of the excess taxi time predicted at the entrance to the AMA (the spot) for metered flights using each of the four departure runways and under each of the four tested STH values. In general, the higher STH values resulted in lower predicted excess taxi times, meaning there were fewer flights ahead of a given flight when it entered the AMA. This data set was pulled from a date range prior to SMP compressions being introduced. These lower values were one of the reasons for introducing SMP compressions.

One note is that the predicted excess taxi time for Runway 18L drops the lowest because a large portion of flights enter the AMA right at the runway end, having spent most of their hold

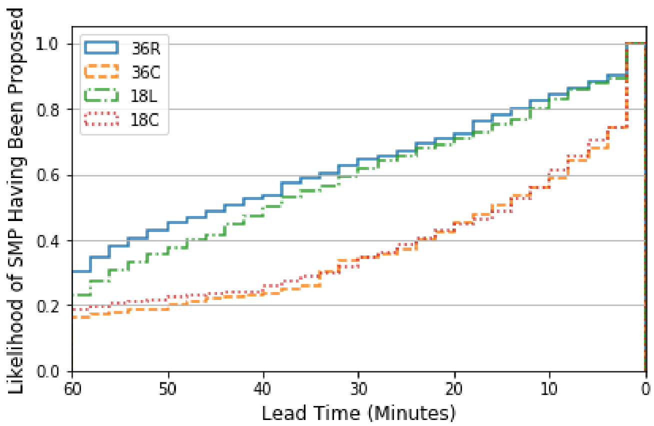

Fig. 9. SMP lead time by runway (2018-10-10 through 2020-04-04).

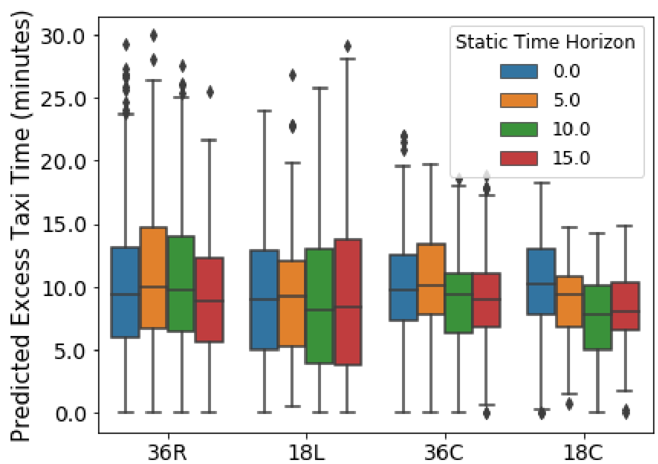

Fig. 10. Excess taxi time predicted at the spot by runway and STH value (2018-10-10 through 2019-09-01).

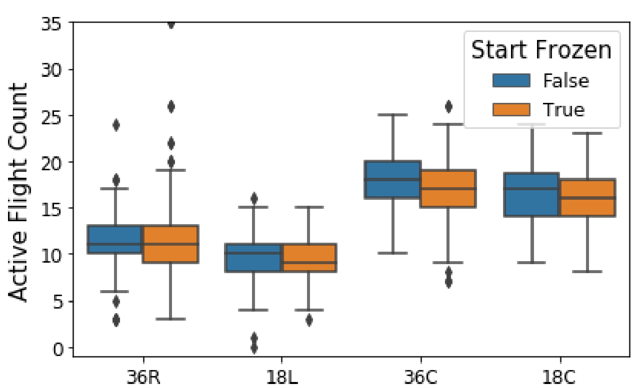

Fig. 11. Active departures at SMP start time (2019-07-02 through 2020-12-18).

time in the ramp. As a result, these flights have very short excess taxi times, which reduced the entire distribution.

C. SMP Start Time Freeze Results

Fig. 11 shows the number of active departures at the SMP start time with and without the SMP start time freeze enabled. Active departures are defined as any departure that has pushed back from the gate but has not yet departed. After the freeze was enabled, the median and interquartile ranges dropped by one or two flights on most runways. This drop indicates that the frozen SMPs were starting slightly early. However, the number of active flights was still high enough to ensure departure demand at the runway. Runways 36R and 18L are the lowest because they are mixed use runways, meaning fewer active departures are needed to have excess taxi times greater than the target. Runway 18L is the lowest because of the short taxi time from the gates to the runway.

D. SMP Compression Results

After SMP compressions were turned on, over half of the SMPs have not required a compression. Between December 19, 2019 and April 4, 2020, a total of 1,010 SMPs went active, 531 of which required no compressions. Of the SMPs that were compressed, 246 were either compressed only once or were compressed once and immediately terminated. The number of SMPs with higher compression counts drops off quickly, as seen in Fig. 12.

When an SMP compression occurs, the ATD-2 scheduler reduces the gate hold assigned to flights. Most compressed flights have a gate hold reduction of 2 minutes, as seen in Fig. 13. This happens because the scheduler is limited to compressing flights only when the gate hold reduction is more than the MTAT parameter, set at 2 minutes.

With compressions enabled, there was a slight increase in the median predicted excess taxi time as compared to the timeframe prior to that, when there were no compressions, as seen in Fig. 14. In both timeframes, the STH was set to 15 minutes and the SMP start time was frozen. The increase in excess taxi time indicates that the compression logic is functioning by reducing gate holds and therefore allowing more flights to be off the gate, which minimizes the risk of the runway queue becoming empty during metering.

VII. Conclusions

The ATD-2 Phase 2 field demonstration has exercised strategic metering capabilities in advance of TFDM deployment. These capabilities are strategic SMPs, freezing of TOBTs and TMATs based on the STH, freezing the start times of SMPs, and SMP compressions. Based on feedback from field users at CLT, the ATD-2 team has learned that auto-affirmation of SMPs helps to improve the usability of SMPs. The longer STHs have allowed the airline ramp managers to view the gate holds in advance and begin formulating plans to leverage surface metering. However, the longer STHs do limit the ATD-2 scheduler's ability to adjust to last minute changes in airport operations. Similarly, freezing the SMP start times provides more certainty about when metering will be in effect, but risks starting metering too early. SMP compressions were effective at mitigating some of these risks. CLT plans to continue to explore strategic metering with ATD-2 up through the transition to TFDM at which point, these results will inform the way SMP parameters are set in the initial TFDM deployment.

Acknowledgment

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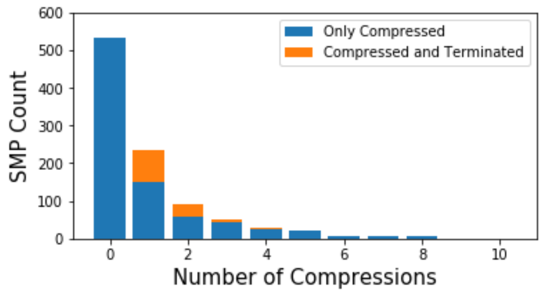

Fig. 12. SMP compressions and terminations (2019-12-19 through 2020-04-04).

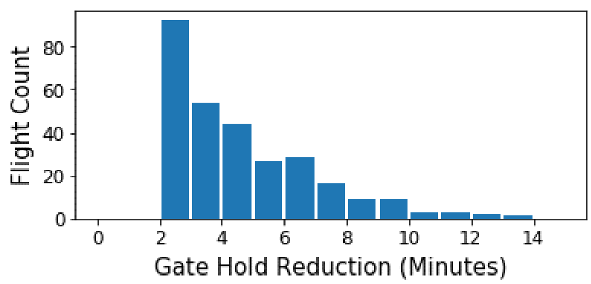

Fig. 13. Gate hold reductions from SMP compressions (2019-12-19 through 2020-01-30).

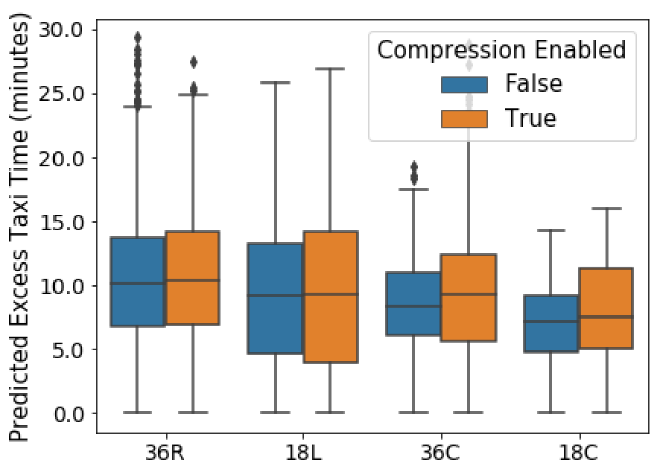

Fig. 14. Excess taxi time predicted at spot with and without SMP compressions (2019-10-03 through 2020-01-30).

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