Assessing Tactical Scheduling Options for Time-Based Surface Metering

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Abstract—This paper presents a parametric analysis of the most recent tactical scheduler design for NASA’s Airspace Technology Demonstration 2 (ATD-2) sub-project, committed to demonstrating time-based surface metering at Charlotte Douglas International Airport (CLT). The tactical scheduler design is implemented in a fast-time simulation model of CLT using NASA’s Surface Operations Simulator and Scheduler. The tactical scheduler is supported by three basic functions: trajectory prediction, runway scheduling, and advisory generation. A key parameter of the advisory generation function is the taxi time delay buffer used when calculating target gate pushback times from runway schedule. Multiple simulations that varied the amount of taxi time delay buffer were analyzed to determine the effect on tactical scheduler performance. The results show an improvement in tactical scheduler performance when the buffer is made sufficiently large to release departures from their gates early enough to maintain scheduler predicted runway throughput.

Keywords—surface operations; surface metering; tactical scheduling

I. INTRODUCTION

NASA is committed to demonstrating a concept of integrated arrival, departure, and surface operations by 2020 under the Airspace Technology Demonstration 2 (ATD-2) sub-project [1]. This will be accomplished in three phases, starting with a demonstration of flight specific time-based surface metering at Charlotte Douglas International Airport (CLT) [2]. ATD-2 tactical metering capability is based on NASA’s Spot And Runway Departure Advisor (SARDA) which has been tested successfully in human-in-the-loop simulations of CLT [3]. SARDA makes use of surface surveillance data and surface modeling to estimate the earliest takeoff time for each flight active on the airport surface or ready for pushback from the gate. The system then schedules each flight to its assigned runway and assigns a target pushback time displayed to ramp controllers as an advisory gate hold time. The objective of this method of surface metering is to move as much delay as possible to the gate to minimize surface congestion and engine on-time while keeping sufficient pressure on the runway to maintain throughput. This flight specific approach enables greater flight efficiency and predictability, facilitating trajectory-based operations, which ATD-2 aims to achieve.

Throughout ATD-2 project formulation and system development, researchers have continuously engaged with stakeholders and future users, uncovering key system requirements for tactical metering that SARDA did not address. These include:

- Pushback time advisories do not change after the pilot calls in ready for pushback so that controllers may communicate a single gate hold to the pilot at this time.
- Make use of and incentivize improved accuracy of air carrier-provided estimates of pushback ready time.
- Facilitate integration with strategic scheduling consistent with the Surface Collaborative Decision Making Concept of Operations [4].

This paper presents a benchmark fast-time simulation evaluation of the tactical scheduler designed to meet these new metering requirements. The scheduler is used to calculate gate holds for flights. Flight operations with the gate holds are simulated using a fast-time medium-fidelity simulation of CLT. A key parameter used in the generation of gate holds, the taxi time delay buffer, is analyzed to determine the value that moves the most delay from the runway queue to the gate without drying out runway operations. Fast-time simulation is used to rapidly develop and test new scheduler design features and future fast-time simulation studies will build upon this benchmark evaluation to explore other design considerations.

The rest of this paper is organized as follows. Section II presents a background of surface metering research. Then the ATD-2 tactical scheduler used for surface metering is presented in section III. Simulation details and results from a benchmark evaluation of the ATD-2 tactical scheduler are presented in sections IV and V, respectively. Finally, conclusions and future work are presented in section VI.

II. BACKGROUND

Prior demonstrations of automation aided surface metering in the U.S. have focused on strategic approaches to enable Collaborative Decision Making (CDM) between flight operators, Air Navigation Service Providers, and other stakeholders in surface and departure operations as defined in the Surface-CDM Concept of Operations [4]. Both the Collaborative Departure Queue Management (CDQM) approach evaluated at Memphis International Airport [5] and the Ground Management Program
得战术流量。因此，SARDA开发人员找到了通过使用承运人提供的延迟时间估计推回或启动战术流量的方法。另一方面，Ramp控制器在繁忙机场如CLT发现更新也会打开波动的通告的潜力，这可能会导致流量管理的不准确。

SARDA还采用基于时间的战术表面流量控制方法，但它在很大程度上已在人类实时仿真中得到验证[3]，不在现场。在波士顿洛根机场的DMA运行中，DMA计算跑道的时间和相应的开始（推回）时间，以便根据每一架飞机的出发状态来确定跑道的流量。概念上，DMA旨在与表面和到达管理的对应物（AMAN和SMAN）合作，以建立到达和出发序列，并优化表面流量计划[12]。在波士顿洛根机场实施了DMA单独使用，使用飞行许可作为事件来更新计算。因此，当航班被发布时，出发的航班被更新，航班的出发时间表在可用时被更新。

SARDA还采用基于时间的战术表面流量控制，但已成功在人类实时仿真中得到验证[3]，不在现场。在波士顿洛根机场的DMA运行中，DMA更新了在波士顿洛根机场的事件，使用实时表面流量数据。这些更新确保了正确的信息用于预测跑道的使用。然而，快速更新也打开了一扇大门，预测的流量会随着流量的增加而增加，这使Ramp控制器在繁忙机场如CLT可能会感到挑战。因此，对于ATD-2战术流量控制而言，为了使所有流量能在到达时冻结，即在到达时计算，Ramp控制器可能需要在到达时通知飞行员，以确保在到达时通知飞行员。
Trajectory prediction calculates a flight’s ERUT differently depending on its flight group. Table I summarizes how ERUTs are calculated for each flight group. These calculations are explained in more detail below.

In the field, Time-Based Flow Management (TBFM) [13], the currently operational tool responsible for arrival metering, will calculate Scheduled Times of Arrival (STAs) for arrivals and send them to the tactical scheduler. Therefore, the Landing Arrival group, consisting of the first two runway usage types, uses landing STAs as ERUTs.

For all other groups, nominal taxi paths between gates and runways and nominal speeds for various aircraft types in different areas of the airport surface are used to calculate an Unimpeded Taxi Time (UTT) between current position and the scheduled runway for each flight. For the Taxi Arrival and Taxi Departure groups, trajectory prediction adds UTT to current time to get each flight’s ERUT. If a Taxi Arrival has not yet landed, UTT is added to its landing STA for its landing runway to get the ERUT for its taxi crossing runway.

The advisory time at which to release a flight for pushback, known as the Target Off Block Time (TOBT), is frozen once a flight calls in ready. Therefore, trajectory prediction for Gate Departure Ready flights adds UTT to the flight’s frozen TOBT to get ERUT.

For Gate Departure Planned group flights, trajectory prediction adds UTT to the EOBT to get ERUT. Because Gate Departure Uncertain group EOBTs are not expected to be very accurate, trajectory prediction adds UTT to current time to get ERUT just in case one of these flights calls in ready and jumps straight to the Gate Departure Ready group.

<table>
<thead>
<tr>
<th>Flight Group</th>
<th>Position</th>
<th>ERUT Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing Arrival</td>
<td>airborne</td>
<td>Landing STA</td>
</tr>
<tr>
<td>Taxi Arrival</td>
<td>airborne</td>
<td>Landing STA + UTT</td>
</tr>
<tr>
<td>Taxi Departure</td>
<td>surface</td>
<td>Current time + UTT</td>
</tr>
<tr>
<td>Gate Departure Ready</td>
<td>gate</td>
<td>TOBT + UTT</td>
</tr>
<tr>
<td>Gate Departure Planned</td>
<td>gate</td>
<td>EOBT + UTT</td>
</tr>
<tr>
<td>Gate Departure Uncertain</td>
<td>gate</td>
<td>Current time + UTT</td>
</tr>
</tbody>
</table>

B. Runway Scheduling

All flights predicted to use the runway are scheduled one at a time in an order that depends on their flight group. Flight groups are scheduled in priority order of decreasing runway usage predictability listed in the previous section. All flights within a single flight group are scheduled before moving on to the next flight group. Within each flight group, flights are scheduled in the order of their ERUTs. The only exception is the Gate Departure Planned flight group, which is ordered by the airline posted Scheduled Off Block Time (SOBT) in compliance with S-CDM ration-by-schedule convention. Using SOBT rather than EOBT to order the flights for scheduling prevents EOBT gaming and stabilizes tactical scheduler advisories in the presence of updating EOBTs.

Time-based spacing requirements between each leader-follower pair of runway use types and aircraft weight categories are adapted to a particular airport and used as constraints for runway scheduling. Only wake separation requirements between departures on the same runway depend on aircraft weight categories. Distance-based rules were converted to time-based separations between departures and arrivals on the same and interdependent runways, and flights taxiing across runways.

ATD-2 also considers other constraints from traffic management initiatives such as Miles-in-Trail (MIT), Expect Departure Clearance Time (EDCT), and Approval Request/Call for Release (APREQ/CFR). However, these are not included in this study.

Within a single scheduling call, each scheduled flight creates spacing constraints for all flights scheduled after it. If a flight’s ERUT does not meet all constraints, the flight is delayed and rechecked for constraint violations. The first time meeting all constraints is assigned to the flight as its Target Runway Usage Time (TRUT) and is used to define spacing constraints for subsequently scheduled flights. The Gate Departure Uncertain group is the only group that is scheduled opportunistically, meaning that these flights are inserted into runway slots when available and do not create constraints for subsequent flights when scheduled.

C. Advisory Generation

When all flights have been scheduled and assigned a TRUT, TOBTs are calculated for all departures still at the gate by subtracting the gate-to-runway UTT times a constant, \( A \), and delay buffer, \( B \), from the TRUT. TOBT is calculated as

\[
TOBT = TRUT - A(UTT) - B, \quad (1)
\]

where \( A \geq 1 \) and \( B \geq 0 \). Factor \( A \) accounts for congestion delay the flight may encounter along its taxi route and assumes this delay is greater the more unimpeded time the flight has left to travel. Factor \( B \) adds queue delay where flights line up from the end of the runway.

The resulting TOBTs are presented to ramp controllers as advisory hold times for metering.

D. Scheduler Dynamics

The tactical scheduler is called every 10 seconds updating TRUTs and TOBTs. Flights move from the Gate Departure Uncertain group to the Gate Departure Planned group when their EOBTs move within the tactical planning horizon.

Flights that become ready between scheduler calls are moved from the Gate Departure Uncertain or Gate Departure Planned group to the Gate Departure Ready group and their TOBTs are frozen at the last TOBT update given when they were in their previous group. This ensures that a static hold advisory is available for a flight as soon as the pilot calls in ready.
Because the Gate Departure Planned group flights create constraints for subsequently schedule flights, they can’t jump in front of each other by calling in earlier than their EOBTs. Because the Gate Departure Uncertain group flight do not create constraints, these flights can jump in front of each other by calling in early. But they can’t jump in front of Gate Departure Planned flights (because those flights are scheduled earlier and create constraints) unless there is a sufficient gap in the schedule due to low demand.

IV. SIMULATION

Fast-time simulations were conducted to evaluate tactical metering performance for varying scheduler parameters.

A. Simulation Environment

The Surface Operations Simulator and Scheduler (SOSS) [14] is used to simulate surface operations at CLT. SOSS simulates both departure and arrival aircraft movements within a network of nodes and links representing the airport surface. Fig. 1 shows a map view of the SOSS CLT surface model identifying the different types of nodes and links. In South flow, runways 18R and 23 are used only for arrivals. Runways 18C and 18L are used predominantly for departures with only occasional use for arrivals to offload 18R.

Departure routes begin at a gate node, transition through ramp, spot, taxiway, and departure queue nodes, and takeoff from departure nodes. Arrival routes begin at an arrival node, transition through taxiways, a spot, and ramp nodes, ending at a gate. Some arrivals may need to taxi across a runway via crossing nodes, such as 18R arrivals crossing 18C. If a gate conflict between and arrival and departure is predicted, the arrival will be diverted and held at a hardstand node until the departure vacates the gate [15]. For the purposes of this study, only arrivals are sent to hardstands to avoid gate conflict induced grid-lock without impacting departure scheduling.

Arrival landing STAs and subsequent entry into the surface model are predetermined by the traffic scenario. Whereas departure SOBTs are predetermined by the traffic scenario, actual gate pushback may be controlled by scheduler TOBT assignments. Departures with assigned TOBTs are held at the gate until current time is greater than or equal to TOBT. Otherwise, departures are released as soon as they are ready. For this evaluation, EOBTs remain static and no ready time uncertainty was modelled. Therefore, all flight ready times are equal to their EOBTs which are equal to their SOBTs as specified in the traffic scenario.

Aircraft are allowed to progress along predefined routes through the node-link network as long as they do not violate separation constraints specific to each part of the network. To avoid violating separation constraints, flights may stop at taxiway intersections and form queue lines at departure runways, resulting in taxi-time uncertainties due to surface congestion. Although SOSS has the capability of modeling uncertainty in various areas of the airport surface, the only uncertainties simulated were surface congestion related taxi-time uncertainties. This minimum level of uncertainty modeling was desired to perform a benchmark fast-time simulation evaluation of the ATD-2 tactical scheduler.

The simulation time step was set to 0.5 sec and the scheduler was called every 10 seconds.

Figure 1. CLT Surface Model
B. Traffic Scenario

As a hub airport for American Airlines, CLT traffic is characterized by tightly spaced departure and arrival banks. A four-hour traffic scenario was generated using CLT surface surveillance data from March 11, 2016, covering two such banks when CLT was operating in South flow. Fig. 2 shows the arrival and departure demand on each runway in 15-minute bins.

![Figure 2. Runway Demand](image)

C. Scheduler Parameters

Scheduler parameters include the planning horizon and taxi time delay buffer parameters. The start of the planning horizon was set to 10 minutes prior to EOBT.

Delay buffer parameters include values \(A\) and \(B\) from (1). Value \(A\) was set to 1.05 to account for a minor amount (5%) of congestion related delay. Value \(B\) is the key parameter which determines how much delay may be absorbed on the surface, passing any excess delay to the gate. To analyze how the amount of delay pushed back to the gate affects scheduler performance, multiple simulations were completed, each with a different \(B\) value. Value \(B\) was increased from 0 in 1-minute intervals until the simulation resulted in no delay passed to the gate as would be the case with no surface metering.

D. Evaluation Metrics

The goal of surface metering is to minimize surface delay and move as much delay as possible from active taxi in the ramp of AMA to the gate with engines off, without negatively impacting runway throughput. To that end, surface metering tries to regulate the flow of departures to the runway to meet the predicted runway departure rate and maintain a queue of flights at the end of the runway just long enough to account for uncertainty. The following delay, runway usage time, throughput, and departure queue metrics are designed to evaluate the performance of time-based surface metering utilizing tactical scheduling in the presence of taxi time uncertainties.

1) Delay

Total departure delay \(d_{\text{dep}}\) is measured as the difference between a departure flight’s ERUT and Actual Runway Usage Time (ARUT). Surface metering attempts to move a portion of the delay from taxiing (in the ramp or AMA) to the gate. Thus, total delay is segregated into gate delay \(d_{\text{gate}}\), ramp delay \(d_{\text{ramp}}\), and AMA delay \(d_{\text{AMA}}\). Gate delay is measured as the difference between a flight’s EOBT and Actual Off Block Time (AOBT). The transition from ramp to AMA occurs at the Movement Area entry Time (MAT). Ramp delay is obtained by subtracting gate delay from the difference between a flight’s earliest and actual MAT (AMAT – EMAT). AMA delay is then obtained by subtracting gate and ramp delay from total departure delay.

\[
d_{\text{dep}} = \text{ARUT} - \text{ERUT} \quad (2)
\]

\[
d_{\text{gate}} = \text{AOBT} - \text{EOBT} \quad (3)
\]

\[
d_{\text{ramp}} = \text{AMAT} - \text{EMAT} - d_{\text{gate}} \quad (4)
\]

\[
d_{\text{AMA}} = d_{\text{dep}} - d_{\text{gate}} - d_{\text{ramp}} \quad (5)
\]

Total arrival delay \(d_{\text{arr}}\) is the difference between an arrival flight’s Earliest Gate Arrival Time (EGAT) and Actual Gate Arrival Time (AGAT), where EGAT is calculated by adding UTT between runway and gate to arrival STA. In this paper, because no arrival time uncertainty was modeled, arrival STA is the same as Actual Time of Arrival (ATA). Total arrival delay is segregated into AMA delay \(d_{\text{AMA}}\) and ramp delay \(d_{\text{ramp}}\). The transition from AMA to ramp occurs at the Ramp Entry Time (RET). AMA delay for arrivals is the difference between a flight’s earliest and actual RET (ARET – ERET). Ramp delay for arrivals is then obtained by subtracting AMA delay from total arrival delay.

\[
\text{EGAT} = \text{STA} + \text{UTT} \quad (6)
\]

\[
d_{\text{arr}} = \text{AGAT} - \text{EGAT} \quad (7)
\]

\[
d_{\text{AMA}} = \text{ARET} - \text{ERET} \quad (8)
\]

\[
d_{\text{ramp}} = d_{\text{arr}} - d_{\text{AMA}} \quad (9)
\]

2) Runway Usage Time Prediction

Because TOBT is frozen at flight ready time, surface metering is dependent on runway scheduler predictions of TRUT made at flight ready time. Let a flight’s predicted runway usage time error be

\[
e = \text{ARUT} - \text{TRUT}(t_{\text{ready}}) \quad (10)
\]

where \(t_{\text{ready}}\) is the flight ready time.

3) Throughput Prediction

Due to taxi time uncertainties and lack of control beyond gate, push back, the tactical scheduler is unlikely to predict the exact sequence of flight operations on the runway, which will negatively impact \(e\). Tactical scheduler performance is evaluated in a less sequence sensitive way by calculating runway departure throughput prediction errors. Let \(t\) be current time and \(\tau\) be a future time for which departure throughput for a given runway is predicted. Let runway departure throughput rate \(R(\tau,t)\) be the
number of departures scheduled to use the runway between time \( t \) - 15 minutes and \( t \), calculated at time \( t \). \( R(t) \) is the actual departure rate calculated at time \( t \), when all flights included in the rate have already departed. \( R(t + 15, t) \) is the earliest rate that is based entirely on predictions or flights that have not yet departed. Let prediction error be

\[
E(\tau, t) = R(\tau, t) - R(t, t).
\]

At CLT, nominal taxi times can take up to 25 minutes. Allowing for some gate hold time, prediction errors for \( \tau \) up to \( \sim 35 \) minutes greater than \( t \) may affect surface metering performance. The most relevant throughput predictions to surface metering are analyzed by computing \( E(\text{ARUT}, t_{\text{ready}}) \) for each flight.

4) Departure Queue

Another metric for tactical scheduler evaluation is departure queue size. Queues are desired to be shorter to minimize congestion related delay. However, they should be long enough to account for taxi time uncertainty and keep the runways from going dry. Four queue values per runway are used: ramp count \( q_{\text{ramp}} \), AMA count \( q_{\text{AMA}} \), taxi count \( q_{\text{taxi}} \), and the queue line \( q_{\text{line}} \). The first three queues are simple counts of departures taxiing in the ramp, AMA, or either (ramp or AMA) bound for each runway. The queue line is the number of aircraft lined up from the end of the runway waiting to depart. This is calculated in post processing by identifying the uninterrupted cascading chain of departures scheduled to use the runway that are within close proximity (200 meters) of one another extending out from the runway entrance node.

The amount of delay buffer used to calculate TOBTs from ERUTs directly influences the average queue size. Good departure throughput predictability should enable surface metering to provide more queue stability, which should enable smaller queues to maintain maximum runway utilization.

V. RESULTS

Simulations of increasing \( B \) from (1) were performed until \( d_{\text{gate}} \) was zero for all departures at a \( B \) value of 14 minutes. At a \( B \) value of 10, \( d_{\text{gate}} \) was zero for all departures using runway 18C. Therefore, results focus on \( B \) values between 0 and 10.

A. Delay

Fig. 3 shows a stacked plot of average departure \( d_{\text{gate}}, d_{\text{ramp}}, \) and \( d_{\text{AMA}} \) for each simulation as \( B \) was increased. Total departure delay \( d_{\text{dep}} \) can be viewed as the sum of the stacked bars. As expected, \( d_{\text{gate}} \) decreases and active taxi delay \( (d_{\text{ramp}} + d_{\text{AMA}}) \) increases as \( B \) is increased. This verifies that \( B \) is an effective parameter to control the amount of delay moved from active taxi to the gate. Compared to \( d_{\text{AMA}}, d_{\text{ramp}} \) changes very little. This means that most if not all of the delay the lower \( B \) values transfer to the gate is queue delay (time waiting in line in the taxiways to use the runway). Note that \( d_{\text{dep}} \) is noticeably greater when \( B < 2 \). When \( B \) is too low, the \( d_{\text{gate}} \) is increased more than \( d_{\text{AMA}} \) can be decreased due to starving the runway.

![Figure 3. Gate, Ramp, and AMA Departure Delay](image)

Fig. 4 shows a stacked plot of average arrival \( d_{\text{AMA}} \) and \( d_{\text{ramp}} \) for each simulation as \( B \) was increased. Total arrival delay \( d_{\text{arr}} \) can be viewed as the sum of the stacked bars. Although average \( d_{\text{arr}} \) is consistently much larger than \( d_{\text{dep}} \), it did not appear to be sensitive to departure taxi time delay buffers. Although extra arrival delay is expected due to additional gate conflicts as arrivals wait longer for departures held at their gates, much of this delay was absorbed as extra taxi path distance for arrivals using hardstands, which is not captured in the presented arrival delay calculations. Whereas departures absorbed most of their active taxi delay in the AMA, arrivals absorbed most of their delay in the ramp. In general, the arrival taxi-in routes are much longer than departure taxi-our routes. Also, the areas where arrivals tended to stack up waiting for use of common taxi route segments happened to be in the ramp area.

![Figure 4. AMA and Ramp Arrival Delay](image)

B. Runway Usage Time Prediction Error

Fig. 5 shows the average and standard deviation of runway usage time prediction error, \( e \), across all departures at their ready times for each simulation of varying \( B \) value. On average, departures use the runway later than predicted as indicated by the positive average \( e \) for each simulation. This bias may be because ERUTs used to derive TRUTs are based on unimpeded transit time. This bias could be reduced by subtracting some expected congestion delay from the ERUT calculations shown in Table I.
The average $e$ increases with $B$ and begins to level off as $B$ exceeds 6 minutes. Despite releasing departures earlier from the gates (higher $B$ values), these departures encounter so much additional congestion delay as to cause their actual use of the runway to be even later. Standard deviation of $e$ also increases with $B$. This indicates that it is more difficult to predict the departure sequence in the presence of additional congestion caused by releasing departures from their gates earlier.

![Figure 5. Runway Usage Time Prediction Error](image)

**C. Throughput Prediction Error**

Fig. 6 shows the average and standard deviation error in throughput prediction made at each departure’s ready time $E(\text{ARUT}, t_{\text{ready}})$, referred to as simply $E$ below. For $B < 2$, runway throughput is over predicted ($E$ is negative) on average. For these simulations, departures were not released from the gate early enough to provide sufficient pressure on the runways allowing instances of excess separation that decreased actual throughput. Like $e$, the average $E$ increases with $B$ and begins to level off as $B$ exceeds 6 minutes. Unlike $e$, the standard deviation of $E$ is similar for all values of $B$ as this metric is less sensitive to departure sequence.

![Figure 6. Throughput Prediction Error](image)

**D. Departure Queue**

Departure queues were analyzed by calculating the maximum and average values separately for each runway and two hours of simulation time capturing a single demand cycle. Results are presented for only the first two hours of simulation time encompassing the larger of the two demand cycles as can be seen in Fig. 2. Figs. 7 and 8 show maximum and average queue sizes for 18L and 18C, respectively.

For both runways, the $q_{\text{AMA}}$ results are similar to the $q_{\text{line}}$ results. The average $q_{\text{AMA}}$ is always slightly higher than the average $q_{\text{line}}$ because most of the line is contained within the AMA. At $B = 10$, maximum $q_{\text{line}}$ exceeds maximum $q_{\text{AMA}}$ for 18L when the line extends out into the ramp. Fig. 9 shows how the last departure counted as part of $q_{\text{line}}$ is in the ramp (blue nodes and links).

![Figure 7. 18L Departure Queues](image)

![Figure 8. 18C Departure Queues](image)
The goal of surface metering is to move as much delay as possible from taxing to the gate without negatively impacting total delay. Because throughout is lost when the departures are over metered, it is better to under predict throughput and allow the queues to temporarily increase than to over predict and allow the queues to reduce to 0 and let the runway go dry. In actual operations, CLT ramp managers prefer maintain a count of departure taxiing to a particular runway $\sim 10$, which runway 18L exceeds for $B > 5$. For these reasons, $B$ values in the range of 2 to 5 minutes are recommended for future SOSS simulation studies for the ATD-2 tactical scheduler implemented at CLT. Other factors, such as additional uncertainties and human factors, may influence the desired delay buffer, requiring it to be calibrated separately in the field.

This study provides a benchmark for fast-time exploration of design options for other ATD-2 tactical scheduler features. Future research building off of this benchmark will include additional uncertainties, external traffic management initiatives, and airline priority flights.

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