Investigating Effects of Controlled Flights through Fast-Time Simulation

Zhifan Zhu
KBR Wyle Services, LLC
Moffett Field, CA, USA
zhifan.zhu@nasa.gov

Hanbong Lee
NASA Ames Research Center
Moffett Field, CA, USA
hanbong.lee@nasa.gov

Vaishali A. Hosagrahara
Tellus Solutions
Moffett Field, CA, USA
vaishali.a.hosagrahara@nasa.gov

Yoon C. Jung
NASA Ames Research Center
Moffett Field, CA, USA
yoon.c.jung@nasa.gov

***Abstract*—Departure flights at major U.S. airports are often subject to Traffic Management Initiatives to mitigate congestion and delay due to demand-capacity imbalances. These controlled flights can lead to inefficiency and delay on the airport surface. The integrated arrival, departure, and surface traffic management capabilities developed by NASA's Airspace Technology Demonstration 2 (ATD-2) sub-project 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. This paper evaluates the impacts of controlled flights on airport performance and assesses the ATD-2 benefits of pushback hold advisories for both controlled and non-controlled flights using fast-time simulation for Charlotte Douglas International Airport.**

Keywords—controlled flight, APREQ, fast-time simulation, surface metering

I. INTRODUCTION

Departing flights at major U.S. airports are often subject to Traffic Management Initiatives (TMIs) in order to alleviate congestion and delay induced by the imbalance between air traffic demand and capacity across the National Airspace System. Strategic TMIs such as the Ground Delay Program and Airspace Flow Program produce an Expect Departure Clearance Time (EDCT) to flights at their departure airports to control the air traffic flow into constrained resources. One commonly used tactical TMI is the Approval Request (APREQ), which is typically issued by the Air Route Traffic Control Center (ARTCC or Center) to assign runway departure times (called release times) to affected flights at airports within the Center, merging into a congested overhead stream. Among all departures at Charlotte Douglas International Airport (CLT) from January 2018 through February 2019, 32,337 flights (10.6% of all departures) were subject to APREQ, EDCT, or both restrictions. Out of 26,733 APREQ flights (8.8% of all departures), 33.2% of these APREQ flights did not meet the given compliance window (within two minutes before and one minute after the assigned release time) [1]. TMI non-compliance often result in lower predictability of overhead stream and thus airspace inefficiency, as well as underutilization of the airspace capacity. In addition, the efforts to meet the runway release times of controlled flights at the airport can lead to higher controller's workload, and possible surface delay and inefficient runway utilization.

NASA has been developing and testing a suite of decision support capabilities for the Integrated Arrival, Departure, and Surface (IADS) operations. Under NASA's Airspace Technology Demonstration 2 (ATD-2) sub-project, through a close partnership with the Federal Aviation Administration, air carriers, airports, and general aviation community [2], the IADS system is being evaluated in a field demonstration conducted in three phases. 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. The users of the IADS system include personnel at CLT Air Traffic Control Tower (ATCT), American Airlines ramp tower, CLT Terminal Radar Approach CONtrol (TRACON), and Washington and Atlanta ARTCCs. According to the operations data analysis, it is estimated that about 5.1 million pounds of fuel savings and 15.7 million CO_2 emission reduction, equivalent to planting over 100,000 urban trees, were achieved during the period of field evaluation between October 2017 and April 2020 [3-4]. Some of the benefits came from gate holds of departures, including both controlled and non-controlled flights subject to surface metering. The ATD-2 IADS system provides ramp controllers with pushback hold advisories for controlled flights at gates to meet the given release times, even when surface metering is not active.

In addition to gate hold advisories and surface metering, another main capability in the ATD-2 IADS system provides electronic negotiation procedures for APREQ flights [5-6]. Without the ATD-2 IADS system, the Call-For-Release (CFR) procedures that had been used at CLT to negotiate the release times of APREQ flights were followed through land-line voice communications. When a pilot of a flight under an APREQ restriction calls for pushback, the ATCT Traffic Management Coordinator (TMC) calls the Center TMC to request a release time and provides the best estimate of when the flight will be ready to depart from the runway. The Center TMC enters the projected runway departure time in the Time Based Flow Management (TBFM) system, assesses the availability of a slot at the meter point, and responds to the ATCT TMC with a release time that is predicted to enable the flight to fit into the overhead stream. Using the ATD-2 IADS system enables non-verbal, electronic coordination of release times at CLT. Prior to pushback, the ATD-2 surface scheduler estimates the Earliest Feasible Takeoff Times (EFTTs) of APREQ flights by which the aircraft will reach the runway with a high level of confidence. These times are shown on the timeline display for the ATCT TMC. When the ATCT TMC selects an APREQ aircraft on the timeline and requests its release time, the Integrated Departure Arrival Capability (IDAC) implemented in the TBFM system at the Center searches for potential windows of release times that would allow the aircraft to be inserted in the available slots in the overhead stream over the constrained meter point. IDAC calculates a runway release time based on the flight's EFTT and slot availability and sends the time electronically to the ATCT. The improved prediction accuracy of takeoff times by the ATD-2 surface scheduler enables the ATCT TMC to coordinate release times with the Center while the aircraft are still at the gates. The surface scheduler calculates Target Off-Block Time (TOBT) based on the negotiated release time. This would allow the controlled flight to be held at the gate until its TOBT and reach the runway to take off within the given compliance window. Also, the electronic coordination procedure makes the renegotiation process easier and faster when the aircraft is predicted to arrive at the runway earlier or later than its release time. The renegotiation of the APREQ time, even while taxiing after pushback, would allow the aircraft to take an earlier slot in the overhead stream, thus resulting in an earlier runway release time and taxi time reduction. The field data at CLT showed that the electronic release time negotiation provided by the ATD-2 IADS system improved APREQ compliance and reduced response time in approving release times [1]. However, the impact of controlled flights on overall airport surface performance has not been evaluated. It is essential to investigate the TMI compliance together with other performance metrics such as taxi time and throughput in different operation situations.

Fast-time simulation can be used to investigate the impact of controlled flights on airport performance that may not be clearly shown by actual data observations. Through fast-time simulation, for instance, the same traffic condition can be iterated with and without pushback hold advisories provided by ATD-2 surface scheduler. It can also aid in revealing the relationship between the APREQ compliance and other performance indicators such as taxi time reduction brought by ATD-2 gate hold advisories and surface metering. NASA has developed and improved a fast-time simulation tool for evaluating new concepts in airport surface operations, called Surface Operations Simulator and Scheduler (SOSS). From previous research [7-8], a SOSS simulation model for CLT was created and validated against actual operations data, and incorporated with the ATD-2 surface scheduler, providing pushback hold advisories for departures when excess taxi out time exceeds a target value. This model was used to evaluate the impacts of estimated flight ready times on surface metering [7] and of general aviation flights on airport performance [8].

In this paper, fast-time simulations using SOSS are performed to evaluate the benefits of the ATD-2 IADS system capabilities with respect to controlled flights. SOSS calculates reasonable release times from available overhead slots, provides pushback advisories for the controlled flights even when surface metering is inactive, and evaluates the airport performance regarding taxi time, runway throughput, and departure queue length. For selected traffic scenarios during busy time periods at CLT having a typical number of controlled flights (i.e., about 10% of total departures), three cases are simulated depending on the control level of surface metering. In the first case, surface metering is off, in which all the departures push back from gates once they are ready, representing the normal operations prior to using the ATD-2 IADS system. In this case, a few controlled flights are expected to leave their gates too early and have long taxi times to meet the assigned release times. In the second case, surface metering is off, but pushback hold advisories are applied to controlled flights only, so that they are held at gates for a certain time to meet the assigned release times for takeoffs, instead of waiting in the queue. In the last case, surface metering is turned on, where a subset of departures, including both controlled and non-controlled flights, are advised to be held at gates to mitigate surface congestion and reduce excess taxi times. Comparison between these cases will show the benefits/costs of managing controlled flights aided by the ATD-2 surface scheduler and the effectiveness of surface metering when controlled flights exist.

It is challenging to mimic various tactical operations of controllers in the fast-time simulation model. Controllers may initiate several different actions in order to meet the assigned release time. The controlled flight can be directed to either a hardstand in the ramp area or a designated holding area on the movement area; use by-pass taxiways for intersection takeoffs (takeoffs that start at some point other than the end of the runway, usually at an intersection of the runway with a taxiway); or assign a flight to wait on the opposite side of the runway, all while maintaining smooth takeoffs and landings with the maximum runway utilization. In this study, it is assumed that all the controlled flights use the inner queue taxiway for takeoffs, whereas non-controlled flights enter the runway through the outer queue taxiway. In this way, a controlled flight can wait for takeoff until the given release time, if it arrives at the runway too early. This assumption also allows a late controlled flight to cut in line and take off right away. Renegotiation of the release time, which is available in the ATD-2 IADS system at the field, is not considered as part of this study.

With these modeling approaches and assumptions, Section II describes the fast-time simulation environment, including the CLT airport configuration, traffic scenarios, simulation setup, and performance metrics. It also describes the TBFM assigned delay model to generate reasonable release times for APREQ flights based on historical data. Section III compares the simulation results between the three cases described above, in terms of compliance rate, surface efficiency, and controller's potential workload. This paper concludes with a results summary and future work in Section IV.

II. Simulation Environment

A. CLT

The simulations used a model of the CLT north flow configuration. According to an earlier study [1], the north flow configuration has a higher percentage of APREQ flights compared to the south flow configuration. Fig. 1 shows the airport layout of CLT with three parallel runways (36R/18L, 36C/18C, 36L/18R) and one diagonal runway (23/5). In the north flow configuration, all three parallel runways, 36R, 36C and 36L, are used for arrivals, and two runways near the main terminal, 36R and 36C, are used for departures. Runway 5 is not used for takeoff or landing. By-pass taxiways are used for intersection departures to make last minute fine-tuned adjustments, usually to have a controlled flight depart ahead of some other flights already in the departure queue or to slightly delay a controlled flight when it would arrive at the runway early, normally more than 4-5 minutes before its release time. As shown in Fig. 1, there are two departure queues, which are inner and outer queues, for departures in each runway, 36R and 36C.

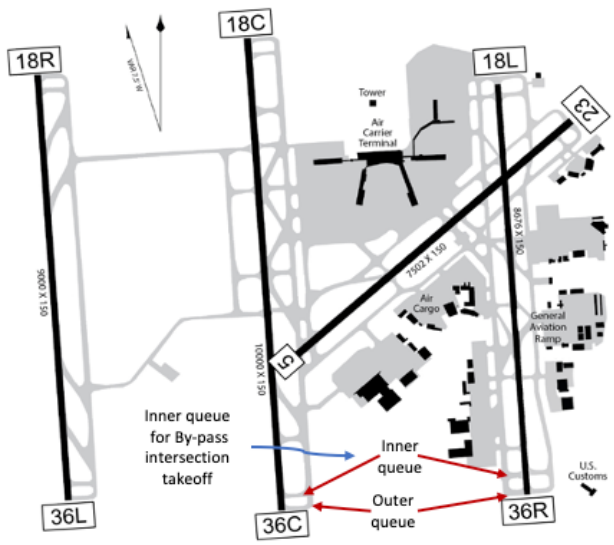

Fig. 1. CLT airport layout (as of 2018)

B. Simulation Setup

The fast-time simulations in this study used NASA's Surface Operations Simulator and Scheduler (SOSS) [7-10] connected to the ATD-2 Tactical Surface Scheduler [11] through the Surface Modeler, as shown in Fig. 2. Apart from facilitating a smooth exchange of input and output between SOSS and the scheduler, the Surface Modeler also contains an Earliest Off-Block Time (EOBT) model [7] and TBFM assigned delay model. The EOBT model provides the estimated flight ready time updates for commercial airline aircraft in the main terminals. The release times for APREQ flights are computed using the TBFM assigned delay model, which will be explained in Section II.C.

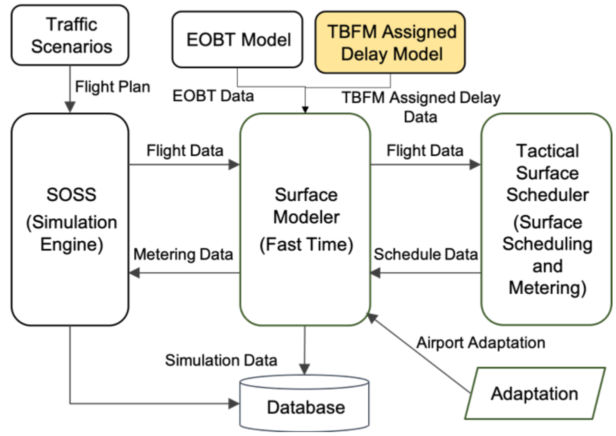

Fig. 2 Data flow between SOSS, Surface Modeler, TBFM Assigned Delay Model, and Tactical Surface Scheduler

The traffic sscenarios used in the simulation were created based on actual flight data at CLT for four days during Bank 2, historically one of the most congested time periods (9-11am) at CLT. Table I shows the actual number of departures, arrivals, and APREQ flights on each of the four selected scenario dates.

TABLE I FLIGHT COUNTS FOR TRAFFIC SCENARIOS

Scenario Dates	**Departure Count (Non-controlled | APREQ)**			**Arrival Count**			
	36C	36R	All	36C	36R	36L	All
1/24/2018	46 | 3	43 | 5	97 (89 | 8)	10	36	47	93
1/25/2018	50 | 3	34 | 3	90 (84 | 6)	10	38	56	104
2/13/2018	56 | 3	32 | 3	94 (88 | 6)	1	37	53	91
2/18/2018	51 | 2	33 | 3	89 (84 | 5)	6	38	57	101

To assess the impact of controlled flights on airport performance, three configuration cases for each scenario were designed. In Case 1, surface metering is off, and all departures are cleared to push back from the gates when ready. In Case 2, surface metering is off, but the controlled flights receive pushback time advisories from the Tactical Surface Scheduler. In Case 3, surface metering is on, and non-controlled flights are subject to metering hold at the gates when the airport surface is congested. The non-controlled flights receive the same pushback time advisories as in Case 2. In all three cases, the simulation tries to meet the release times of the controlled flights calculated by the TBFM assigned delay model.

In the given scenarios, several APREQ and EDCT flights were observed. To simplify the simulation, this study focuses on the APREQ flights only, which means that controlled flights hereinafter are equivalent to APREQ flights.

C. TBFM Assigned Delay Model

For an APREQ flight, its release time is computed as the sum of the EFTT estimated by the scheduler and additional delay assigned by TBFM, considering the slot availability in the overhead stream, called TBFM assigned delay. This is depicted in Fig. 3.

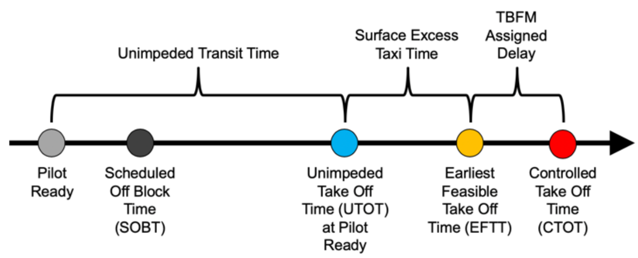

Fig. 3. Definition of APREQ times

In this study, a statistical model to generate the TBFM assigned delay was developed based on actual operations data at CLT, since the proposed fast-time simulation framework was not connected to the TBFM system nor did it have controller inputs. The model was based on actual TBFM assigned delay values from four months of historical data from January and February of 2018 and 2019. About 60% of the TBFM assigned delay values for the APREQ compliant flights in actual data were zero seconds, whereas the rest of the 40% had positive TBFM assigned delay values. Several probability distribution models were fitted to the data to find the best fit. Generalized Extreme Value (GEV) probability distribution model [12] fitted the positive TBFM assigned delay data the best. Fig. 4 shows the actual data for the month of January 2018 and the two closest fitting probability distributions, GEV and Loglogistic. Apart from visual comparison, both the Anderson-Darling test [13] and One-sample Kolmogorov-Smirnov test [14] assessed the GEV distribution as the better fit to the actual data.

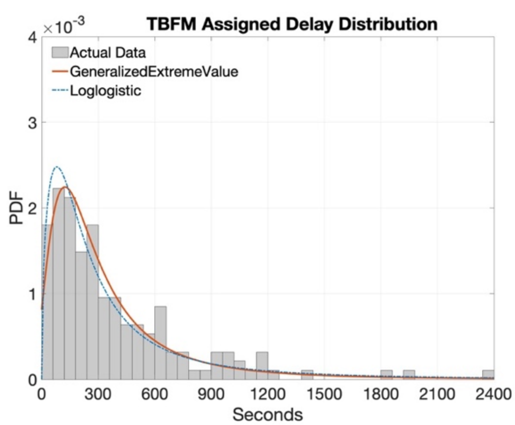

Fig. 4. Positive TBFM assigned delay distribution

The GEV distribution parameters based on the actual data are shown in Table II.

TABLE II TBFM ASSIGNED DELAY MODEL PARAMETERS

Shape (k)	Scale (sigma)	Location (mu)	Percentage Zero
0.451	183.49	182.14	60.00%

The proposed TBFM assigned delay model sets 60% of the controlled flights to have zero for their TBFM assigned delay values, and the remaining 40% of the APREQ flights follow the GEV probability distribution using the parameters listed in Table II. For model validation, the TBFM assigned delay values generated from the proposed model were compared with actual data, as shown in Fig. 5. The two-sample Kolmogorov-Smirnov test indicated that the two TBFM assigned delay value distributions from the actual data and the proposed model were similar.

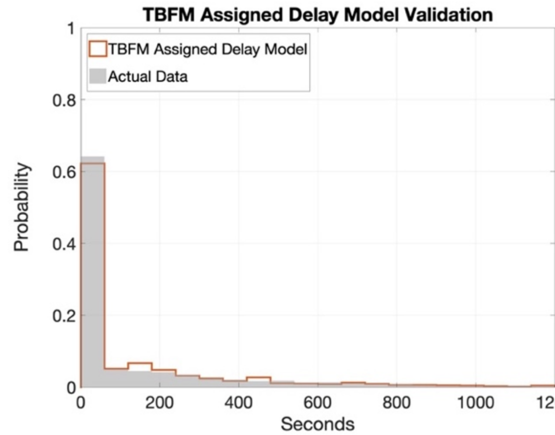

Fig. 5. TBFM assigned delay model validation

D. Simulation Limitations

Human interventions by the ATCT TMC and controllers play a critical role in controlled flight operations on the airport surface. For instance, when the TMC notices that a controlled flight already taxiing in the movement area has a release time that is either 20 minutes in the future or predicted to miss its release time, the TMC will try to renegotiate a new release time at an earlier or later time, respectively. In addition, ground controllers use various tactics to insert controlled flights in the right position of a departure sequence to meet the release times while not blocking taxiway traffic, such as holding them at the hardstand or taxiway and using the by-pass taxiway for intersection takeoffs via the inner queue. However, it is challenging to model the controller's tactical maneuvers for the controlled flights in fast-time simulations. Therefore, some assumptions were made in the simulations for this study, considering the following limitations:

- The release time renegotiation after pushback was not considered. In other words, the release times were assumed final at pushback time. According to operational data at CLT in January 2018, about 22.5% of APREQ flights had release times updated when the aircraft were taxiing in the ramp and airport movement areas. In other words, about 77.5% of APREQ flights had their final release times at or before pushback.
- In this study, it is assumed that a controlled flight absorbs its excess taxi out time in the by-pass departure queue only. In the simulations, the scheduler can hold a controlled aircraft only at the gate. Once it started taxiing, there was no hold short maneuver at the taxiway intersections instructed by the scheduler. In addition, to prevent a controlled flight waiting for its release time in the departure queue from blocking the traffic behind, all the controlled aircraft were assigned to the by-pass departure queue (inner queue shown in Fig. 1), and the non-controlled aircraft to the normal, outer queue.
- The use of the inner queue for the intersection takeoff approach worked well in the simulations except when

two controlled flights were taxiing to the same runway within a short time window and the release time of the leading aircraft was far in the future. In real operations, the controller could hold the leading aircraft in a holding area early or divide the two aircraft between different departure queues. In the simulation, however, this situation could result in the second controlled aircraft extruding from the inner queue and blocking traffic. Fig. 6 illustrates an example of such a situation at Runway 36C, where two controlled flights (highlighted in yellow) block the non-controlled flights (highlighted in cyan) from entering the outer queue. In this study, a few runs had to be eliminated in order to avoid this gridlock situation.

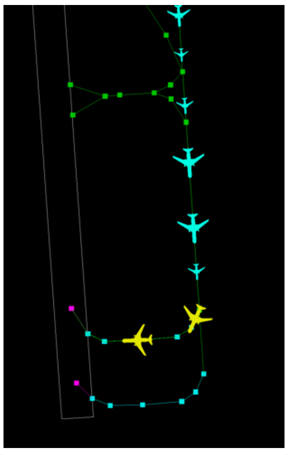

Fig. 6. Controlled flight blocks departure traffic behind

III. Simulation Results and Analysis

In this study, forty simulation runs were implemented with perturbated variables for each scenario and each case for data collection. The three cases tested include: Case 1) Metering off, all departure flights push back when ready; Case 2) Metering off, controlled flights held at gates as advised; and Case 3) Metering on, all departure flights follow gate hold advisories. The perturbation variables were the TBFM assigned delay, EOBT, and pushback ready time. The TBFM assigned delay came from the model described in the previous section. The EOBT values were produced by the EOBT model developed in [7]. The pushback ready times were generated by SOSS.

This section presents the simulation results and analysis from the first scenario on 1/24/2018 which had the most APREQ flights, but the simulation results from other scenarios showed similar trends. Table III lists the number of flights and runway assignments in the scenario. The number of APREQ flights in parentheses are included in the total counts of departure flights.

TABLE III NUMBER OF FLIGHTS AND RUNWAY ASSIGNMENT

Runway	36L	36C	36R	Total
Arrival	47	10	36	93
Departure	0	49	48	97
APREQ	0	(3)	(5)	(8)

A. APREQ compliance under three conditions

The APREQ compliance was measured as the difference between the release time and the actual wheels-off time, in minutes. The compliance window for APREQ flights is within two minutes before to one minute after the release time.

Fig. 7 shows the histograms of the overall APREQ compliance for the three configuration cases. The bin size of the histograms is one minute. The two vertical dashed lines represent the -2/+1 minutes of the compliance window. The compliance rate, annotated at each histogram, is the fraction of the APREQ flights whose compliance values fall inside the compliance window.

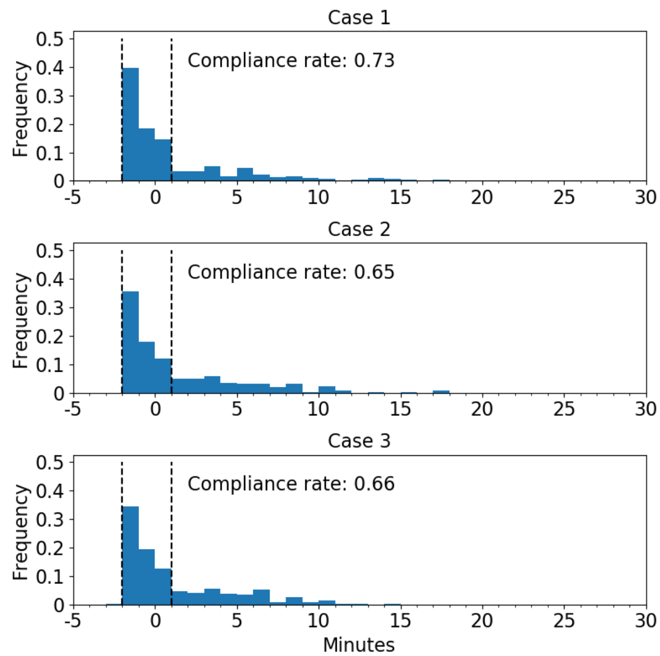

Fig. 7. Histogram of APREQ compliance rates for three cases

The compliance rates of Case 2 and Case 3 were very close to each other at 65-66% which were also close to the average number found in actual operations [1]. Case 1 showed higher performance by about eight percent. When a controlled flight arrived at the inner queue before its compliance window, it waited in the queue. Thus, those controlled flights that taxied to the runway in time would most likely meet the compliance window. On the other hand, if a controlled flight was not able to taxi to the runway before the release time window, i.e., arriving in the inner queue either already inside the compliance window or later, it would not wait. Those aircraft that arrived at the runway after the compliance window would be marked as non-compliant. For those aircraft that arrived at the runway inside the –2/+1-minute compliance window, some of them were able to take off to meet the release times. The others, however, could still miss the compliance window, if there was an arrival landing or if another non-controlled departure was already in the runway position for takeoff. In real operations, if a controlled flight is predicted in advance to arrive in the queue later (or earlier) than the release time, the ATCT traffic manager may renegotiate with the Center TMC for a later (or earlier) release time to avoid the non-compliance situation. This renegotiation may cause extra workload to both the traffic manager and the controller. However, the SOSS simulation lacks this capability of human intervention as described earlier.

Although the controlled flights in Case 1 had a better compliance rate, they spent more time on the surface. Fig. 8 shows the relation between the amount of waiting time in the inner queue and the compliance. In the scatter plots, the inner queue waiting time, on the horizontal axis, was measured as the time a controlled aircraft waited in the queue before takeoff. The corresponding compliance value is plotted along the vertical axis. Each marker represents a controlled flight's compliance versus its inner queue waiting time. The area under the dashed line represents the compliance window of –2/+1 minute from the release time. The plot shows that in the Case 1 condition, where the aircraft pushed back from the gate when ready, more controlled flights waited in the queue and spent longer time there until the given release time as well, compared to Case 2 and Case 3 where the controlled flights were subject to gate hold advisories. The controlled flights in Case 1 achieved better overall compliance at a higher cost through increased taxi time and more fuel burn. Again, human interventions such as trying to renegotiate for an earlier release time, if available, would help reduce the excess taxi time in this case.

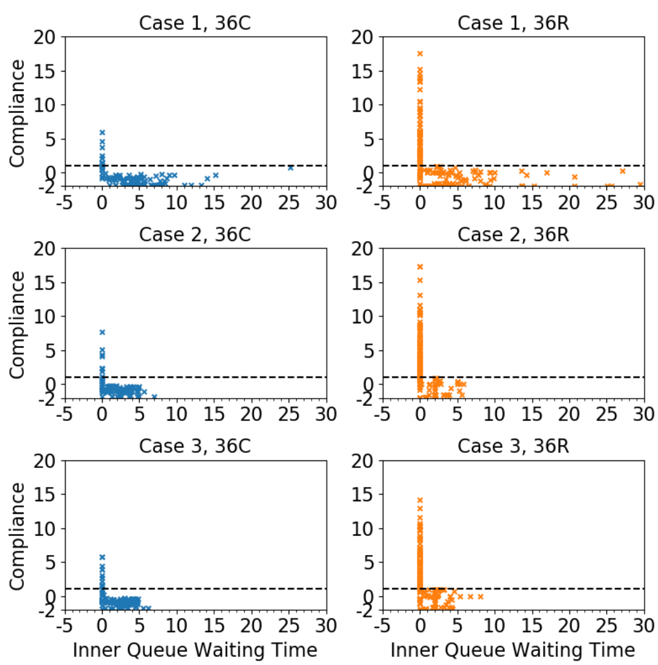

Fig. 8. Compliance vs. inner queue waiting time (in minutes)

In all three cases, more aircraft going to Runway 36R missed the compliance window in the simulations shown by the orange markers at the zero inner queue time and above the horizontal dash line. This is also evident in the runway breakdown compliance rates shown in Fig. 9. The reason appeared to be that the tactical scheduler used in the simulation underestimated taxi times when assigning release times to 36R, which may be due to the heavily mixed departure and arrival traffic at this runway during the bank.

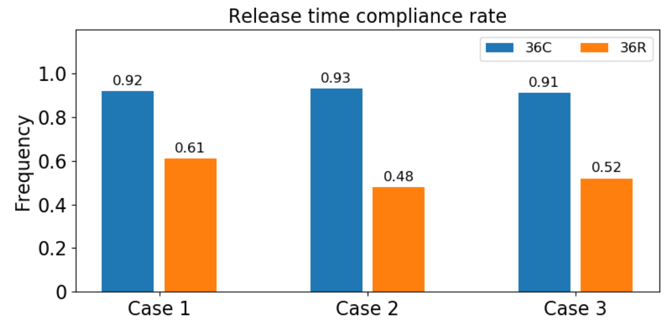

Fig. 9. Compliance rate by runway

Fig. 10 displays the average controlled flight inner queue waiting times per aircraft in minutes for the three cases. Case 1 had longer queue times than Case 2 and Case 3 because the aircraft had pushed back at their ready times and tended to arrive at the runway before the release time window. The inner queue times of Case 2 and Case 3 were comparable since in both cases, the controlled aircraft were subject to gate hold for their release times. Between the two runways, the average queue times for 36C were longer than 36R, suggesting more controlled aircraft taxied to 36C with more breathing room for the compliance window.

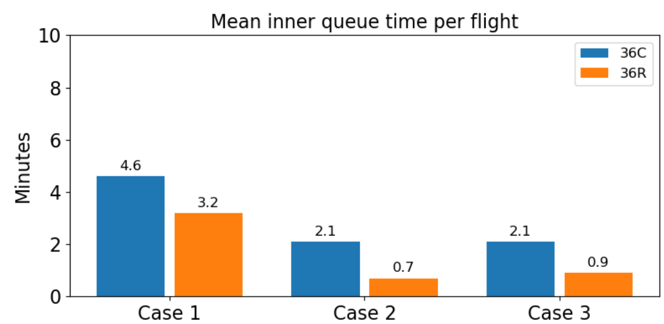

Fig. 10. Mean inner queue time per flight (in minutes)

In summary, among the three simulation conditions, Case 1, where the controlled flights were not subject to gate hold, showed better compliance rate, but the aircraft had to absorb higher taxi times on the airport surface than the other two cases. The compliance performance of the controlled flights taking off from Runway 36R was evidently lower than Runway 36C in all three cases, which was likely caused by the underestimated taxi out times due to the heavier traffic with more arrivals at the runway. Both situations, i.e., arriving at the runway earlier and later, could be mitigated by human interventions in real operations, but they were not available in the simulations.

B. *Surface Efficiency and Runway Throughput*

This section examines the airport performance metrics related to efficiency and throughput, including gate hold, taxi out time, and departure throughput by runway.

In the Case 2 and Case 3 conditions, the Tactical Surface Scheduler calculates the TOBTs for controlled aircraft at gates. In Case 2, where surface metering is off, only the APREQ flights were given TOBTs as pushback advisories for controllers to meet the release time, whereas in Case 3 (surface metering on) both controlled and non-controlled flights were given TOBTs based on the surface metering algorithm. The objective of surface metering is to reduce excess taxi out times by holding departing aircraft at the gates, thus effectively shifting some surface delay from the queue to the gate. Fig. 11 shows the total gate hold time for each case.

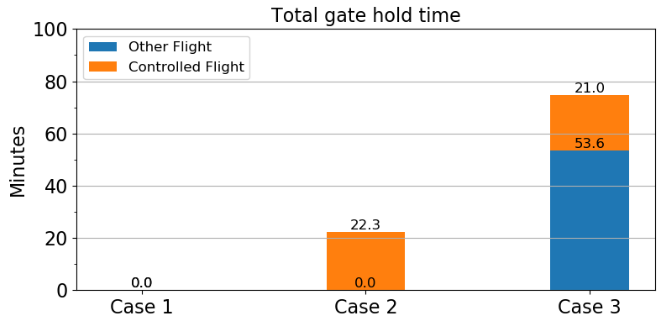

Fig. 11. Total gate hold time (in minutes)

As designed in the simulation setup, Case 1 had no gate hold. Case 2 and Case 3 showed a similar amount of total gate hold time (22.3 and 21.0 minutes) for the APREQ flights. The gate hold for these controlled flights helped reduce the inner queue waiting time, as shown in the previous inner queue time analysis. In Case 3, the non-controlled flights were also subject to gate hold due to surface metering, which can help reduce excess taxi out time and surface congestion. Table IV shows the total and average (in parentheses) hold times in minutes grouped by the two runways for the Case 2 and Case 3 conditions.

TABLE IV. GATE HOLD TIME BREAKDOWN

	Case 2		Case 3	
Runway	**Controlled**	**Non-controlled**	**Controlled**	**Non-controlled**
36C	9.2 (5.6)	0	7.4 (4.8)	11.9 (3.4)
36R	13.2 (5.2)	0	13.6 (5.1)	41.7 (4.4)

The data show that in both cases, Runway 36R had more total gate hold time for the APREQ flights than 36C because of five APREQ flights were assigned to 36R and only three to 36C. For the non-controlled flights, Case 3 had significantly more gate hold time at 36R than 36C. This was probably due to more arrivals landing on Runway 36R, and the scheduler had to hold departures at the gates longer to manage the taxi out times.

Table V shows the gate hold percentages for Case 3. Between the two departure runways, the total percentage of aircraft that were assigned to Runway 36R but held at the gates (25.4%) was more than twice of those departing from Runway 36C (10.5%) because of the heavier traffic at 36R. Overall, between the controlled and non-controlled flights, more than half of the controlled flights (54.1%) were held at the gates, and less than twenty percent (16.5%) of the non-controlled flights were held at the gates. This reflects the difference in scheduling objectives. The scheduling for controlled flights aims to deliver the aircraft to runways to meet the release times; where more flights have future release times, more gate hold can be advised. On the other hand, the scheduling strategy for non-controlled flights is to reduce their excess taxi out time.

TABLE V. PERCENTAGE OF FLIGHTS HELD AT GATES IN CASE 3

Runway	**36C**	**36R**	**Overall**
Controlled	55.0%	53.5%	54.1%
Non-controlled	7.6%	25.9%	16.5%
Total	10.5%	25.4%	17.9%

Fig. 12 illustrates the total taxi out time for the three cases. The taxi out time was measured as the duration from pushback start to wheels-off. For the controlled flights, it includes the waiting time in the departure queue for their release times.

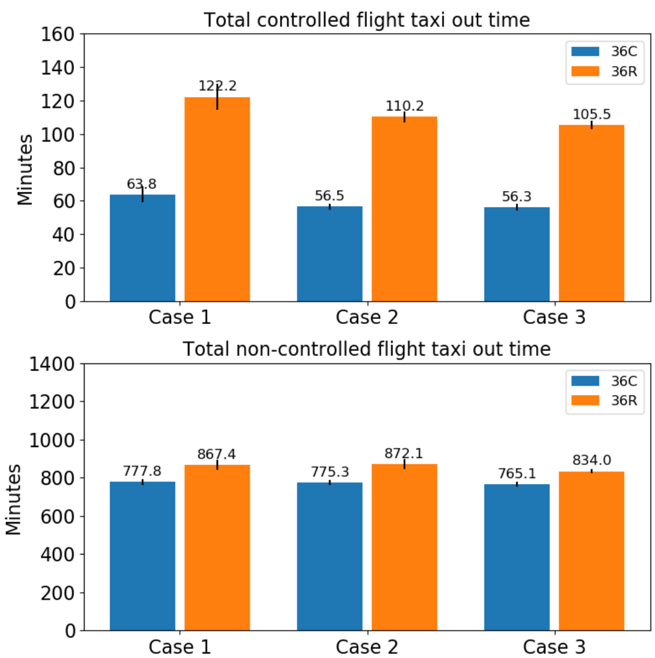

Fig. 12. Total taxi out times (in minutes)

In Fig. 12, the top bar chart shows the total taxi out times for the APREQ flights, and the bottom bar chart shows the total taxi out times for the non-controlled flights. For the controlled flights to either runway, the taxi out times show a decreasing trend from Case 1 to Case 3. In Case 1, the controlled flights had more taxi out time. The extra taxi out time included the waiting time in the inner queue, as shown earlier in Fig. 10. In Case 2 and Case 3, the controlled flights spent less time on the surface than in Case 1. However, their compliance rates were also lower as indicated in Fig. 7. Despite the small amount of difference among the three cases, they suggest a possible tradeoff between the two performance metrics. For the non-controlled flights, a slight decreasing trend from Case 2 to Case 3 is also visible. In Case 1 and Case 2, the non-controlled flights were not metered, so they showed similar performance. Compared to Case 2, Case 3 showed better taxi performance because of the gate hold applied to both the controlled and non-controlled flights. The amount of improvement at 36C was less than that at 36R since less aircraft going to 36C were held, as shown at Table V.

The average taxi out time per flight is shown in Fig. 13. The controlled flights produced greater taxi out times than the non-controlled flights due to the controlled release time conformance. In fact, the average difference in Case 1 was about four minutes, compared to two minutes for Case 2 and Case 3. The average numbers exhibited the similar decrease trend from Case 1 to Case 2 and Case 3, which is consistent with the total taxi out time numbers.

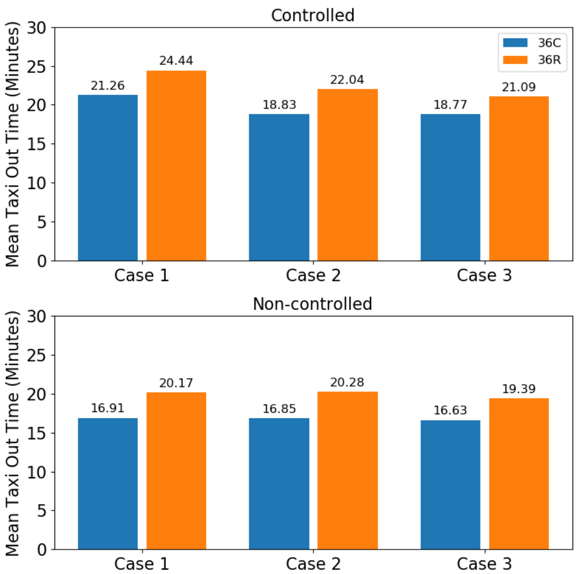

Fig. 13. Average taxi out time per flight (in minutes)

The runway throughput comparison is shown in Fig. 14 (a) and (b). The throughput includes both controlled flights and non-controlled flights, as well as arrivals. Each bar represents the runway usage count in a 5-minute time bin. At Runway 36C, the peak departures happened between 40 and 60 minutes into the simulations in all three cases, with five departures in five minutes that corresponded to about 60-second runway separation. No loss of departure throughput was found. At Runway 36R, many arrival landings (green bars) can be found. The highest runway usage occurred at 90 minutes into the simulations, where six combined departure and arrival runway operations were observed. In general, the runway throughput charts for the three cases were very similar to each other because the simulations filled the runway slots with either controlled or non-controlled flights, whenever they were ready to take off, without leaving any gaps.

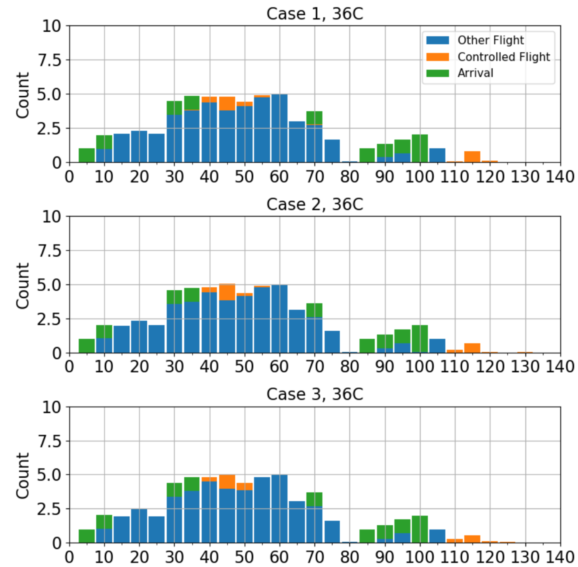

Fig. 14 (a). Runway 36C departure throughput

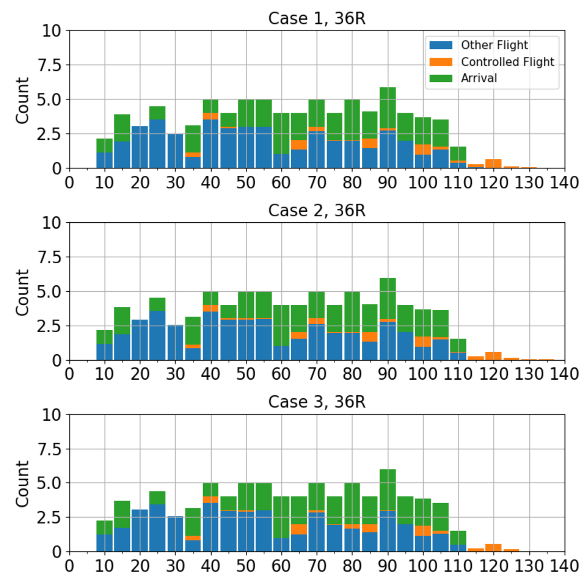

Fig. 14 (b). Runway 36R departure throughput

C. *Controller's potential workload*

Human controllers are an integral part of airport surface operations and managing their workload is important to system performance. One of the expected benefits of providing decision support tools is to enhance system efficiency without increasing controller workload [15-16]. Although it is beyond the capability of fast-time simulations to directly measure controller workload, there are two metrics in this study that can be explored to compare the notional workload differences between the three cases. The assumption is that workload is associated with the number and duration of aircraft operating on the airport surface.

The first metric is the departure aircraft count in the movement area. A congestion factor was derived from this metric. It was computed as the fraction of time that the departure aircraft count in the movement area exceeds a threshold value over the whole simulation time. The larger the fraction value is, the longer the surface is congested. For example, if the number of departures on the surface has been greater than a threshold for half the simulation time, the congestion factor would be 0.5.

The second metric is the direct measurement of inner queue waiting time. In actual operations, if a controlled flight experiences a lengthy delay, a controller may hold it short on taxiways and use the by-pass intersection takeoff through an inner queue until the flight's assigned release time, which would require the controller to monitor the situation. In this study, the inner queue was used to absorb the surface delay of controlled flights. So, the amount of inner queue waiting time was used as an indicator of the overall delay consumed on the surface. Therefore, the longer a controlled aircraft waited in the queue, the more workload was deemed to be required by the controller.

Table VI displays the two measurements along with the compliance rate for the APREQ flights assigned to Runway 36R, the busier of the two runways. The threshold value for the aircraft count on the movement area was set to ten for the congestion factor. This value was arbitrarily chosen for comparison purposes only. It does not imply a subjective mental threshold of the surface congestion condition to controllers. The compliance rate and the congestion factor are shown in a ratio, and the inner queue time is in minutes.

TABLE VI. CONGESTION FACTOR VS. NOTIONAL WORKLOAD

	Case 1	**Case 2**	**Case 3**
Compliance rate	0.61	0.48	0.52
Congestion factor	0.07	0.07	0.01
Inner queue time (min)	3.2	0.7	0.9

The results indicate that in the Case 1 condition, where the controlled flights pushed back when ready, had the highest compliance rate, but at the same time, may require more controller attention because of the long inner queue waiting time. Case 2 and Case 3 experienced relatively lower compliance rates, but workload demand was lower as expressed by the inner queue time. Case 1 and Case 2 showed the same congestion factor, because surface metering was off in both cases. In contrast, Case 3, where surface metering was on, showed noticeable drop in the congestion level. It is evident that controlled flight operations may have directly impacted controller's workload. A human factors investigation of the relationship between controlled flight compliance and controller's workload is warranted and can be a potential topic for future work.

IV. CONCLUSIONS

In this work, a fast-time simulation-based study was conducted to investigate the effects of controlled flight operations on airport performance during Bank 2 at Charlotte Douglas International Airport (CLT). First, a TBFM assigned delay model was created using actual operational data at CLT. In the simulations, the delay value was added to the Earliest Feasible Takeoff Times (EFTTs) of controlled flights, estimated by the ATD-2 Tactical Surface Scheduler, in order to obtain realistic release times for the controlled flights. Depending on the level of gate holding applied to controlled and non-controlled flights, three simulation cases were configured with NASA's fast-time simulation engine (SOSS), ATD-2 Tactical Surface Scheduler, and the release time model. In the first case, surface metering was off, and neither controlled flights nor non-controlled flights were held at the gates. All departures pushed back at their ready times. In the second case, surface metering was inactive, but the controlled flights were subject to gate hold by the scheduler to meet their release times. In the third case, surface metering was on, and so all the controlled and non-controlled departure aircraft were subject to gate hold.

Because there were no human interventions in the fast-time simulation environment, release time renegotiation while the aircraft was taxiing was not considered, and all the controlled flights were assumed to use the by-pass inner queues for intersection takeoffs.

In summary, simulation results showed that:

- Without surface metering or gate holds (Case 1), better release time compliance rates were observed because the controlled aircraft left the gate earlier once they were ready to push back. However, they spent more taxi out time on the airport surface. The taxi out time included the time waiting in the departure runway queue before their release times. The waiting location could be at the hardstand in the ramp or at a designated area on the movement area in real operations.
- The controlled flights in the other cases, Cases 2 and 3, with gate holds produced shorter taxi out times and benefited from pushback hold advisories, but had lower release time compliance rates, compared to Case 1.
- Surface metering (along with gate holds) in Case 3 showed additional taxi out time reduction over gate holds alone for controlled departures in Case 2, because some of the non-controlled departures were also held at the gates, which helped reduce surface congestion.
- Between the two mixed-use runways of 36C and 36R, the controlled flights to 36R showed a worse compliance rate compared to 36C due to more arrival traffic which led to underestimated taxi out time to the runway. The compliance performance difference was consistent with actual operational data analysis [1].
- Runway throughput of all departures among the three cases showed similar performance.

One of the key performance metrics for controlled flights is the compliance of their release times. It would be desirable for a controlled flight to taxi to the runway earlier rather than later for compliance. However, arriving too early would result in extra taxi out time and increase controller workload. Using the amount of excess taxi out time of the controlled flights and the departure count on the surface, a notional workload indicator was calculated for the three cases. It showed that in without surface metering or gate holds, where the controlled departures push back at their ready times, the notional controller workload was higher than the other two cases.

The TMC and controllers play significant roles in controlled flight operations. The lack of human intervention logic in the fast-time simulations, such as release time renegotiation during taxi, imposed limitations to this study. Future work may consider adding a controller heuristic logic to model controller inputs and support release time renegotiation during taxiing. The scenarios in this study were simplified to have APREQ flights only as controlled flights, but the future study can be extended to investigate more complicated scenarios having both APREQ and EDCT flights that have different compliance windows.

Acknowledgment

The authors would like to thank Mr. Pete Slattery, ATC/Traffic Management Specialist, for sharing his knowledge and experience about air traffic control at CLT, especially in handling controlled flights.

References

[1] T. J. Callantine, R. Staudenmeier, L. Stevens, W. J. Coupe, and A. Churchill, "Electronic Departure Approval Requests in ATD-2 Daily Operations," 2019 AIAA Aviation Forum, Dallas, TX, June 2019.

[2] Y. Jung, et al., "Airspace Technology Demonstration 2 (ATD-2) phase 1 Concept of Use (ConUse)," February 2018.

[3] Y. C. Jung, W. J. Coupe, A. Capps, S. Engelland, and S. Sharma, "Field evaluation of the baseline integrated arrival, departure, and surface capabilities at Charlotte Douglas International Airport," 13th USA/Europe Air Traffic Management Research and Development Seminar, Vienna, Austria, June 2019.

[4] ATD-2 team, "ATD-2 Benefits Mechanism," revision v2, May 2020.

[5] L. Stevens, L. Martin, K. Jobe, B. Parke, E. Chevalley, H. Lee, S. Verma, and V. Dulchinos, "Evaluation of Approval Request/Call for Release Coordination Procedures for Charlotte Douglas International Airport," 36th Digital Avionics Systems Conference (DASC), St. Petersburg, FL, September 2017.

[6] L. Stevens, T.J. Callantine, and R. Staudenmeier, "Evolution of Electronic Approval Request Procedures at Charlotte Douglas International Airport," 37th Digital Avionics Systems Conference (DASC), London, UK, September 2018.

[7] H. Lee, Y. C. Jung, S. J. Zelinski, Z. Zhu, and V. Hosagrahara, "Fast-Time Simulation for Evaluating the Impact of Estimated Flight Ready Time Uncertainty on Surface Metering," 38th Digital Avionics Systems Conference (DASC), San Diego, CA, 2019.

[8] Z. Zhu, V. Hosagrahara, H. Lee, Y. C. Jung, and D. L. Bakowski, "Impact of General Aviation Operations on Airport Performance Through Fast-Time Simulations at Charlotte Douglas International Airport," 2020 AIAA Aviation Forum, June 2020.

[9] R. D. Windhorst et al., "Validation of simulations of airport surface traffic with the Surface Operations Simulator and Scheduler," AIAA Aviation Technology, Integration and Operations Conference, Los Angeles, CA, August 2013.

[10] S. Zelinski and R. Windhorst, "Assessing tactical scheduling options for time-based surface metering," 36th Digital Avionics Systems Conference (DASC), St. Petersburg, FL, September 2017.

[11] W. J. Coupe, H. Lee, Y. Jung, L. Chen, and I. Robeson, "Scheduling improvements following the phase 1 field evaluation of the ATD-2 integrated arrival, departure, and surface concept," 13th USA/Europe Air Traffic Management Research and Development Seminar, Vienna, Austria, June 2019.

[12] Generalized Extreme Value distribution, https://gmao.gsfc.nasa.gov/research/subseasonal/atlas/GEV-RV-html/GEV-RV-description.html

[13] Anderson-Darling Test, https://www.itl.nist.gov/div898/handbook/eda/section3/eda35e.htm

[14] Kolmogorov-Smirnov Goodness-of-Fit Test, https://www.itl.nist.gov/div898/handbook/eda/section3/eda35g.htm

[15] Stevens, L. K. S., Jung, Y. C., Coupe, W. J., Lee, H., Parke, B. K., "Assessment of Ramp Times (ART 2) Human-in-the-Loop (HITL) Simulation – Final Results," March 2019. https://aviationsystemsdivision.arc.nasa.gov/publications/atd2/tech-transfers/4_Evaluation_Results/4.09%20ATD2_ART2_HITL_Results_2019-03-06.pdf

[16] Parke, B., Stevens, L. K. S., Coupe, W. J., Lee, H., Jung, Y. C., Bakowski, D. L., and Jobe, K., "Alternatives for Scheduling Departures for Efficient Surface Metering in ATD-2: Exploration in a Human-in-the-Loop Simulation," 10th International Conference on Applied Human Factors and Ergonomics, Washington, D. C., July 2019.