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Accrued Delay Application in Trajectory-Based Operations

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***Abstract*— The air traffic management system lacks integration among its elements often due to using inconsistent information, models, and metrics about the traffic. Transitioning to trajectory-based operations, whereby flights are managed by full trajectories in space and time, will enable more integration, with the help of increased automation. Building on trajectory-based operations, an "accrued delay" metric is proposed, which continuously measures the amount of delay that a flight has accumulated up to the current time, including delays incurred during the current flight and inherited from previous flights through the turnaround process. Through a time-based metering and scheduling example, we show how using accrued delay as a metric can help integrate the decision-making across multiple decision horizons, leading to more efficient and balanced access to airspace services. We show that when prioritizing flights that have already accrued high delay because of a constrained runway resource, significant gains are achieved in terms of reducing total delay and its variance. We studied the sensitivity of these gains to a number of factors such as time-based versus distance-based horizons, horizon size, and errors in conformance to scheduled times.**

Keywords-accrued delay; trajectory-based operations; time-based flow management.

I. Introduction

As air traffic management processes become increasingly digitized and interconnected, they can migrate to new paradigms featuring higher levels of information sharing, automation and distributed control. An example of this migration is the current transition from managing the traffic using speed, heading, and altitude vectors, which are generated and communicated by human agents, to managing it using full-flight trajectories in time and space, which are generated, communicated, and negotiated with the help of digital agents. Building on trajectory-based traffic management, services that maintain safe and efficient operations can be integrated and provided more strategically and optimally. Trajectories can be adjusted more dynamically and be tailored to flight objectives while optimizing system performance.

In order to help achieve integrated air traffic services, performance metrics need to be measured consistently across flights and across the airspace network and used in integrated decision-making. Current services lack this integration due largely to using inconsistent information, models, and metrics about the traffic that they are managing. One example is the application of time-based metering and scheduling of arrivals to congested airports. Reference [1] describes how arrivals to a congested airport that are departing from close-in origin airports may be allocated significantly higher delays than arrivals originating from airports farther away. For arrivals into Newark Liberty International Airport (EWR), the ratio was, on average, ten to three minutes [1]. Key causes of these differences were identified as being lack of coordination between multiple traffic management systems (such as the strategic ground delay program and the tactical time-based flow management program) imposing delay on the same flights at different times. Other inconsistencies included using different acceptance rates between these systems and inaccurate estimated flight times.

In this paper we propose a metric we call "accrued delay" of a flight, which continuously measures the amount of delay that a flight has accumulated from its inception up to the current time. A flight may accumulate delay after departure (e.g., because of deviations due to weather or other flow constraints) or pre-departure (e.g., because of mechanical or pre-flight preparation delays). It may also incur delay that has propagated from previous flights that delayed equipment, passengers, or crews that were needed to conduct the flight. Therefore, accrued delay represents flight as well as network effects. We then propose to use this metric in scheduling decisions that attempt to recover accrued delay to the extent possible while maintaining system throughput. We show how using accrued delay as a metric can help integrate the decision-making among services provided to the same flights, leading to more efficient and balanced access to airspace services. Reducing service variability may ultimately induce higher capacity through reduced flight block times, which are often increased by airlines to accommodate uncertain delays.

A comprehensive analysis of the effects of the interaction between different traffic management initiatives found unbalanced increases in individual flight delays caused by interference between initiatives [2]. Reference [3] developed a model and used fast-time simulation to explore the impact of different combinations of traffic management initiatives. Reference [4] presents an analytical approach that quantifies the delay propagation between multiple initiatives, based on a Brownian Motion formulation, evaluating the probability that one initiative over-controls or under-controls the flow to a downstream initiative. The propagation of delay between airports in a network has also been studied. In [5], delay propagation between airports is examined over several years in spatial and temporal terms, with one model tracking individual aircraft and another model relating delays between airports. Similarly, [6] describes an analytical queuing and network decomposition model to study the propagation of delays within a large network of major airports. Queuing models compute delays at individual airports while a delay propagation algorithm updates flight schedules at the airports in the network in response to the individual airport delays. In [7], delay propagation was estimated to isolate delays incurred at an airport from delays transported from other airports, to identify airports that constitute choke points. Reference [8] describes an agent-based model for characterizing the spreading of delays through the European network, simulating aircraft rotations, passenger connections, and slot reallocation. Reference [9] analyzed empirically the amplifying or mitigating factors in delay propagation in European air traffic.

While these approaches allow for the prediction of delay propagation, either during turnaround or en-route, they do not consider using that delay to mitigate downstream impacts. This is the goal of this paper. In section 2, we describe the accrued delay concept and in section 3, the accrued delay metric and its estimation methods used in this paper. In sections 4 and 5, we present an application of accrued delay as a metric in scheduling of arrivals and an analysis of the impact on delay allocation. We end the paper with concluding remarks and future work.

II. Accrued Delay Concept

The accrued delay concept is that the air traffic management system maintains a delay status of each flight continuously and uses it as it attempts to expedite each flight, recover the delay it has accrued to the extent possible, and maximize the throughput of the airspace network. This concept will enable the integration of time-based traffic management in a number of ways:

1. As flights are scheduled to use a constrained resource, such as a runway, they may incur delays multiple times at different horizons from that resource. For example, a ground delay may be followed by several airborne delays as the flight undergoes successive metering initiatives for the resource. Often the upstream delays are ignored when applying downstream delays. Maintaining a continuous flight delay status helps integrate the successive delay decisions and reduce the disproportionate delay application, for example, by prioritizing flights that have already incurred delay due to the same resource.

2. As flights progress from one constrained resource to another (e.g., from a weather-impacted airspace sector to a constrained runway), they may also incur multiple delays imposed by flow management initiatives of the different resources. While the resources are different, the delays are imposed by the same traffic management system and may be considered for integrated decision-making. Maintaining a continuous flight delay status helps integrate the delay decisions among separate resources, for example, by prioritizing flights that have already incurred delay due to an upstream resource.

3. Flights may also incur delays that are passed on from previous flight legs due to delayed equipment, crew or passenger connections. Some of these delays may be caused by the air traffic management system if the delays of the previous flight were incurred due to constrained airspace resources. Such delays are also candidate for integrated decision-making across flights over the airspace network. A continuous flight delay status that captures these network effects helps integrate decision-making across the network by, for example, prioritizing flights that have inherited delays from previous flights.

A delay may be incurred due to the air traffic management of constrained resources such as runways and airspace sectors or because of operator causes such as delayed passengers, piloting errors, or equipment issues. These causes may be handled differently by the air traffic management system, which may attempt to recover delays caused by the system but only optionally delays caused by operators. Therefore, one challenge is to differentiate between delay causes in the accrued delay metric. The system may also lower the priority of flights with negative delays or account only for positive delays.

Accrued delay can be applied in air traffic management decisions in a number of ways to enhance time-based operations. For example, flights may be prioritized based on their accrued delay to generate more proportionate delay allocation and reduce excessive delays and congestion that may result in further blockage of traffic. Accrued delay may be used in automated sequencing and scheduling algorithms. It may also be displayed optionally to air traffic service providers to give them insights as to which flights are in more need of their expediting decisions as they sequence traffic. In this way, using accrued delay enables air traffic service providers to proactively anticipate and respond to user preferences without the users explicitly requesting them.

III. Accrued Delay Estimation and Propagation

In order to achieve this concept, an accrued delay metric should be defined and estimated as a continuous variable and fed back into traffic management decisions. A flight may accrue delay during the flight or inherit delay from a previous flight through the turnaround. The following two subsections discuss methods for estimating these two types of accrued delay.

A. Accrued delay of a flight

Delay is measured as the actual travel time relative to an undelayed travel time. There are many choices for what may be considered undelayed travel time, which gives rise to several delay metrics, each with possible useful applications.

Delay may be measured relative to the fastest expected time of arrival, which can be estimated, for example, by the travel time along a shortest path and with the highest feasible ground speed. It can be useful for flights that need to minimize their time of arrival, such as emergency flights. The fastest time represents undelayed travel time; however, it is not a robust reference because only one or a few trajectories could achieve it, and it may be rendered infeasible with slight disturbances.

Delay is often measured relative to a nominal expected time of arrival, represented by a trajectory along a desired flight plan and using a desired speed profile. However, the nominal time is not a purely undelayed reference. Users do not usually share their trajectory profile preferences, represented by a cost index. Therefore, the air traffic management system has to approximate such trajectories with, for example, parameters published by aircraft manufacturers.

B. Accrued delay propagation across flights

A flight may start with a delay that was propagated from a previous flight or during the turnaround between flights. Airlines have reported that a significant component of their flight delays is due to the late arrival of a previous flight, constituting 39 percent of flight delay according to Aviation Service Quality Performance (ASQP) data, as shown in Fig. 1. Therefore, we postulate that significant benefits can be gained if accrued delay included this propagation effect, and the air traffic management system attempted to recover the delay that was passed on from previous flights.

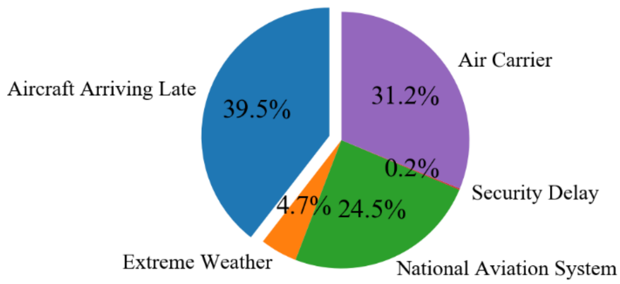

Figure 1. Percentage of total delayed minutes by airline-reported cause, May 2018 (ASQP).

This propagated delay may be approximated relative to the scheduled departure time. This reference can be used as a basis to help maintain schedule integrity in terms of flight connectivity and on-time performance. However, airlines often build some delay (padding) into their scheduled times in order to maintain desired on-time performance numbers despite anticipated delays. Therefore, airline schedule times are not representative of undelayed travel time, for maximizing throughput. In order to measure the delay that is propagated from one flight to another flight, the effect of padding should be removed.

As an example of the delay accrual across the turnaround at an airport, we studied the propagation of delay between successive flights conducted by the same aircraft. We analyzed one month of Aviation System Performance Metrics (ASPM) individual flight records (May 2018) and estimated accrued delay for flights turning around at several New York area airports. Using aircraft tail numbers reported in ASPM, we paired inbound flights that originated at any ASPM airport destined to one of these airports with outbound flights that originated at these airports destined to any ASPM destination airport. There are 77 airports covered by ASPM. We then estimated the accrued delay of these paired flights at the events for which actual arrival times are reported in ASPM. These events are the pushback (OUT), takeoff (OFF), landing (ON) and parking at the gate (IN) times. ASPM also reports scheduled departure and arrival times and unimpeded travel times between the events.

In order to measure the effect of airline padding on their schedule, we used two reference points for estimating the accrued delay at the ON and IN events: the airline schedule, which includes the built-in delay due to padding and the expected time had the flight traveled unimpeded from the origin airport, which does not include the effect of padding. At the ON event, the schedule reference is (scheduled IN time – unimpeded taxi-in time) and the unimpeded reference is (actual OFF time + unimpeded airborne time). The unimpeded airborne time is measured as the median actual airborne time for a given origin-destination pair and aircraft class (turboprop, regional, narrowbody, widebody), providing a conservative reference compared to using the ASPM-reported unimpeded times. Two measurements are then available at the IN event: (scheduled IN time) and (unimpeded ON time + unimpeded taxi-in time) for schedule and unimpeded references, respectively. Fig. 2 shows the resulting accrued delay curves for LaGuardia Airport (LGA), averaged over all flight pairs, highlighting the difference between the two measurements at ON and IN events.

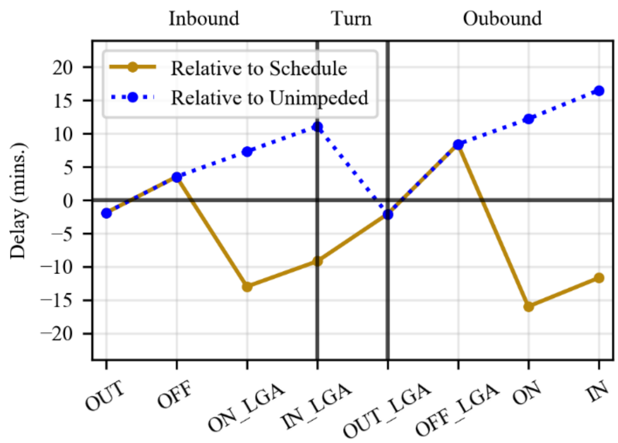

Figure 2. Median delay accrual for inbound-outbound pairs of LGA.

Fig. 2 shows how, when using the scheduled travel time as a reference, accrued delay increases on average during taxi-out while it decreases on average during the en-route segment. In contrast, when unimpeded time is used as a reference, accrued delay increases in both segments. This illustrates how airline padding of the schedule hides accrued delay en-route. This indicates the importance of using reference travel times that are closer to the undelayed travel time, when attempting to recover delay and increase system throughput. Fig. 3 compares the average padding as the difference between the two accrued delay measurements in Fig. 2, for five analyzed airports: LGA, J.F. Kennedy (JFK), EWR, MacArthur (ISP) and White Plains (HPN). More padding is observed at the first three major airports, which feature more scheduled operations with connections. Note that only scheduled operations were included.

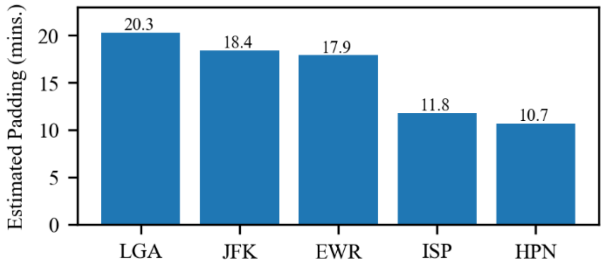

Figure 3. Estimated median padding for ASPM New York area airports.

In order to measure the propagation of delay from the first flight to the second flight in the pair conducted by the same aircraft, we used an estimate of the undelayed turnaround time between the two flights. We used the manufacturer reported expected turnaround time per aircraft type and size. We added the estimated unimpeded turnaround time to the actual IN time to estimate the first feasible OUT time. The positive difference between this time and the scheduled OUT time was considered to be propagated from the first flight. Table I shows various delay propagation statistics for LGA, JFK, and EWR. Reference [10] provides more details on this analysis.

TABLE I. DELAY PROPAGATION STATISTICS FOR LGA, JFK, EWR

Airport	LGA	JFK	EWR
Mean Turnaround Delay Propagation (mins.)	5.77	3.51	6.95
Percentage of Flights with Positive Turnaround Delay Propagation	12.5%	7.6%	14.3%
Mean Turnaround Delay Propagation for Delayed Outbounds (mins.)	46.36	46.17	48.55

IV. ACCRUED DELAY APPLICATION

In this and the next section, we demonstrate the application of accrued delay to a time-based metering situation. We evaluate how accrued delay can help allocate delay more evenly and even recover some accrued delay to improve system efficiency. We estimate accrued delay relative to the airline schedule before takeoff (ignoring the padding effect in the schedule) and then relative to unimpeded travel time after takeoff. In this section, we describe the scenario and the metering algorithm with accrued delay prioritization. In Section V we present simulation results from applying accrued delay in the scenario.

A. Time based metering scenario

Metering with accrued delay was simulated for an arrival push at EWR under reduced airport capacity. Time-based metering was applied as it is in current-day operations with a strategic ground delay program (GDP) followed by the tactical time-based flow management (TBFM) program (modified to account for accrued delay) as described below.

1) GDP and TBFM interaction

When an airport capacity is forecast to be constrained later in the day, a GDP is run to pre-condition the scheduled arrival demand to more closely meet the available Airport Arrival Rate (AAR). In a GDP, some flights (usually those originating closer to the airport) are assigned delayed departure times, called Expected Departure Clearance Times (EDCTs). Certain flights originating farther away are exempt from the GDP and keep their original scheduled departure time. Because of departure conformance errors (departing before or after the assigned EDCT), the exemption of some flights from the GDP, and changes in the airport capacity constraint, arrival demand may still exceed the AAR. Hence, additional delay is assigned by TBFM as flights cross the TBFM horizon closer to the airport [11]. TBFM schedules flights "first-come, first-served" based on their estimated times of arrival (ETAs), computed when they enter the TBFM system. Previous delays incurred, in the GDP or elsewhere, are ignored in the allocation of delay by TBFM. This often results in what are known as "double delays" to flights that have delay allocated by both the GDP and by TBFM. In our analysis, we account for the GDP accrued delay to help rectify the disparity in delay allocation by TBFM.

2) Distance-based versus time-based freeze horizons

Due to fluctuating ETAs and pop-up inbound flights, the TBFM scheduled time of arrival (STA) of each flight is continuously updated, up until the flight crosses a specified freeze horizon. At that point, the flight's STA is "frozen," and air traffic controllers assign speed reductions and path stretches to absorb delay to meet the STA. External departures (henceforth referred to as "externals") originate from airports outside the freeze horizon. They are assigned airborne delay and their STA is frozen as they fly across the freeze horizon. Internal departures (henceforth referred to as "internals") originate from airports inside the freeze horizon. They can be assigned ground delay by TBFM in addition to airborne delay. The ground delay is assumed to be assigned twenty minutes before departure time, consistent with [11] and [12]. At this time, the internals are added to the scheduling list, and their STAs are continuously updated by TBFM until takeoff, when they are frozen.

The TBFM freeze horizon is set at fixed distances from the airport (for externals) or at takeoff (for internals), motivated by easing controller workload. However, the distance-based freeze horizon is a source of inefficiency. The current locations of EWR's horizons are: 472 miles to the south, 406 miles to the west, and 360 miles to the north (dashed in Fig. 4). All else being equal, flights coming from the south therefore have an advantage since they are frozen earlier than flights coming from the west or north. Being frozen earlier generally means fewer inbounds are being scheduled by TBFM at that point in time, resulting in an earlier STA. Moreover, the distance-based horizons can cause a loss of throughput. Consider a situation where either a fast Flight B (with an earlier unfrozen STA) or a slow Flight C (with a later unfrozen STA) will be frozen behind Flight A. If the slow Flight C is frozen behind flight A, there may be more separation between Flight C and Flight A than required, resulting in throughput loss if the gap is not filled. This gap may not exist if the fast Flight B were frozen behind Flight A instead.

We explore a time-based freeze horizon (TBH) as an alternative to the distance-based horizon (DBH). With a TBH, externals are frozen once their STAs are within a certain time threshold from the current time. Because they may not be airborne when this threshold is met, internals are frozen at the later of their takeoff time and the time when their STA is within the threshold from the current time. Thus, internals that are very close-in to EWR will tend to be frozen at takeoff, while those farther from EWR are more likely to be frozen while airborne like an external. One feature of a TBH is that the direction from which a flight comes does not influence when it is frozen. In addition, the TBH attempts to reduce the frequency with which flights with later STAs are frozen before flights with earlier STAs. We investigate metering based on accrued delay with both a DBH and TBH. Fig. 4 compares the freeze location of flights into EWR using the existing DBH versus a TBH of 63 minutes, which is the mean timespan between when flights are frozen and their STAs when using distance-based horizons.

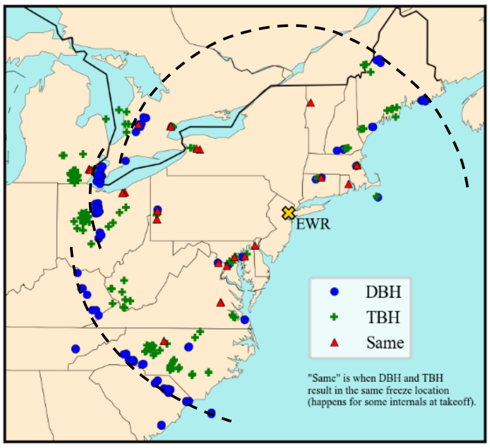

Figure 4. Freeze location of flights with distance and time-based horizons.

3) Scenario simulation

The traffic scenario simulated consists of 187 flights destined for EWR. 42 of these flights were airborne at the start of the simulation, with the schedule shape set to put pressure on the airport, as in [12]. Arrival operations were constrained to a single runway – 22L – with the AAR set to 44 aircraft per hour (11 aircraft per quarter-hour). To try to meet this rate, a GDP emulator generated EDCTs for flights that were not airborne at the start of the simulation. EDCTs were assigned to 56 of 66 internals and 62 of 121 externals. The sum of EDCT delay calculated was 2,697 minutes, with internals averaging 17 minutes and externals 13 minutes. The only source of uncertainty in the scenario is EDCT departure conformance errors, which were added according to empirical distributions from [12]. The mean error was almost zero and standard deviation 4.4 minutes. Flights were simulated using the Multi-Aircraft Control System (MACS) [13]. TBFM operations were then simulated using a TBFM emulator in post-processing, described in [11]. TBFM imposes an additional inter-arrival spacing of 0.4 nmi at the final approach fix to match the AAR, and 0.7 nmi at the meter fixes.

B. Metering with accrued delay algorithm

TBFM generates a scheduling list of inbound flights sorted based on runway threshold ETA, from earliest to latest. TBFM then goes down this list assigning STAs that satisfy the required inter-arrival spacing at the runway threshold and meter fixes. We augment this baseline TBFM algorithm by prioritizing flights based on their accrued delay values instead of the baseline TBFM order, which ignores any previously accrued delay. We do so without sacrificing throughput—potentially even increasing throughput relative to the baseline TBFM schedule without accrued delay.

The accrued delay of a flight may vary during the scenario. When a flight is on the ground, its accrued delay is its EDCT delay plus any applicable TBFM ground delay (for internals). After takeoff, the departure conformance error is added to the accrued delay. Since this scenario is deterministic except for this error, the accrued delay is not updated while airborne. When a flight's STA is frozen, its accrued delay is also updated by adding the assigned TBFM airborne delay. Note that for this scenario, updating accrued delay at other times is not needed because flights are assumed not to incur any delay except on the ground or after the STA is frozen. In a more dynamic setting, accrued delay updating may need to be applied more frequently.

Prioritization by accrued delay is applied when internals are scheduled (20 minutes before their departure time) and every time a flight is considered for freezing. At these instances, the baseline TBFM algorithm is run, generating STAs for all flights with unfrozen STA. We take this schedule generated by TBFM and attempt to decrease the total delay (accrued delay plus delay added by TBFM) and/or standard deviation across all flights by giving flights with higher accrued delay earlier feasible slots. The flight displaced by the flight with higher accrued delay shifts back one slot, and the flight it displaces shifts back one slot, and so on (but frozen flights keep their slots). In this way, we generate a candidate schedule that has flights in these new slots while still meeting all capacity constraints. The resulting total delay of this candidate schedule and its standard deviation are compared to those of the previous schedule. If at least one metric decreases while the other metric decreases or remains the same (e.g., standard deviation decreases, and total delay remains the same), the candidate schedule is kept. We test all feasible earlier slots for flights with accrued delay. After the flight with the highest accrued delay is allocated a slot, we move on to the flight with the next highest accrued delay and repeat the process, with the caveat that the previous flight with higher accrued delay cannot take a later slot. Once all of the flights with accrued delay are allocated slots, the flight of interest is frozen/rescheduled and its accrued delay is updated.

Table II steps through an example of using accrued delay when freezing a flight. In this example, Flight B is being frozen, while Flight C has already been frozen (using a distance-based freeze horizon). Assume that runway constraints make the earliest possible STA 7:02 and slots two minutes wide on average. Test Schedule 0 shows the schedule generated by the baseline TBFM, prioritizing by runway ETA. The total delay is 50 minutes, and the standard deviation is 7.40 minutes. Flight D has the highest accrued delay value so it is considered first for prioritization based on accrued delay. Flight D can be swapped with Flights A or B (Flight C has a frozen STA). These two options are compared in Test Schedule 1 and Test Schedule 2, respectively. Placing Flight D at 7:02 shifts Flights A and B to later STAs. As a result, total delay has decreased by one minute and its standard deviation has decreased by nearly 2.5 minutes. Total delay decreases by one minute because Flight A can trail Flight D by one minute, whereas Flight B had to trail Flight A by two minutes in the baseline schedule. This is because Flight

A and Flight B are arriving from the same meter fix, increasing required separation, whereas Flight A and Flight D are arriving from different meter fixes, reducing the required separation. On the other hand, placing Flight D at the second slot behind Flight A (Test Schedule 2) results in higher standard deviation across all flights. Therefore, we keep Test Schedule 1. Note that accrued delay for Flight B is not updated until it is frozen, but its total delay is.

TABLE II. EXAMPLE OF USING TBFM WITH ACCRUED DELAY

Test Schedule 0: Baseline					Test Schedule 1: Insert D before A				
ID	**ETA**	**Accrued Delay**	**STA**	**Total Delay**	**ID**	**ETA**	**Accrued Delay**	**STA**	**Total Delay**
A	7:00	0	7:02	2	D	7:02	15	7:02	15
B	7:01	0	7:04	3	A	7:00	0	7:03	3
C	7:02	4	7:06	8	C	7:02	4	7:06	8
D	7:02	15	7:08	21	B	7:01	0	7:08	7
E	7:04	10	7:10	16	E	7:04	10	7:10	16
Total Delay: **50** mins. Standard Deviation: **7.40** mins.					Total Delay: **49** mins. Standard Deviation: **4.96** mins.				

Test Schedule 2: Insert D before C					Test Schedule 3: Insert E before B				
ID	**ETA**	**Accrued Delay**	**STA**	**Total Delay**	**ID**	**ETA**	**Accrued Delay**	**STA**	**Total Delay**
A	7:00	0	7:02	2	D	7:02	15	7:02	15
D	7:02	15	7:03	16	A	7:00	0	7:03	3
C	7:02	4	7:06	8	C	7:02	4	7:06	8
B	7:01	0	7:08	7	E	7:04	10	7:08	14
E	7:04	10	7:10	16	B	7:01	0	7:10	9
Total Delay: **49** mins. Standard Deviation: **5.46** mins.					Total Delay: **49** mins. Standard Deviation: **4.35** mins.				

Thus, we are done reprioritizing Flight D. In Test Schedule 3, we prioritize Flight E, the flight with the next highest accrued delay, and shift it to Flight B's 7:08 slot. Total delay remains the same while standard deviation across all flights decreases by 0.6 minutes, so this candidate schedule is kept. Compared to the baseline schedule, total delay has decreased by 2% and standard deviation by 43%. Since there are no more flights with accrued delay to be reprioritized, the STA of Flight B is now frozen at 7:10 and its accrued delay updated. Note that Flight C was not able to move closer to Flight A because its STA was already frozen at 7:06. In addition, Flight D is not frozen yet, so it may not be able to maintain its slot due to future changes in ETA. If STAs were frozen based on a time-based horizon, earlier STAs in this example would be frozen before later STAs, potentially resulting in a more compressed schedule.

V. IMPACTS OF ACCRUED DELAY

In this section, we describe the impact of applying accrued delay in terms of total delay and its standard deviation. We start with a deterministic case without errors, before analyzing the impact with departure conformance errors. We then analyze the sensitivity of the impacts to the size of the freeze horizon and to how early internals are considered for scheduling.

A. Delay allocation in deterministic case

In this section we analyze the effect of applying accrued delay in a deterministic case without departure conformance error (i.e., flights take-off exactly at their scheduled departure times or EDCTs). We measured the TBFM-applied delay ("TBFM Delay"), which consists of airborne delay applied to externals and internals and ground delay applied to internals. The TBFM delay is added to the sum of EDCT delay (modeled as a constant in this scenario) to get the total delay. We also measured the standard deviation of the total delay across all flights to assess the impact of accrued delay application on the delay variability. Three different variations of TBFM were run: the baseline TBFM algorithm without accrued delay ("No AD"), TBFM with prioritization of airborne and non-airborne flights with accrued delay ("AD All"), and TBFM with prioritization of only airborne flights with accrued delay ("AD AB"). These variations were run with the baseline DBH and with a TBH set to 63 minutes. In addition, we include a maximum speed-up allowance—an amount of time that a flight is assumed to be able to land earlier than its nominal ETA—that varies from zero to three minutes. While flights can use this maximum speed-up allowance, not all do because of spacing requirements. We assume that these allowances are feasible through either speed change or path shortcuts and ignore the impacts of increasing fuel cost as a result. Subject-matter experts indicated that a one-minute speed-up is typically possible in existing operations.

Fig. 5 shows total delay, highlighting the TBFM delay component as the difference between total and EDCT delay, vs. maximum speed-up for the three variations of TBFM, with a DBH on the left and a TBH on the right. As maximum speed-up increases, TBFM delay decreases, because the speed-up allows flights to take earlier slots, reducing their delays. (Note that the TBFM delay here only measures the effect of delay imposed to balance demand with the capacity constraints, eliminating the time advance due to the speed up.)

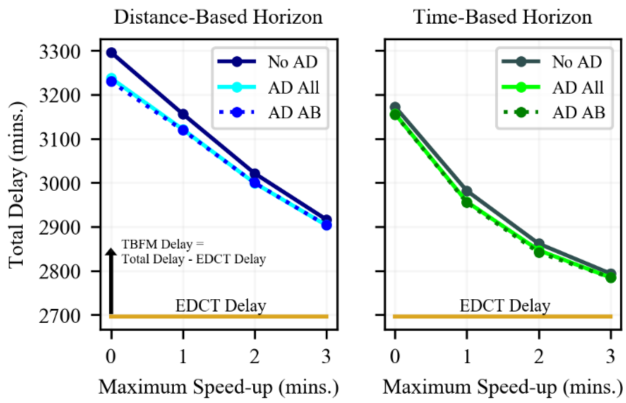

Figure 5. Total delay vs speed-up, without departure error.

In addition, even without accrued delay prioritization, the TBH results in at least 100 minutes less TBFM delay than the DBH across all speed-up values (amounting to about 25% decrease without speed-up to about 50% decrease with a three-minute speed-up). The TBH closes schedule gaps because the order in which flights are frozen more closely matches the STA ordering at the runway, increasing the compression of the schedule relative to the DBH. This can be indicated by counting how many inter-arrival separations are exactly the minimum separation stipulated by wake-vortex and other capacity constraints. A higher number of instances implies a more compressed schedule. When running TBFM without accrued delay and with zero speed-up, the DBH has 143 separations that are the minimum possible, compared to 172 such separations with the TBH. With DBH, applying accrued delay decreases the TBFM delay by around 60 minutes with no speed-up (about 10 percent). This indicates that freezing at prescribed distances from the airport leaves gaps in the schedule, some of which can be filled by prioritizing based on accrued delay. The reduction in TBFM delay by applying accrued delay decreases as speed-up increases until it almost disappears at a three-minute speed-up for the DBH. With such a large speed-up, accrued delay has little effect on the TBFM delay.

When paired with a TBH, prioritizing accrued delay has less effect on TBFM delay than when paired with the DBH, because TBH already effectively closes schedule gaps relative to DBH. There is, however, still some benefit to applying accrued delay with the TBH, particularly at one-minute and two-minute speed-ups. The shape of the curve for TBH is convex, suggesting that maximum speed-up has diminishing returns. For both the DBH and TBH, there is effectively no difference in the TBFM delay between applying accrued delay prioritization to airborne and non-airborne flights or applying it to just airborne flights.

Fig. 6 is arranged similarly to Fig. 5, but displays the standard deviation in delay across all flights instead of total delay. With a DBH, speed-up has little effect on standard deviation, but with a TBH, as speed-up increases, standard deviation gradually decreases. The TBH also shows less variation with speed-up than the DBH. Without accrued delay, the TBH has 2-3% lower standard deviation than the DBH, depending on what speed-up was used. However, when accrued delay prioritization is applied, the DBH performs similarly to the TBH. TBFM with accrued delay prioritization applied to all airborne and non-airborne flights lowers the standard deviation more than accrued delay applied to just airborne flights, even though both produced nearly identical TBFM delays.

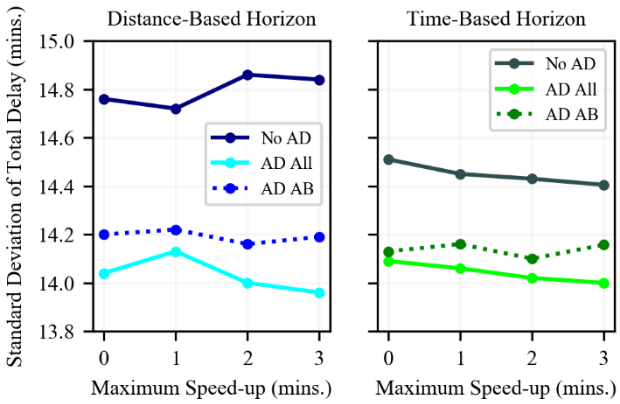

Figure 6. Delay standard deviation vs speed-up, without departure error.

Overall, the results suggest that the TBH performs better than the DBH in terms of reducing TBFM delay and standard deviation even when accrued delay prioritization is not applied. Applying accrued delay prioritization yields reductions in TBFM delay, particularly with DBH at lower speed-up values. The standard deviation of delay across all flights is reduced by applying accrued delay prioritization with both DBH and TBH, but more so when applying the accrued delay to all flights.

B. Delay allocation with departure conformance error

In this section we repeat the analysis in Section V-A except with departure conformance error. The same set of errors was used across all simulations. Fig. 7 shows the TBFM-applied delay and is the counterpart to Fig. 5. Like the deterministic case, TBFM delay decreases as speed-up increases and the TBH reduces TBFM delay. However, the TBFM delays are 30 to 170 minutes higher with the error than without. In addition, the error clearly caused an increase in the TBFM delay relative to the baseline in some of the cases with accrued delay prioritization. Namely, TBFM delay was higher when accrued delay prioritization was applied to all flights with either zero (for both DBH and TBH) or one-minute speed-up (for DBH).

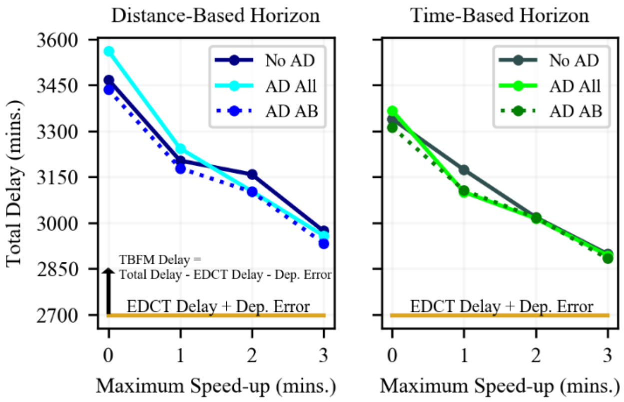

Figure 7. Total delay vs speed-up, with departure error.

TABLE III. IMPACT OF ACCRUED DELAY ON TBFM DELAY WITH AND WITHTOUT DEPARTURE ERROR

Maximum Speed-up (mins.)		0		1		2		3	
Horizon Type		DBH	TBH	DBH	TBH	DBH	TBH	DBH	TBH
No Dep. Error	No AD	600	476	462	282	331	170	226	94
	AD All	-9.8%	-3.4%	-6.7%	-8.7%	-7.7%	-12.3%	-6.1%	-10.7%
	AD AB	-11.1%	-3.6%	-7.3%	-7.7%	-7.2%	-10.1%	-5.9%	-9.8%
Dep. Error	No AD	770	641	516	467	462	38	262	183
	AD All	12.2%	4.2%	5.8%	-13.6%	-11.4%	-0.7%	-3.0%	-1.6%
	AD AB	-4.2%	-4.2%	-7.4%	-12.7%	-11.8%	-0.2%	-10.9%	-5.9%

These trends are detailed in Table III, which compares the TBFM delay across all simulations performed with and without departure conformance error. The "No AD" row contains the baseline TBFM delay values, while "AD All" and "AD AB" display the percent change relative to "No AD" for the maximum speed-up, horizon type, and error combinations. Without error, applying accrued delay prioritization caused a decrease in TBFM delay ranging between 3.4% and 12.3%. With the error, applying accrued delay prioritization to only airborne flights reduced TBFM delay between almost zero and 12.7%. In contrast, applying it to airborne and non-airborne flights ranged between increasing TBFM delay by 12.2% for zero speed-up with DBH and reducing it by 13.6% for two-minute speed-up with TBH.

The increase in TBFM delay with departure conformance error is because some airborne flights are unnecessarily frozen to a later STA than the baseline schedule—increasing airborne delay—to hold slots open for non-airborne flights. When these non-airborne flights depart late, they may not fill these slots and be given a later STA, also increasing airborne delay. TBFM does not predict departure errors. Applying accrued delay to only airborne flights reduces this effect and hence restores the advantage of applying accrued delay prioritization.

Fig. 8 and Table IV show the standard deviation of delay across all flights and they are the counterparts to Fig. 7 and Table IV, respectively. The simulations with departure conformance error have higher delay standard deviation than those without error. Applying accrued delay prioritization decreases the delay standard deviation; however, this decrease is less than found in the simulations without the error. Without error, applying accrued delay prioritization to all flights consistently resulted in lower standard deviation than applying it to airborne flights only. Table IV shows that the reduction ranged between 2.0% and 6.4%. With the error, the two accrued delay paradigms perform similarly for the DBH, but applying accrued delay prioritization to only airborne flights mostly has lower delay standard deviation than applying it to all flights for TBH (with the exception of three minutes of speed-up).

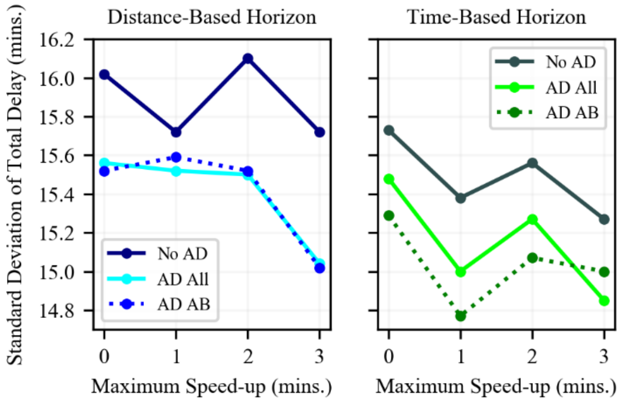

Figure 8. Delay standard deviation vs speed-up, with departure error.

TABLE IV. IMPACT OF ACCRUED DELAY ON STANDARD DEVIATION OF TOTAL DELAY WITH AND WITHOUT DEPARTURE ERROR

Maximum Speed-up (mins.)		0		1		2		3	
Horizon Type		DBH	TBH	DBH	TBH	DBH	TBH	DBH	TBH
No Dep. Error	No AD	14.76	14.51	14.73	14.47	14.94	14.44	14.91	14.42
	AD All	-4.9%	-2.9%	-4.1%	-2.8%	-6.3%	-2.9%	-6.4%	-2.8%
	AD AB	-3.8%	-2.6%	-3.5%	-2.2%	-5.5%	-2.4%	-5.0%	-2.0%
Dep. Error	No AD	16.02	15.73	15.69	15.38	16.14	15.54	15.72	15.31
	AD All	-2.9%	-1.6%	-1.2%	-2.5%	-3.9%	-1.6%	-4.2%	-2.9%
	AD AB	-3.1%	-2.8%	-0.8%	-4.2%	-3.8%	-2.9%	-4.4%	-2.0%

Overall, without departure conformance error, applying accrued delay to airborne and non-airborne flights is preferable given its larger reductions in delay standard deviation. With the error, applying accrued delay prioritization to only airborne flights seems to be preferable given that it consistently reduces TBFM delay, while applying accrued delay to airborne and non-airborne flights sometimes increases TBFM delay relative to baseline TBFM. More broadly, when prioritizing flights with accrued delay, the level of uncertainty associated with these flights should be accounted for. Prioritizing flights with high accrued delay appears to be more effective if these flights have low uncertainty and, thus, high probability of using earlier slots held for them. In this scenario, the main source of uncertainty is departure conformance error, but generally, capacity constraints or convective weather may be the root cause of uncertainty.

C. *Breakdown between airborne and ground delay*

Fig. 9 breaks down the TBFM delay (labeled "Airborne + Ground") into three categories: airborne external, airborne internal, and ground internal delay. Both the DBH and TBH are run with no speed-up and without departure conformance error. Fig. 10 shows the same breakdown for the case with the error. Both figures show that external flights benefit most from the TBH, accounting for the majority of the decrease in TBFM delay. Internals also benefit from the TBH in the deterministic case, mostly in terms of airborne delay reduction. With departure conformance errors, applying accrued delay prioritization to airborne and non-airborne flights increases TBFM delay for both the DBH and TBH; however, the increase is carried mostly by the externals airborne delay under the DBH while it is carried by the internals airborne delay under the TBH. This may be because internals are frozen at their takeoff time or later under the TBH, which limits their benefit relative to externals.

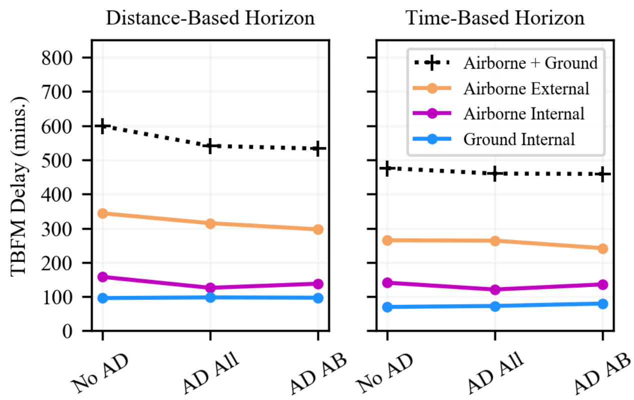

Figure 9. Breakdown of TBFM delay, without departure error.

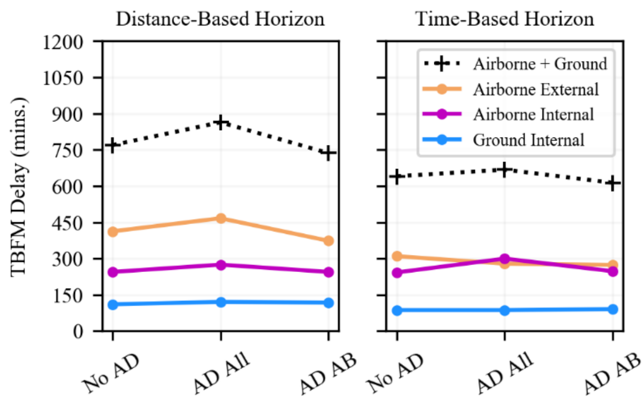

Figure 10. Breakdown of TBFM delay, with departure error.

D. *Sensitivity to time-based freeze horizon size*

In this section we analyze the sensitivity of the accrued delay impact in relation to the size of the TBH by varying it between 55 and 70 minutes. These are approximately the minimum and maximum times-to-STA when flights are frozen under the DBH.

Fig. 11 displays the results with and without departure conformance error on the same plot. The total delay is plotted against the time-based horizon for the three variations of TBFM. As flights are frozen earlier, the total delay increases, particularly when the horizon is set at seventy minutes. One cause of this is that when internals popup at 20 minutes prior to takeoff requesting time slots, there may be limited slots available since externals are frozen so early. Therefore, increasing the freeze horizon reduces the number of slots available for internals. Freezing earlier can be advantageous for the flight being frozen, since it is competing with fewer flights for slots. However, it reduces flexibility for accommodating uncertainty.

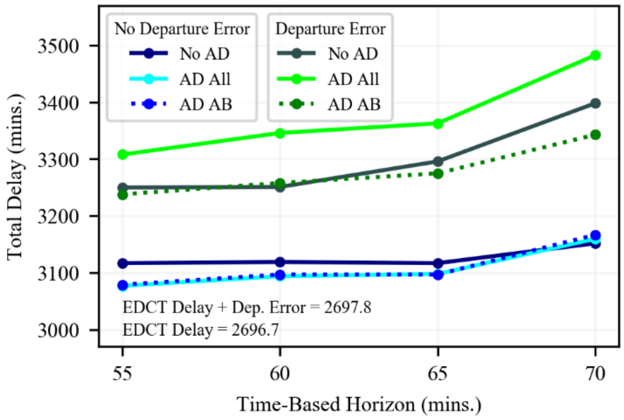

Figure 11. Total delay vs time-based horizon.

Fig. 12 shows the trend in the standard deviation of delay across all flights, across all TBH simulations. Similar to the total delay, the delay standard deviation increases sharply as the freeze horizon increases, particularly at 65-minute TBH with departure conformance error. Clearly, reducing the freeze horizon size is beneficial from a delay and variability perspective because of the added flexibility. However, operationally this also has challenges, as a smaller freeze horizon means that controllers have less time and space for flights to absorb the required delay. Automation will reduce the need for air traffic controllers to absorb delays, thus enabling time-based freeze horizons at smaller values.

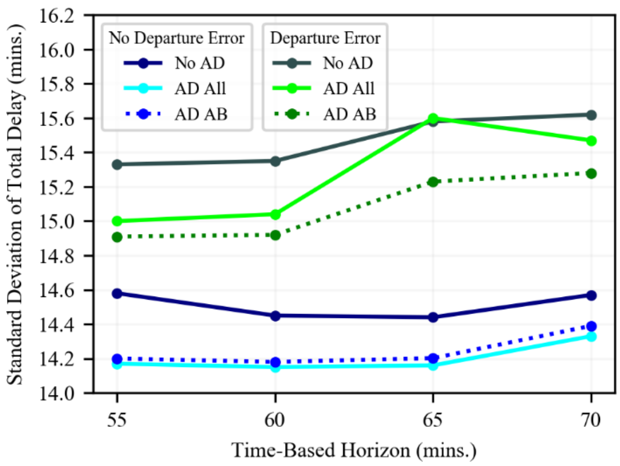

Figure 12. Standard deviation of total delay vs. time-based horizon.

E. Sensitivity to internals planning horizon size

Twenty minutes before scheduled departure (or EDCT if applicable), internals are rescheduled and receive a TBFM ground delay if necessary. From this point on, they are included in the TBFM schedule. However, they are not frozen until takeoff with a DBH or potentially at a later time with a TBH. When they are frozen, internals may be assigned airborne delay because the slot tentatively allocated to them has been taken. Although a TBH attempts to eliminate this disparity in freeze horizon, internals are still disadvantaged because they are not included by the TBFM scheduler until they are rescheduled. In order to provide more scheduling opportunities to the internal departures, we analyzed the sensitivity to the size of the lookahead planning horizon for the internal departures.

Fig. 13 compares the three variations of TBFM when using a TBH and with 20, 35, 50, and 65-minute lookahead for the internal departures. Total delay is plotted against lookahead time for the two cases: with and without departure conformance error. The general trend is that the total delay decreases as the internal departures are considered for scheduling earlier. This trend is true with and without the error, although it is more pronounced in the deterministic case without the error.

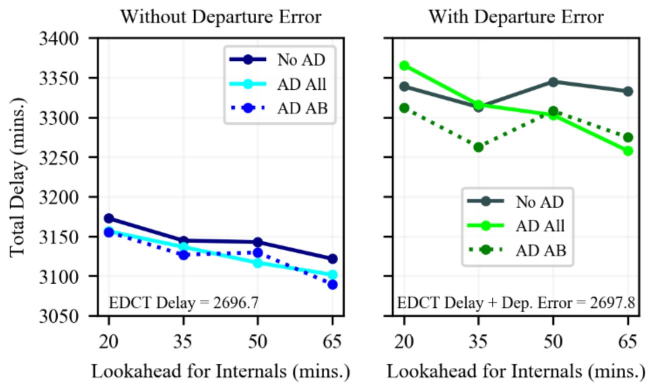

Figure 13. Total delay vs. lookahead for internals.

One reason for the reduced delays is that increasing the lookahead time gives the internal departures more opportunity to be scheduled among flights that are still unfrozen. This means that they get an earlier slot during rescheduling and thus have a lower ground delay. Indeed, close examination indicated that the ground delay component of the internals decreased when they were considered earlier for scheduling. On the other hand, externals may have to incur more airborne delay to hold slots open for non-airborne internals. Such slots are less likely to be filled by the internals when there is departure conformance error. This may explain the reduction in the trend of reduced delay with increased lookahead when the error is included.

One observation in the case with departure conformance error is that applying accrued delay prioritization to all flights switched from being worse than the baseline at 20 minute lookahead to being better than the baseline at lookahead times higher than 35 minutes. Therefore, considering the internal departures earlier helped mitigate the effect of the uncertainty due to the error. However, with a large lookahead, uncertainty increases as the internal departure aircraft may still be at the gate or may not be at the airport because it is operating a previous flight leg. The schedule of the flight may be used as a reference to calculate its accrued delay for the sake of reprioritization as was done in this analysis. However, the techniques described in Section III could be used to predict the delay propagation from the previous flight conducted by the aircraft and hence to more accurately calculate the accrued delay of the internal departure based on delays already incurred by the previous flight leg.

Fig. 14 shows the standard deviation of the delay across all flights for the same scenarios as Fig. 13. As the internals lookahead increases from 20 to 65 minutes, the delay standard deviation decreases, particularly in the case with error. This indicates the significance of the earlier lookahead in reducing the uncertainty about the internals. In the deterministic case the effect is less pronounced as earlier lookahead does not reduce any uncertainty. Applying accrued delay prioritization improves the delay standard deviation over the baseline for all cases.

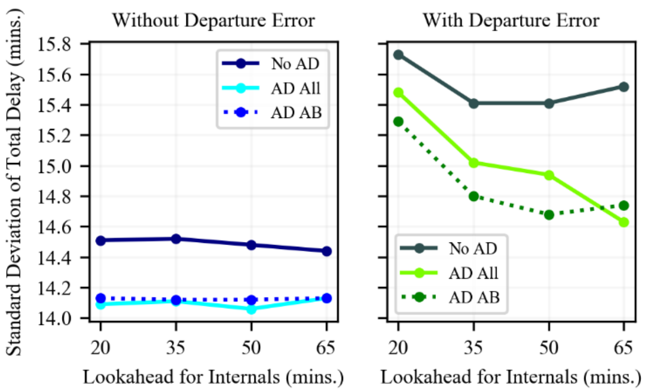

Figure 14. Standard deviation of total delay vs. lookahead for internals.

VI. Conclusions and Future Work

We introduced an accrued delay concept whereby the air traffic management system maintains a delay status of each flight continuously and uses it to recover the delay to the extent possible without sacrificing the system throughput. We showed through a time-based metering and scheduling example that by prioritizing flights that have already accrued high delay because of a constrained runway resource, significant gains can be achieved in terms of reducing total delay and its variance. We studied the sensitivity of these gains to a number of factors and observed that prioritizing by accrued delay: (1) reduced total delay in a similar fashion to using a time-based freeze horizon instead of a distance-based freeze horizon for scheduling, (2) reduced delay variance resulting in more balanced airspace access, and (3) was more effective when applied to more predictable traffic with higher probability to meet their assigned slots. Future work includes assessing the impacts of applying accrued delay and time-based horizons on human control and the role of automation and autonomy in enabling them; generalizing the insights to more operations and conditions; and improving the estimation of accrued delay based on delay propagation across the turnaround process, which involves prediction of operator behaviors by the air traffic management system.

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