Accrued Delay Application in Trajectory-Based Operations

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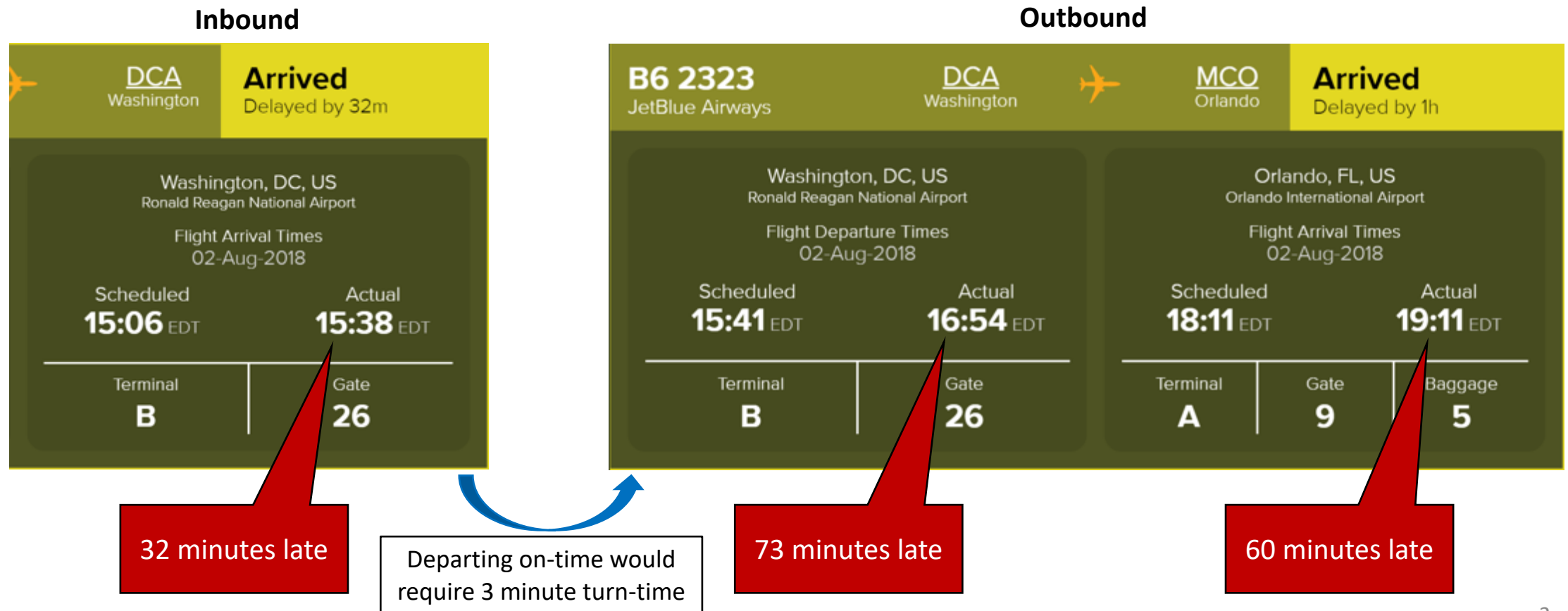13th USA/Europe Air Traffic Management R&D Seminar

Vienna, Austria

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Motivation: Network Delay Accrual

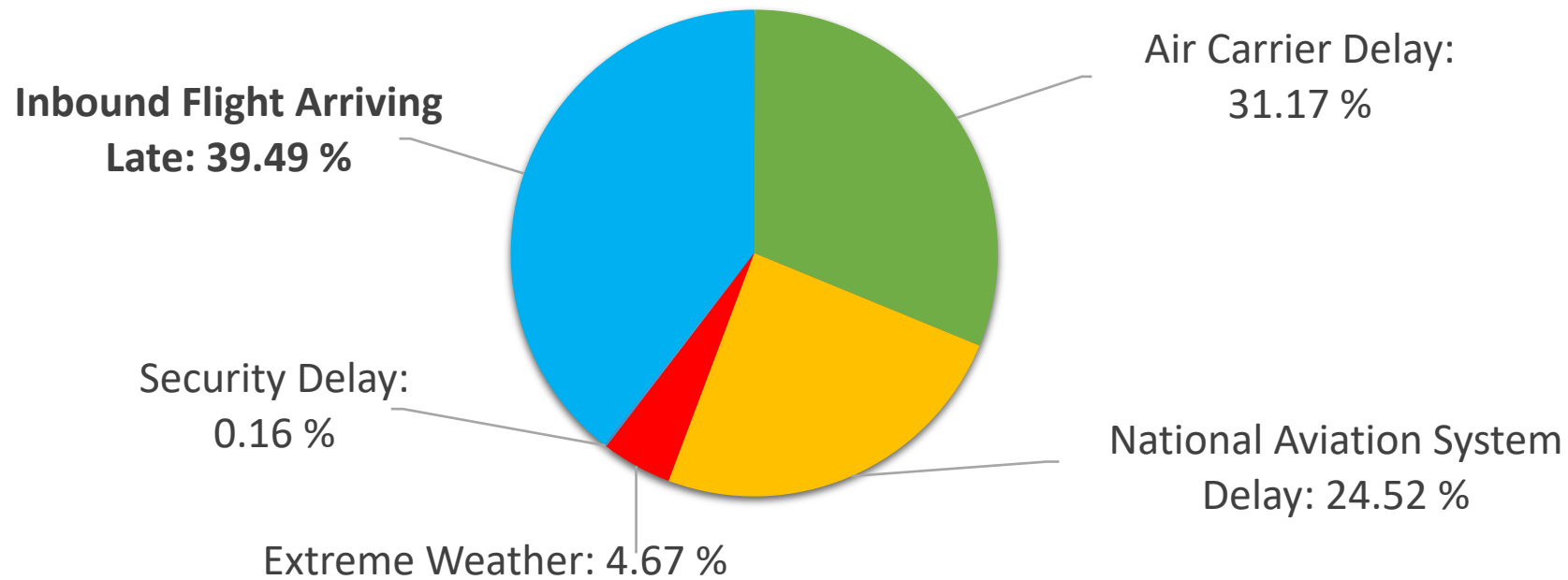## Example of delay propagated from inbound to outbound

Inbound

Outbound

32 minutes late

Departing on-time would require 3 minute turn-time

73 minutes late

60 minutes late

Source: flightstats.com

Motivation: Network Delay Accrual

Late arriving aircraft from inbound flight are major source of delay

Delay Cause as % of Total Delay Minutes

Inbound Flight Arriving Late: 39.49 %

Air Carrier Delay: 31.17 %

Security Delay: 0.16 %

Extreme Weather: 4.67 %

National Aviation System Delay: 24.52 %

Source: Airline Service Quality Performance (ASQP), May 2017- May 2018

Motivation: Multiple-Restriction Delay Accrual

Delay programs are often not integrated, leading to multiple delays imposed on the same flight

Capacity at EWR is limited, so a *ground delay program* assigns an Expect Departure Clearance Time (EDCT) to certain flights
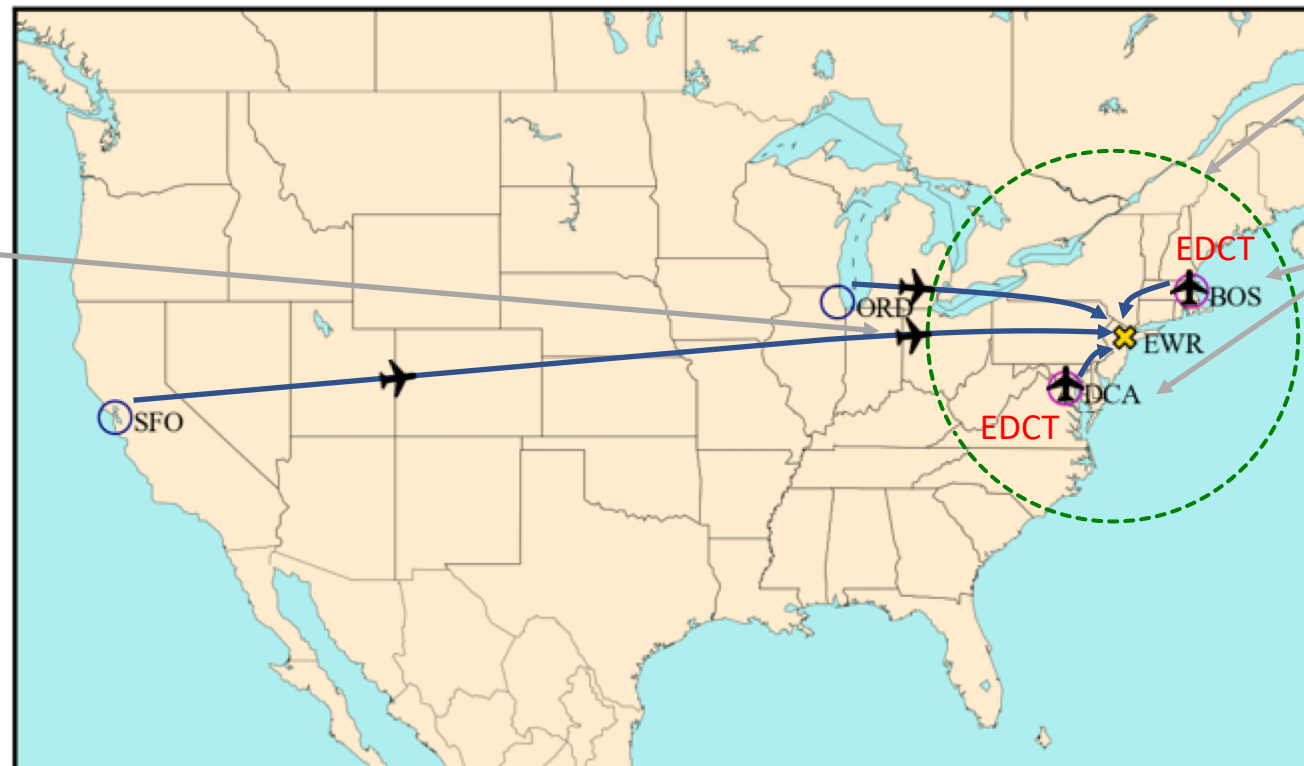

SFO = San Francisco International
ORD = Chicago O'Hare International
BOS = Boston Logan International
DCA = DC Reagan National
EWR = Newark International

Motivation: Multiple-Restriction Delay Accrual

Delay programs are often not integrated, leading to multiple delays imposed on the same flight

As flights get closer to EWR, *time-based flow management (TBFM)* assigns additional airborne delay for metering and delay is frozen inside freeze horizon

TBFM Freeze horizon

~20 minutes before scheduled departure, TBFM assigns additional *ground* delay to flights originating inside freeze horizon (internals)

At takeoff, internals are assigned additional *airborne* delay and their delays are frozen

SFO = San Francisco International
ORD = Chicago O'Hare International
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DCA = DC Reagan National
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Outline

- **Accrued delay concept**
- Estimation of accrued delay and its propagation across turnaround
  - Accounting for airline schedule padding
  - Propagation across turnaround
- Example application of accrued delay to integrating multiple restrictions during flight
  - Arrival scheduling scenario
  - Simulation methodology
  - Results and sensitivity analysis
- Conclusions and future work

Accrued Delay Concept

Accrued delay is a continuous measurement of delay

- As it propagates from previous flight legs due to aircraft, crew, or passenger connectivity

- As it accumulates throughout progress of flight

  - Strategic then tactical delay due to *same* resource (e.g. ground delay program then time-based flow management for same airport)

  - Multiple delays due to *different* resources (e.g. weather-impacted sector then constrained runway)

Accrued Delay Concept

- Air traffic management maintains accrued delay status of each flight continuously and feeds it back in decision making

- Flights with high accrued delay can be prioritized in scheduling and sequencing decisions by automation, service providers, or users

- Causes of delay may be identified – e.g., system-caused delays may be managed differently than carrier-caused delays

Accrued Delay Concept

- Delay is actual travel time relative to reference travel time

- Some options for reference times include:

  - *Fastest*: e.g. travel along shortest path at highest feasible speed

  - *Schedule*: based on airline published scheduled times - airline schedules include padding by airlines to mitigate uncertainties and improve on-time performance

  - *Unimpeded*: estimated based on undelayed travel times

Literature on Delay Accrual

- Accrued delay relative to schedule discussed as possible way to prioritize flights in ground delay program (Hoffman et al., 2005)

- Delay banking system assigns airlines numerical credit for incurred delays – credit can be used to get higher priority in later constraints (Green, 2007)

- Several papers explored interaction/integration between delay programs (Evans and Lee, 2016; Dwyer et al., 2011; Rebollo and Brinton, 2015)

- Other papers analyzed propagation of delay across airports (Churchill et al., 2010; Idris, 2015; Campanelli et al., 2014)

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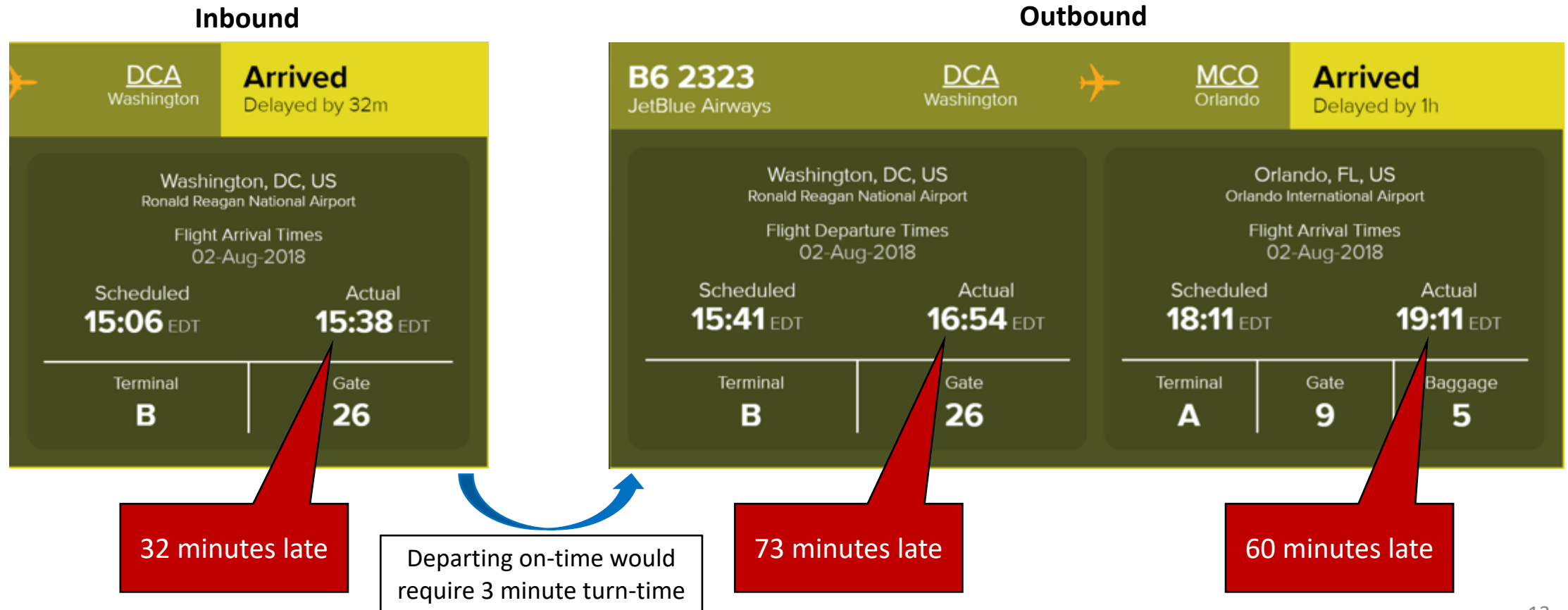
Objectives of Accrued Delay Estimation

Estimate accrued delay during flight and account for airline schedule padding, which can hide accrued delay

32 minutes late

11 minutes early

Source: flightstats.com
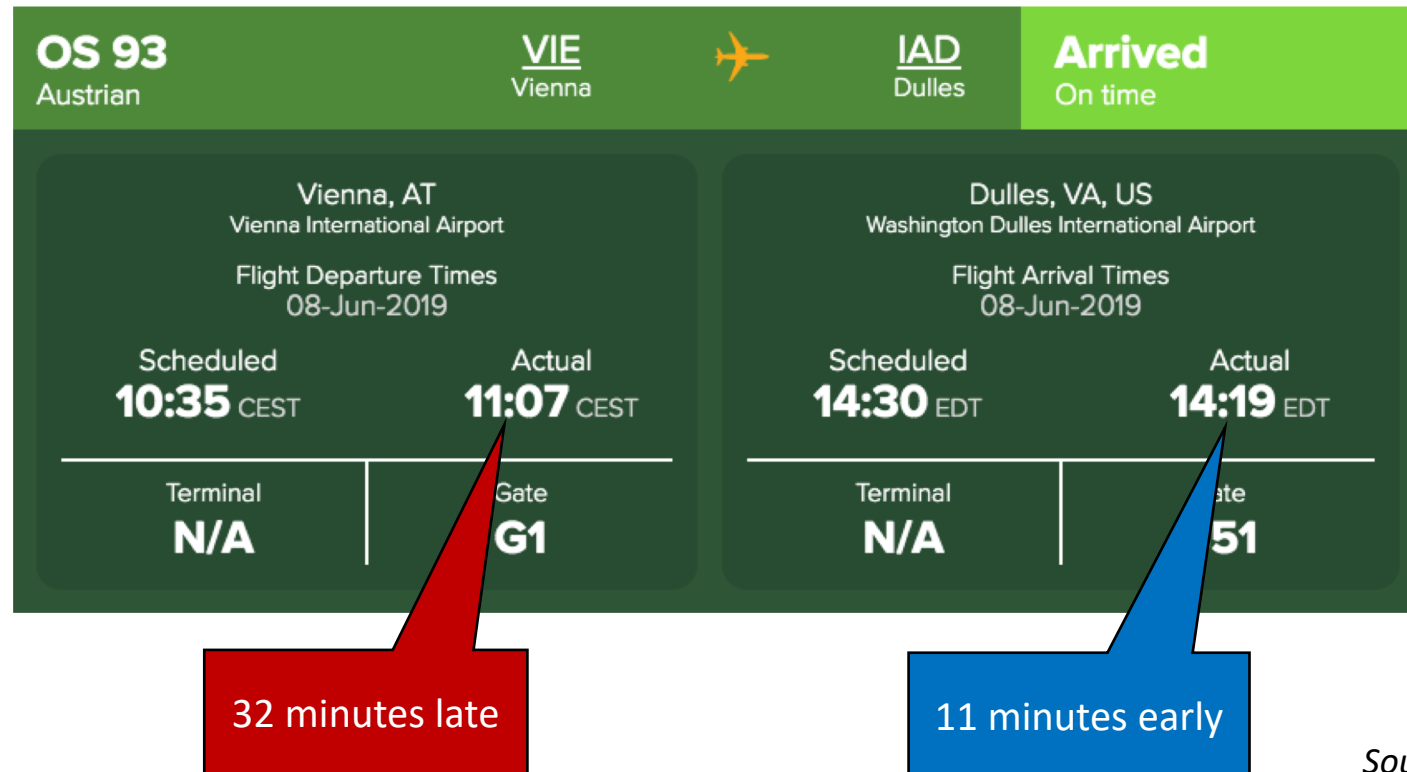
Objectives of Accrued Delay Estimation

Estimate how much of outbound delay is propagated from inbound

Inbound

Outbound

32 minutes late

Departing on-time would require 3 minute turn-time

73 minutes late

60 minutes late

Source: flightstats.com

Methodology of Estimating Accrued Delay

- Calculated accrued delay from actual and scheduled times at key events reported in FAA Aviation Systems Performance Metrics (ASPM)

- Used tail numbers (i.e. aircraft registrations) reported in ASPM to match *inbound* and *outbound* flights operated by the same aircraft

- Analyzed one month of ASPM data at 5 NYC airports
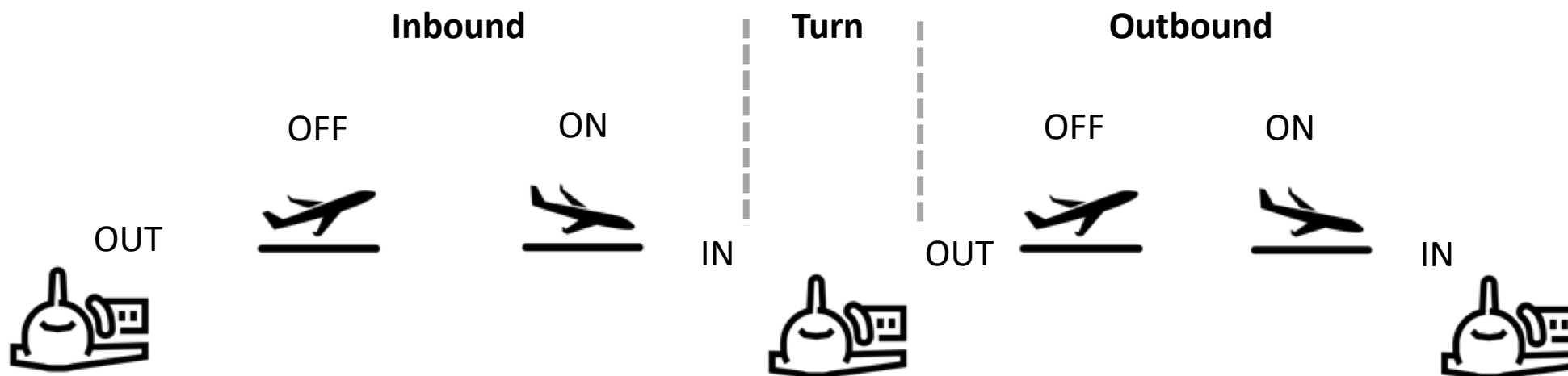
Calculation of Accrued Delay

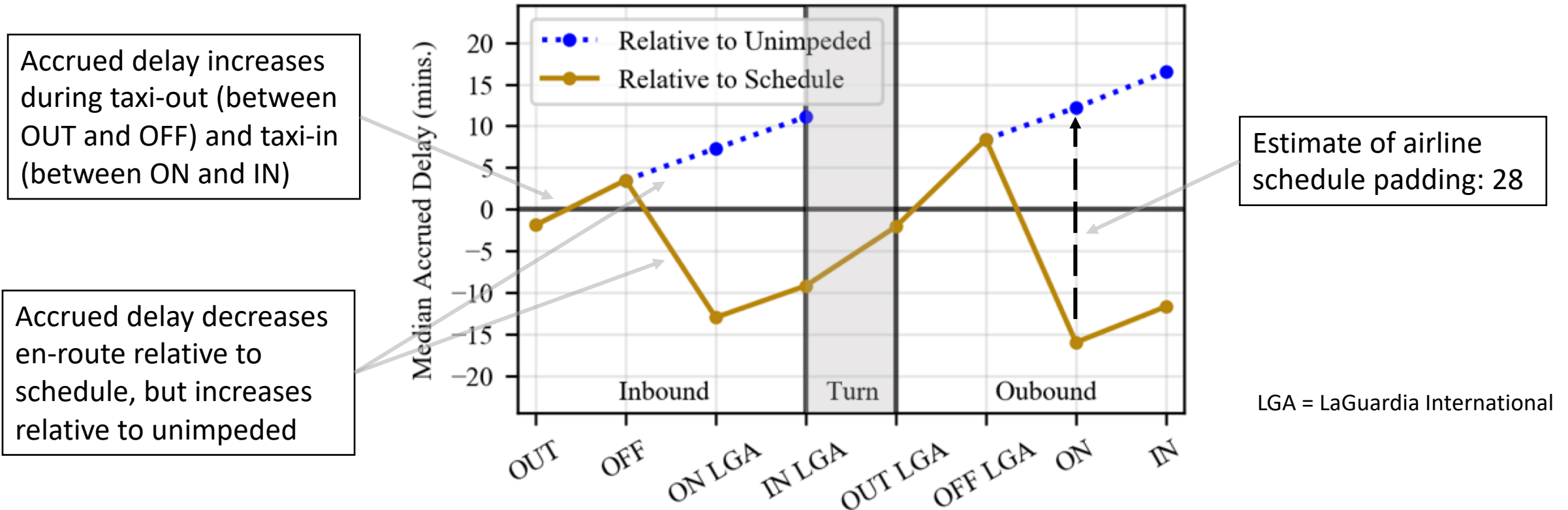(Accrued delay) = (Actual Time) − (Reference Time)

- Used two reference times: schedule (provided by ASPM) and unimpeded (based on ASPM) to isolate padding effect

- Estimated unimpeded times at ON and IN events
  - (Unimpeded ON) = (Actual OFF) + (Median Actual Airborne Time for origin-destination pair and aircraft class)
  - (Unimpeded IN) = (Unimpeded ON) + (Unimpeded Taxi−in Time)
  - (Airline Schedule Padding) = (Scheduled IN) − (Unimpeded IN)

OFF   ON

OUT

IN
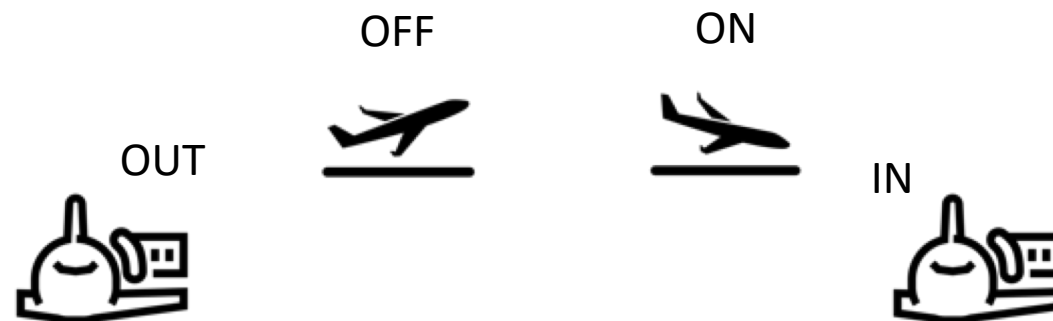
Example of Accrued Delay Propagation at LGA

Airline schedule padding hides accrual of delay relative to unimpeded – some of this delay may propagate to next flight flown by same aircraft

Accrued delay increases during taxi-out (between OUT and OFF) and taxi-in (between ON and IN)

Accrued delay decreases en-route relative to schedule, but increases relative to unimpeded

Estimate of airline schedule padding: 28

LGA = LaGuardia International

Comparison of Airline Schedule Padding

- (Airline schedule padding) = (Scheduled IN) – (Unimpeded IN)
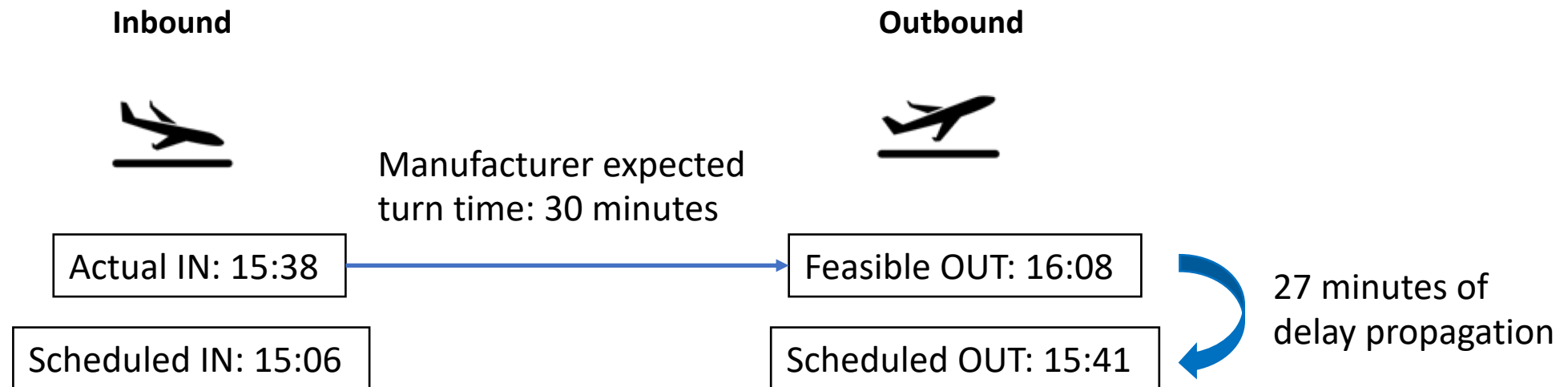- Estimated airline schedule padding is higher at busier airports
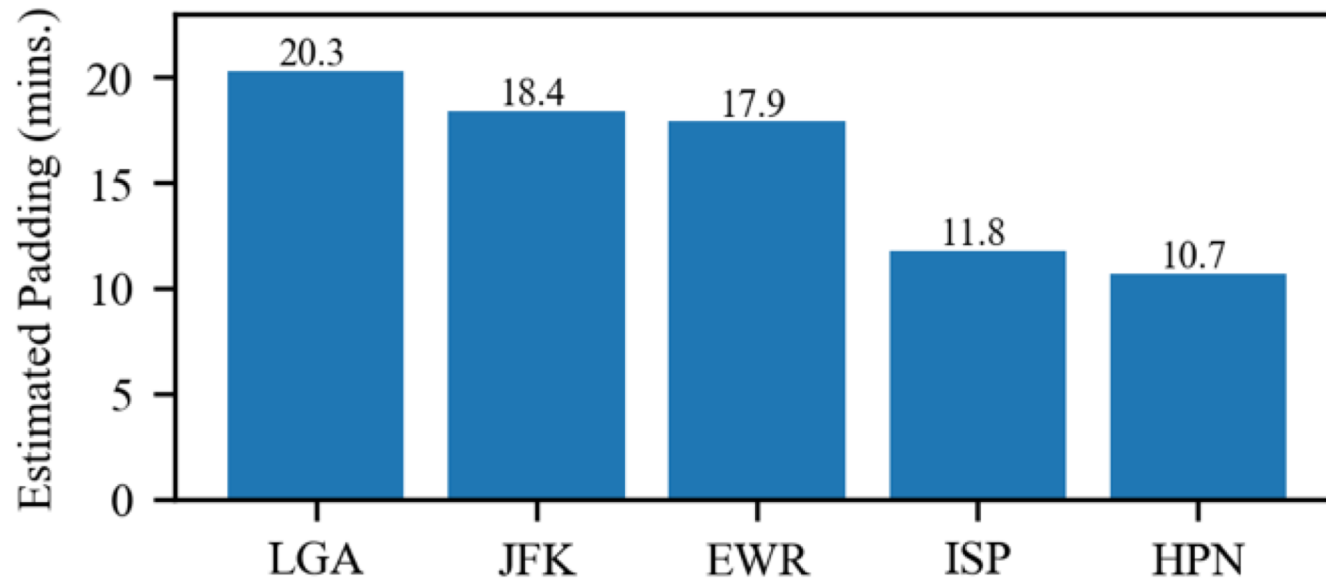
LGA = LaGuardia International
JFK = John F. Kennedy International
EWR = Newark International
ISP = Long Island MacArthur
HPN = Westchester County

Methodology of Estimating Delay Propagation

- Some delay propagates from inbound flight to outbound flight during turnaround process

- One method to estimate propagated delay:

Inbound

Outbound

Manufacturer expected
turn time: 30 minutes

Actual IN: 15:38

Feasible OUT: 16:08

27 minutes of
delay propagation

Scheduled IN: 15:06

Scheduled OUT: 15:41

Delay Propagation Statistics

Considerable delay propagates from inbound to outbound flights though aircraft turnaround

- More than 45 minutes for delayed outbound flights at New York major airports
- About 20 of these 45 minutes may be masked by airline schedule padding

Airport	LGA	JFK	EWR
Mean (Propagated Delay across Turnaround) for All Flights (mins.)	5.77	3.51	6.95
Mean (Propagated Delay across Turnaround) for Delayed Outbound Flights (mins.)	46.36	46.17	48.55

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- **Example application of accrued delay to integrating multiple restrictions during flight**
  - Arrival scheduling scenario
  - Simulation methodology
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Multiple Restrictions Scenario

Capacity at EWR is limited, so a *ground delay program* assigns an Expect Departure Clearance Time (EDCT) to certain flights

Flights originating from far away are often not assigned EDCTs and can depart as scheduled

Flights originating closer to EWR are often assigned EDCTs

SFO = San Francisco International
ORD = Chicago O'Hare International
BOS = Boston Logan International
DCA = DC Reagan National
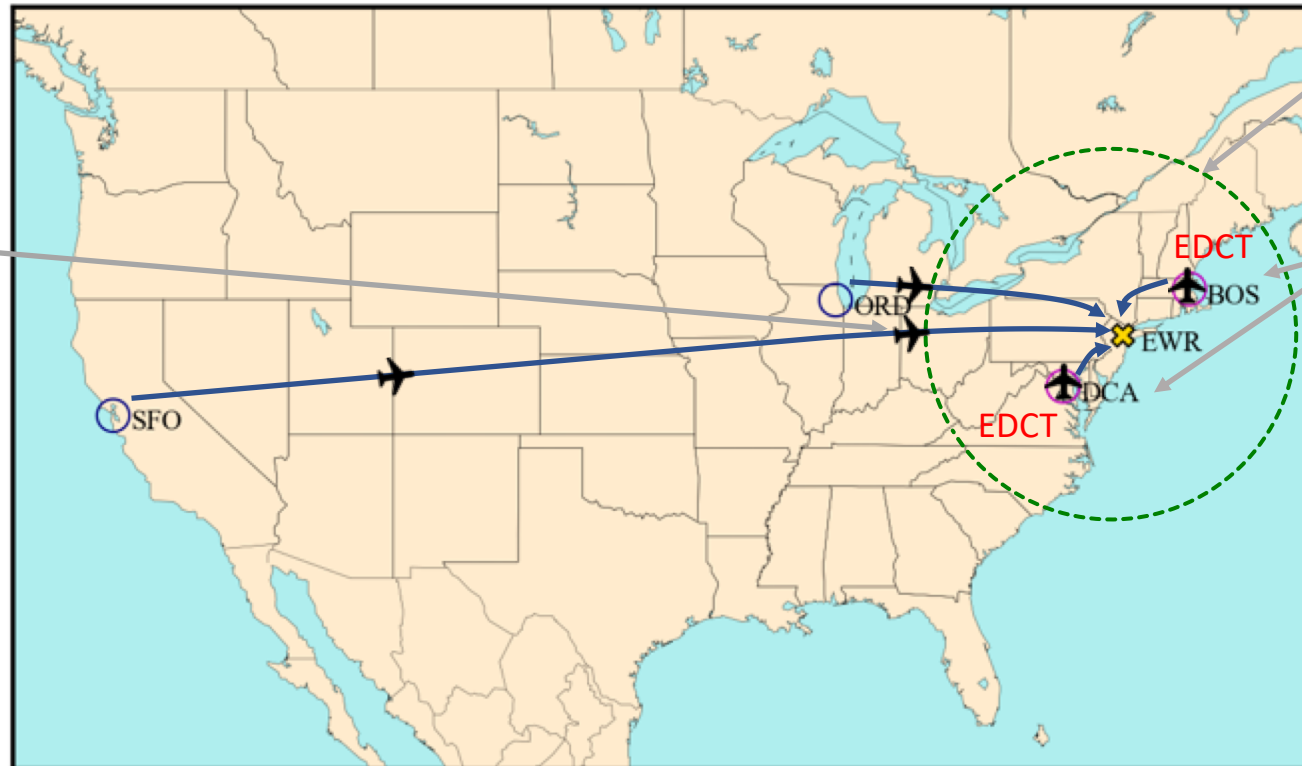EWR = Newark International

Multiple Restrictions Scenario

As flights get closer to EWR, *time-based flow management (TBFM)* assigns additional airborne/ground delay as needed

At freeze horizon, TBFM assigns additional *airborne* delay to flights originating outside freeze horizon (externals), and their scheduled times of arrival (STAs) are frozen

TBFM Freeze horizon

~20 minutes before scheduled departure, TBFM assigns additional *ground* delay to flights originating inside freeze horizon (internals)

At takeoff, internals are assigned additional *airborne* delay and their STAs are frozen

SFO = San Francisco International
ORD = Chicago O'Hare International
BOS = Boston Logan International
DCA = DC Reagan National
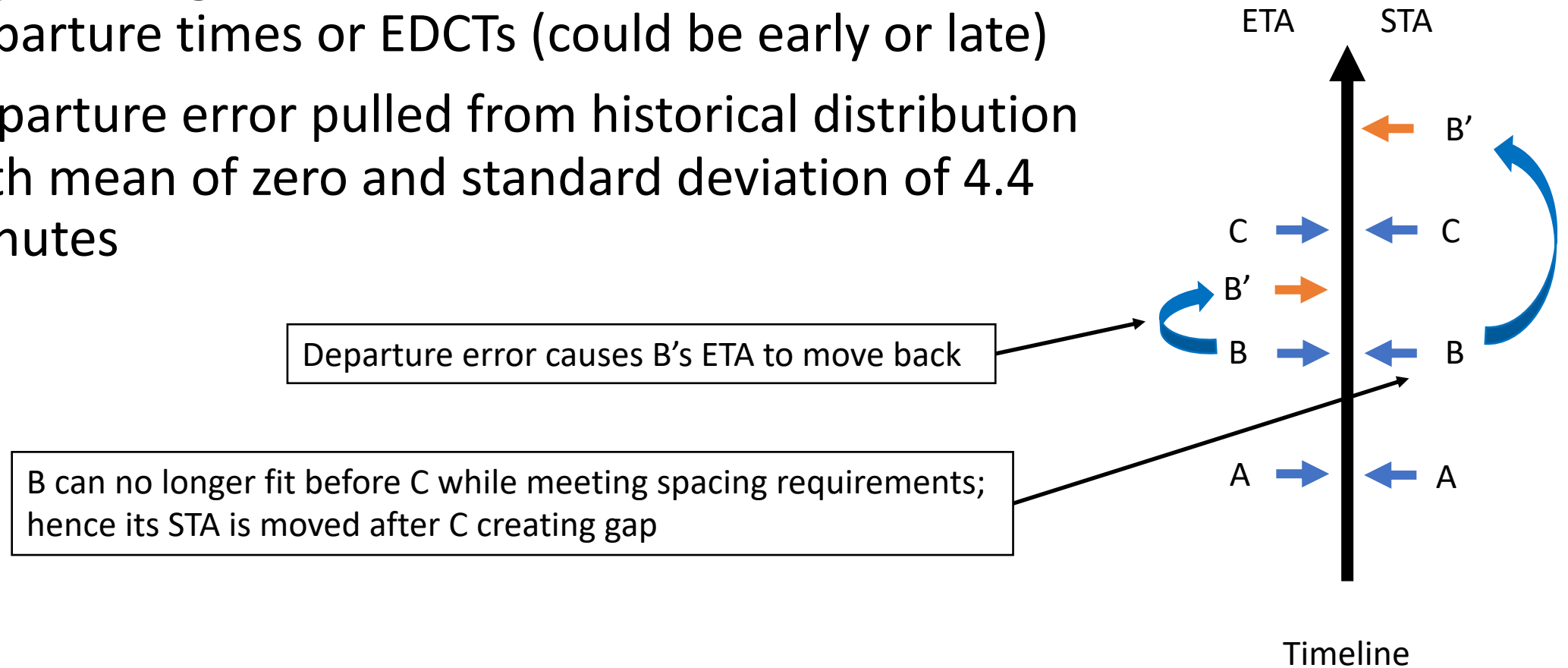EWR = Newark International
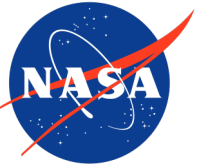
Simulation Methodology: Scenario

- EWR Airport Arrival Rate limited to 44 aircraft/hour

- 187 flights arriving into EWR over 4.5 hours of simulation time

- 118 flights assigned EDCT by ground delay program

Simulation Methodology: Departure Error

- Flights not guaranteed to meet their scheduled departure times or EDCTs (could be early or late)

- Departure error pulled from historical distribution with mean of zero and standard deviation of 4.4 minutes

Departure error causes B's ETA to move back

B can no longer fit before C while meeting spacing requirements; hence its STA is moved after C creating gap

ETA   STA

B'

C   C

B'

B   B

A   A

Timeline

Simulation Methodology: Measuring Accrued Delay

- (Accrued delay of externals) = (EDCT delay) + (departure error)

- (Accrued delay of internals) = (EDCT delay) + (departure error) +

$$(\text{TBFM ground delay})$$

Modified TBFM Algorithm with Accrued Delay Prioritization

- Prioritize by accrued delay only if TBFM performance is improved

- At every flight scheduling decision:

  1. Run baseline TBFM algorithm without accrued delay prioritization and compute total delay and its standard deviation

  2. Move flights with high accrued delay to earlier time slots only if total delay and its standard deviation do not increase and either decreases

Example of Modified TBFM Algorithm

Start with baseline schedule generated by TBFM where flights are prioritized by ETA

Test Schedule 0: Baseline					
ID	ETA	STA	TBFM Delay	Accrued Delay	Total Delay
A	7:00	7:02	2	0	2
B	7:01	7:04	3	0	3
C	7:02	7:06	4	4	8
D	7:02	7:08	6	15	21
E	7:04	7:10	6	10	16
Total Delay: **50** mins. Standard Deviation: **7.40** mins. (over currently scheduled flights)					

STA order follows First-Come-First-Serve by ETA

Flight C is already frozen, so its STA cannot be changed

Example of Modified TBFM Algorithm

Test earlier feasible slots for D (flight with highest accrued delay)

Test Schedule 0: Baseline					
ID	ETA	STA	TBFM Delay	Accrued Delay	Total Delay
A	7:00	7:02	2	0	2
B	7:01	7:04	3	0	3
C	7:02	7:06	4	4	8
D	7:02	7:08	6	15	21
E	7:04	7:10	6	10	16
Total Delay: **50** mins. Standard Deviation: **7.40** mins. (over currently scheduled flights)					

Test Schedule 1: Insert D before A					
ID	ETA	STA	TBFM Delay	Accrued Delay	Total Delay
D	7:02	7:02	0	15	15
A	7:00	7:03	3	0	3
C	7:02	7:06	4	4	8
B	7:01	7:08	7	0	7
E	7:04	7:10	6	10	16
Total Delay: **49** mins. Standard Deviation: **4.96** mins. (over currently scheduled flights)					

Both metrics improve, so keep this change

Example of Modified TBFM Algorithm

Test earlier feasible slots for E (flight with next highest accrued delay)

Test Schedule 1: Insert D before A					
ID	ETA	STA	TBFM Delay	Accrued Delay	Total Delay
D	7:02	7:02	0	15	15
A	7:00	7:03	3	0	3
C	7:02	7:06	4	4	8
B	7:01	7:08	7	0	7
E	7:04	7:10	6	10	16
Total Delay: **49** mins. Standard Deviation: **4.96** mins. (over currently scheduled flights)					

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

Delay remains same, but standard deviation decreases, so keep this change
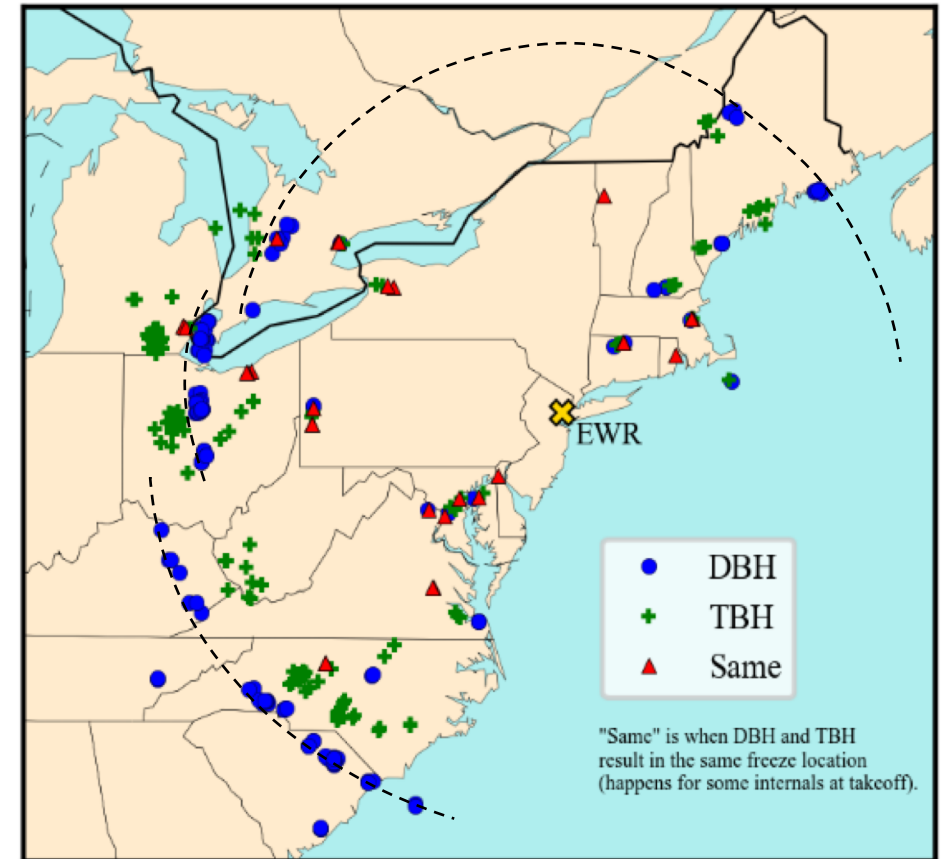
Sensitivity Analysis

- With and without departure error
- Accrued delay prioritization applied to all flights or only airborne flights
  - Airborne flights less susceptible to departure error since departure error (if any) has already occurred
- Speed-up to arrive slightly earlier – this could help close schedule gaps
  - Subject matter experts say currently 1 minute speed-up is used
  - Tested 1-3 minute speed-up (no assessment of feasibility of speed-up)
- Distance-based freeze horizon vs time-based horizon (explained next slide)
- Time-based freeze horizon size
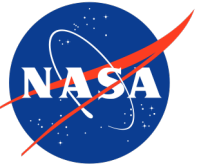- Internal departure lookahead time: modified how early internals were added to scheduling list

Simulation Methodology: Distance-based vs. Time-based Freeze Horizon
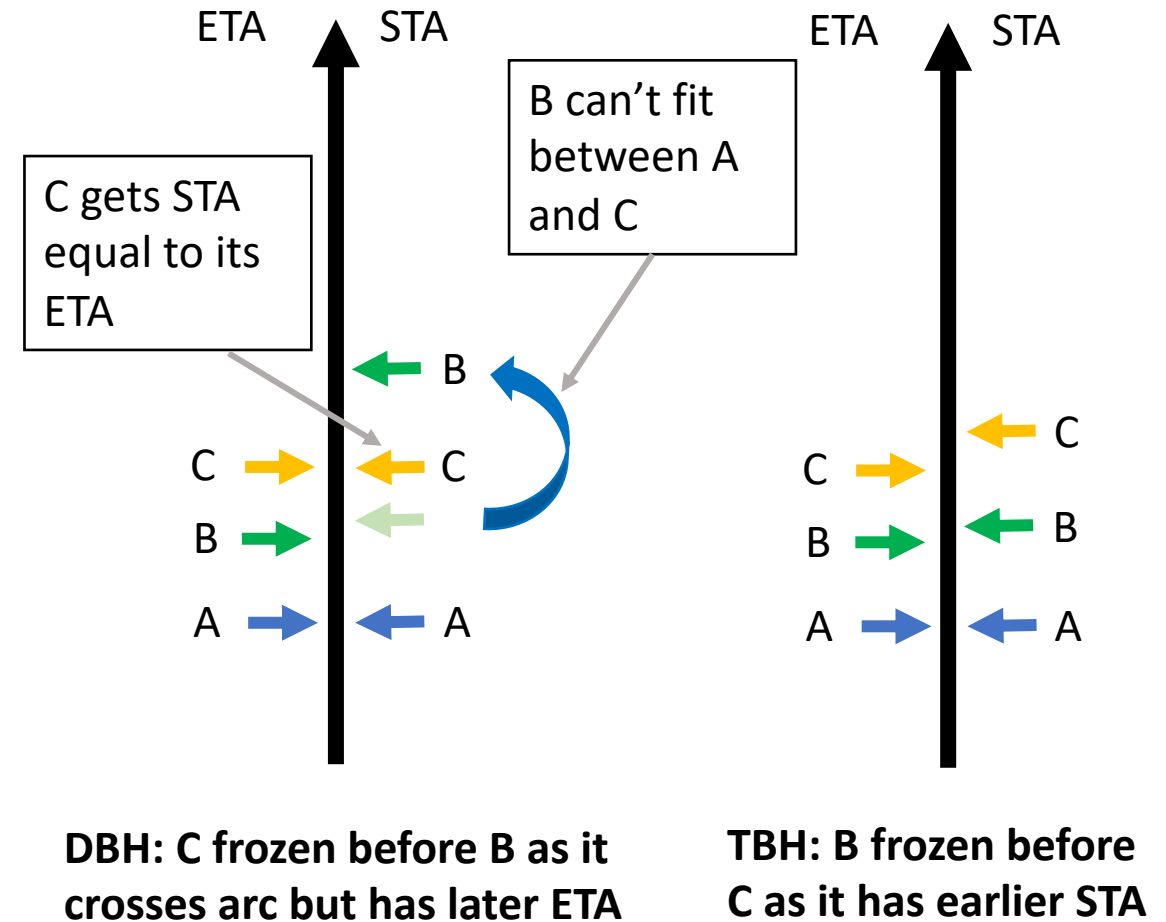
- Distance-based horizon (DBH) freezes STA when flight crosses distance from airport
  - Order is not aligned to ETA's because arcs are at different distances and aircraft speeds are different
  - Results in loss of throughput and equity

- Time-based horizon (TBH) freezes STA when it is within time threshold from current time
  - Order is aligned with ETAs
  - Increases throughput and equity

- Time-based horizon set at 63 minutes: mean timespan between when flights are frozen with distance-based horizon and their STAs

Legend:
- ● DBH
- ✚ TBH
- ▲ Same

"Same" is when DBH and TBH result in the same freeze location (happens for some internals at takeoff).

Simulation Methodology: Distance-based vs. Time-based Freeze Horizon

- Distance-based horizon (DBH) freezes STA when flight crosses distance from airport
  - Order is not aligned to ETA's because arcs are at different distances and aircraft speeds are different
  - Results in loss of throughput and equity

- Time-based horizon (TBH) freezes STA when it is within time threshold from current time
  - Order is aligned with ETAs
  - Increases throughput and equity

- Time-based horizon set at 63 minutes: mean timespan between when flights are frozen with distance-based horizon and their STAs

DBH: C frozen before B as it crosses arc but has later ETA

TBH: B frozen before C as it has earlier STA

Simulation Methodology: Evaluation Metrics

(flight delay) = (EDCT delay) + (departure error) + (TBFM delay)

- Total delay which is sum of all flight delays
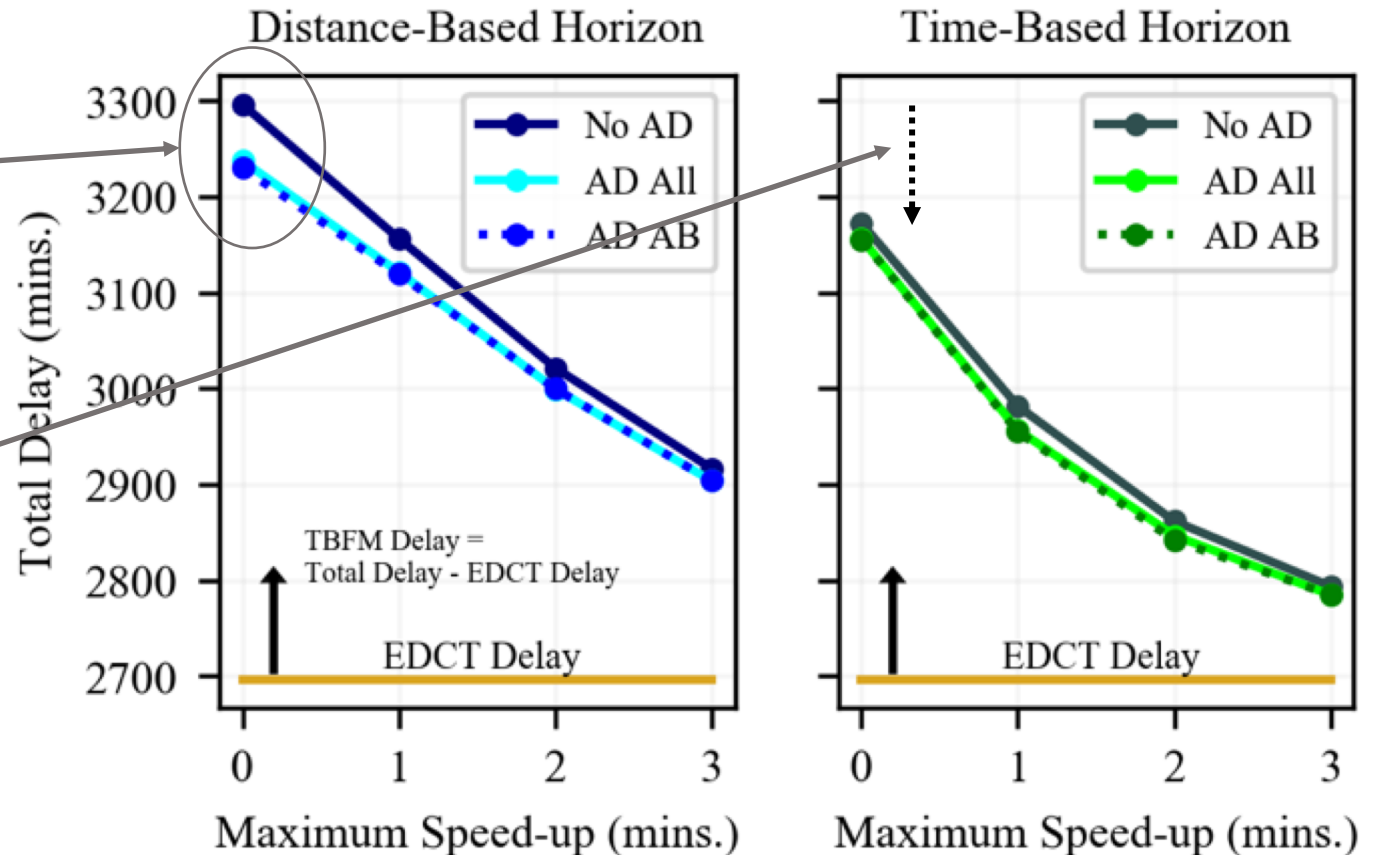- Standard deviation of flight delay

Impact on Total Delay: no Departure Error

Accrued delay prioritization reduced TBFM delay up to 11% for distance-based horizon (4% for time-based horizon)

Time-based horizon and speed-up resulted in large reduction in total delay

Accrued delay prioritization has less effect on total delay with time-based horizon and with more speed-up because there are less gaps in schedule
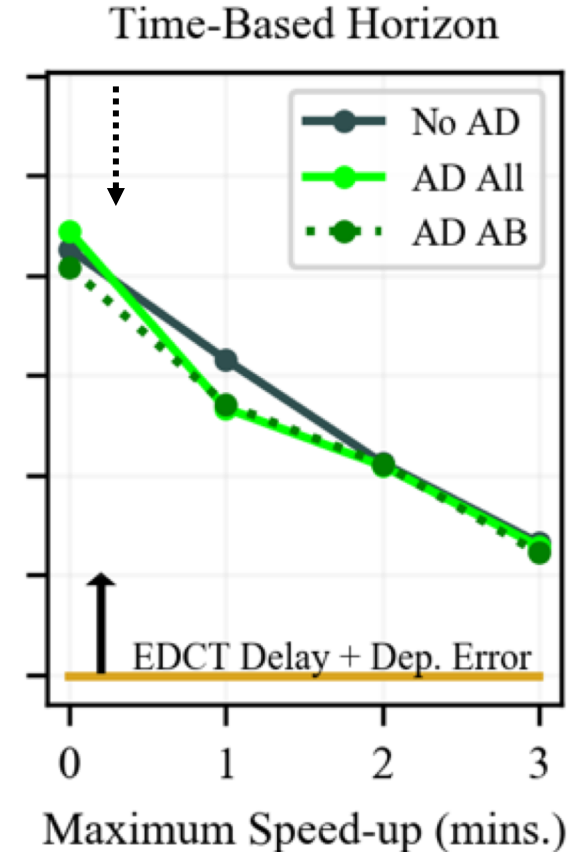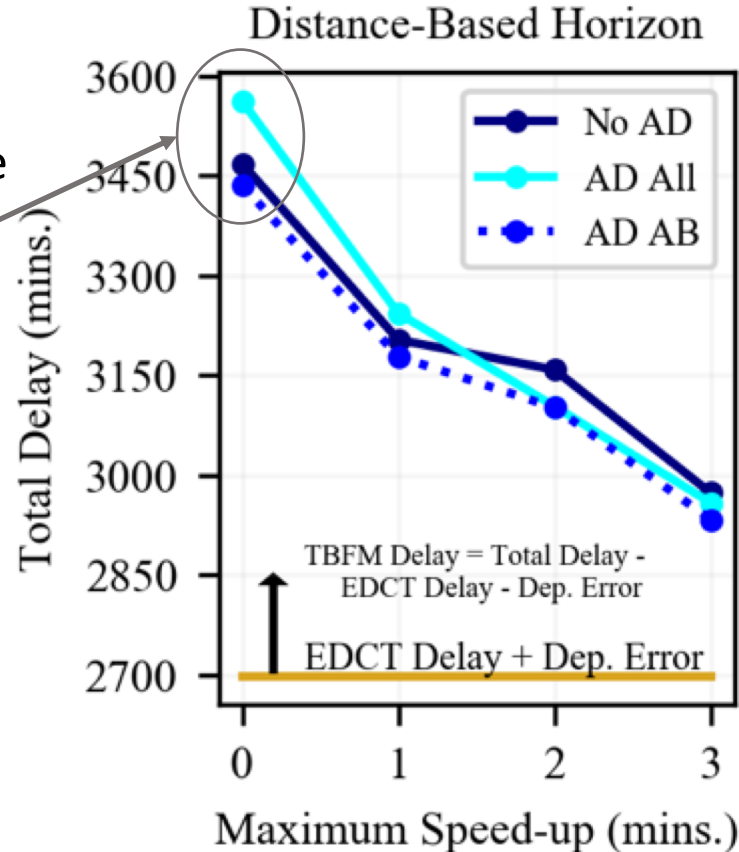
Impact on Total Delay: with Departure Error

With departure error, trends with speed-up and with distance vs time-based freeze horizons remained same

Applying accrued delay prioritization to all flights (AD All) can lead to increases in delay because departure error causes non-airborne flights to miss their assigned time slots

On the other hand, applying accrued delay prioritization to only airborne flights (AD AB) reduced delay
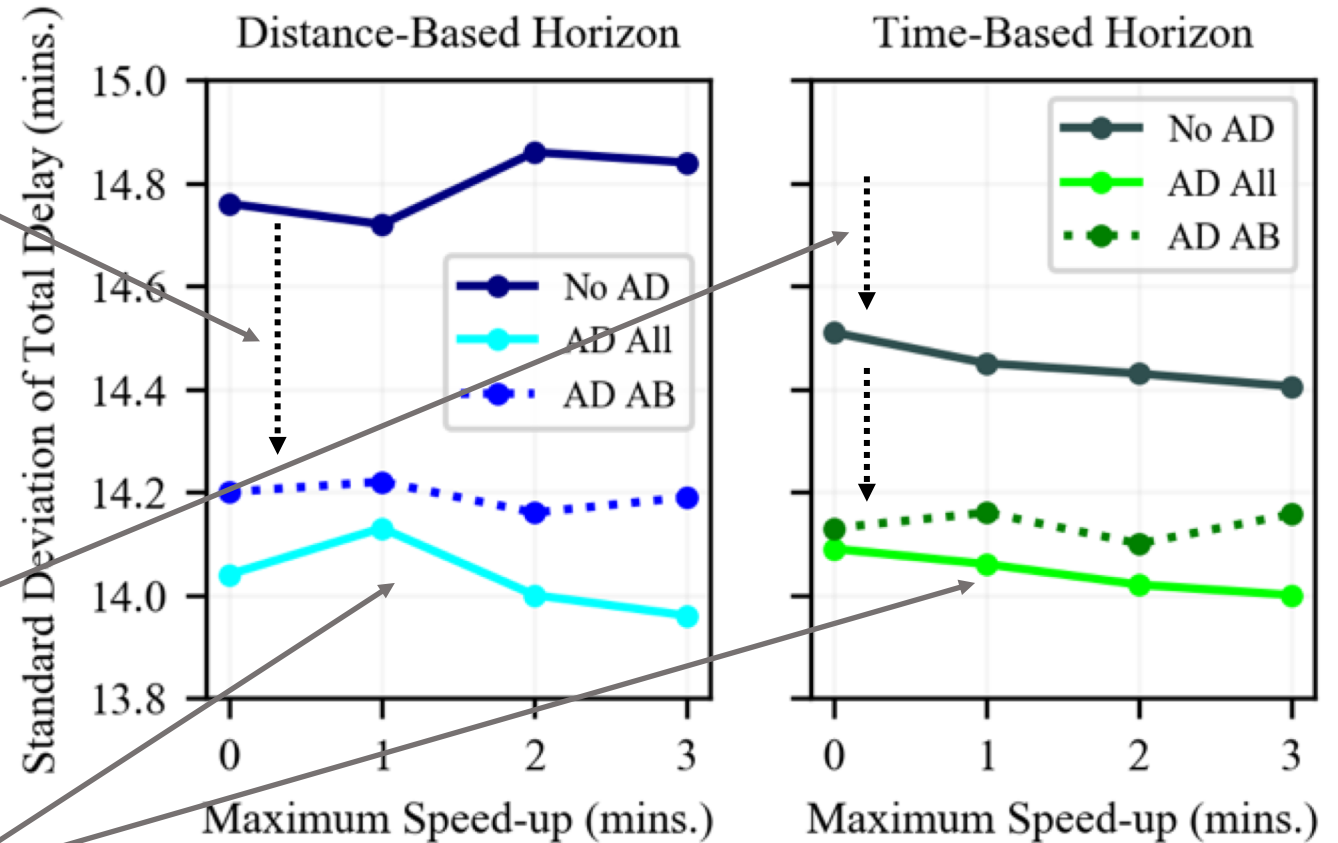
Impact on Delay Standard Deviation: no Departure Error

Accrued delay prioritization reduced standard deviation of total delay up to 6% with distance-based horizon (3% with time-based horizon), particularly when applied to all flights

Time-based horizon resulted in 2-3% less standard deviation of total delay than distance-based horizon

With accrued delay prioritization, time-based horizon resulted in similar delay standard deviation as distance-based horizon
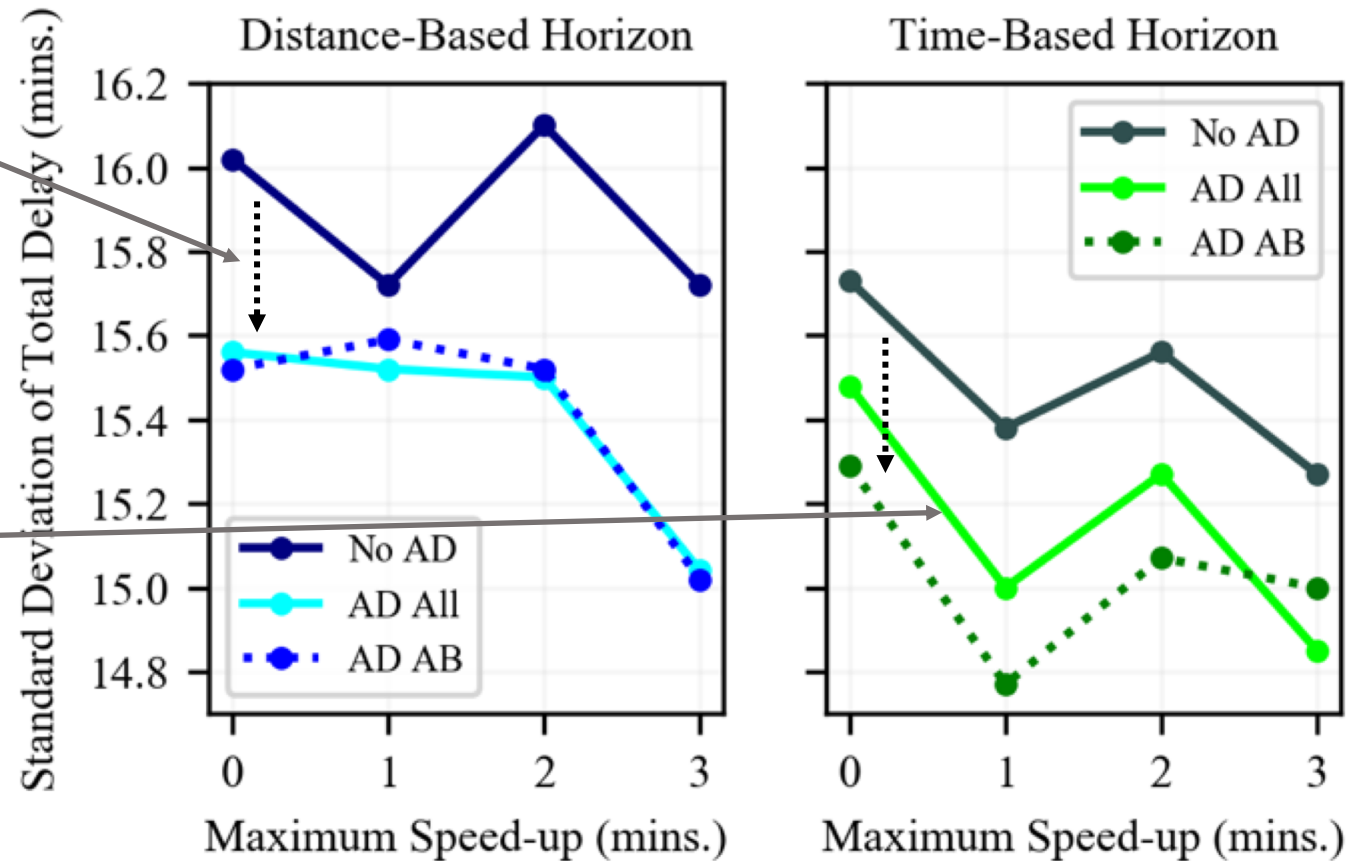
Impact on Delay Standard Deviation: with Departure Error

Accrued delay prioritization reduced standard deviation of total delay even with departure errors

Prioritizing all flights with accrued delay can lead to higher standard deviations than prioritizing only airborne flights, particularly with time-based horizon

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Summary and Conclusions

- Accrued delay can be an effective metric for integrating strategic and tactical decisions, and mitigating or limiting delay propagation

- Considerable delay propagates from inbound to outbound flights though aircraft turnaround
  - More than 45 minutes for delayed outbound flights at New York major airports
  - About 20 of these 45 minutes may be masked by airline schedule padding

- Prioritizing by accrued delay for integrating strategic and tactical restrictions
  - Can reduce total delay in conjunction with distance-based freeze horizon (there are opportunities to close schedule gaps)
  - Reduces delay standard deviation in all cases
  - Is more effective when applied under less uncertainty, with longer lookahead, and with shorter freeze horizons

Future Work

- Estimate accrued delay propagation across turnaround process, which involves predicting airline behavior

- Apply accrued delay continuously across flight and network

- Assess impacts of accrued delay and time-based horizons on human control and need for automation

- Apply accrued delay metrics for distributed scheduling services in service-oriented architectures

- Investigate accrued delay as enabler for migrating from gate-to-gate to more network-oriented and passenger-oriented paradigms
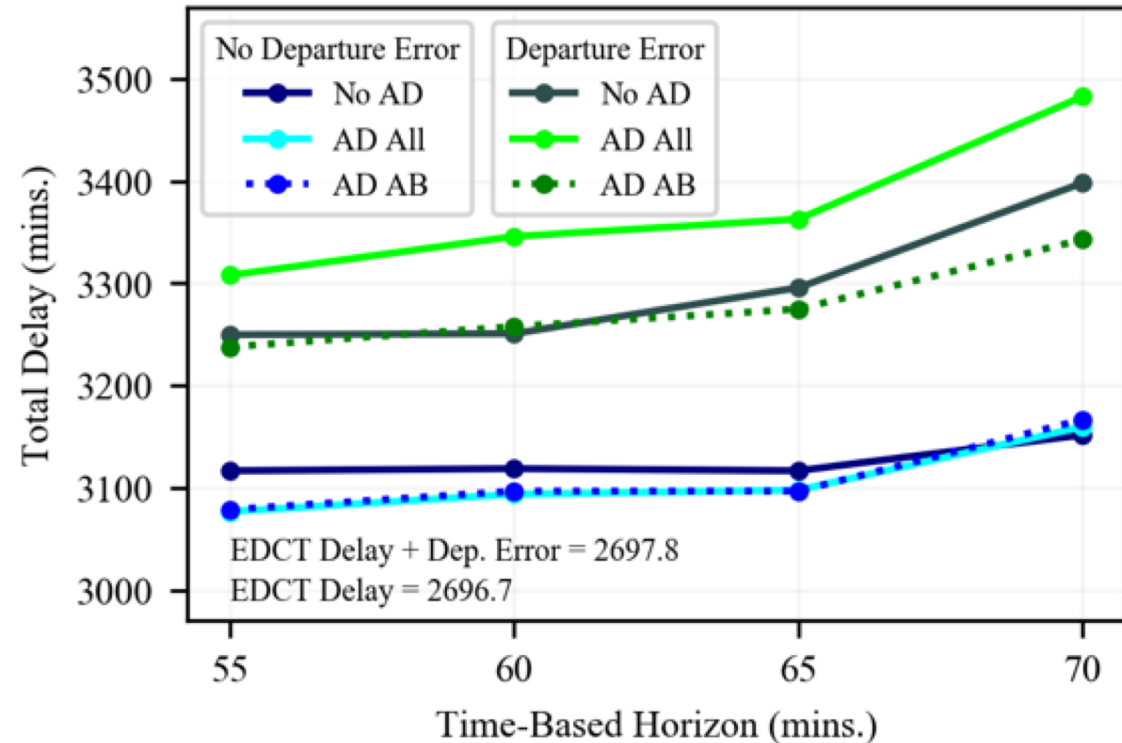
Back-up slides

Delay Sensitivity to Time-based Horizon Size

Smaller freeze horizon increases flexibility by allowing externals and internals more opportunities to find earlier time slots and close gaps in the schedule
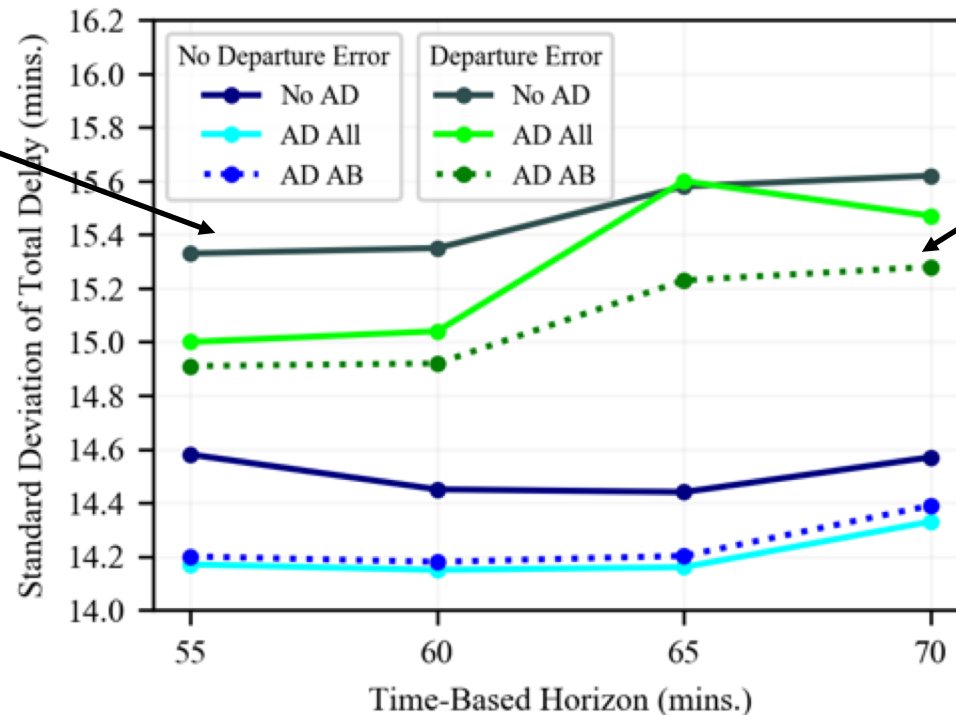
As freeze horizon size decreases, total delay decreased in all cases

Delay standard deviation sensitivity to time-based horizon size

As horizon size decreases, standard deviation of total delay decreases

With departure error, applying accrued delay prioritizing to only airborne flights is more effective than applying it to all flights
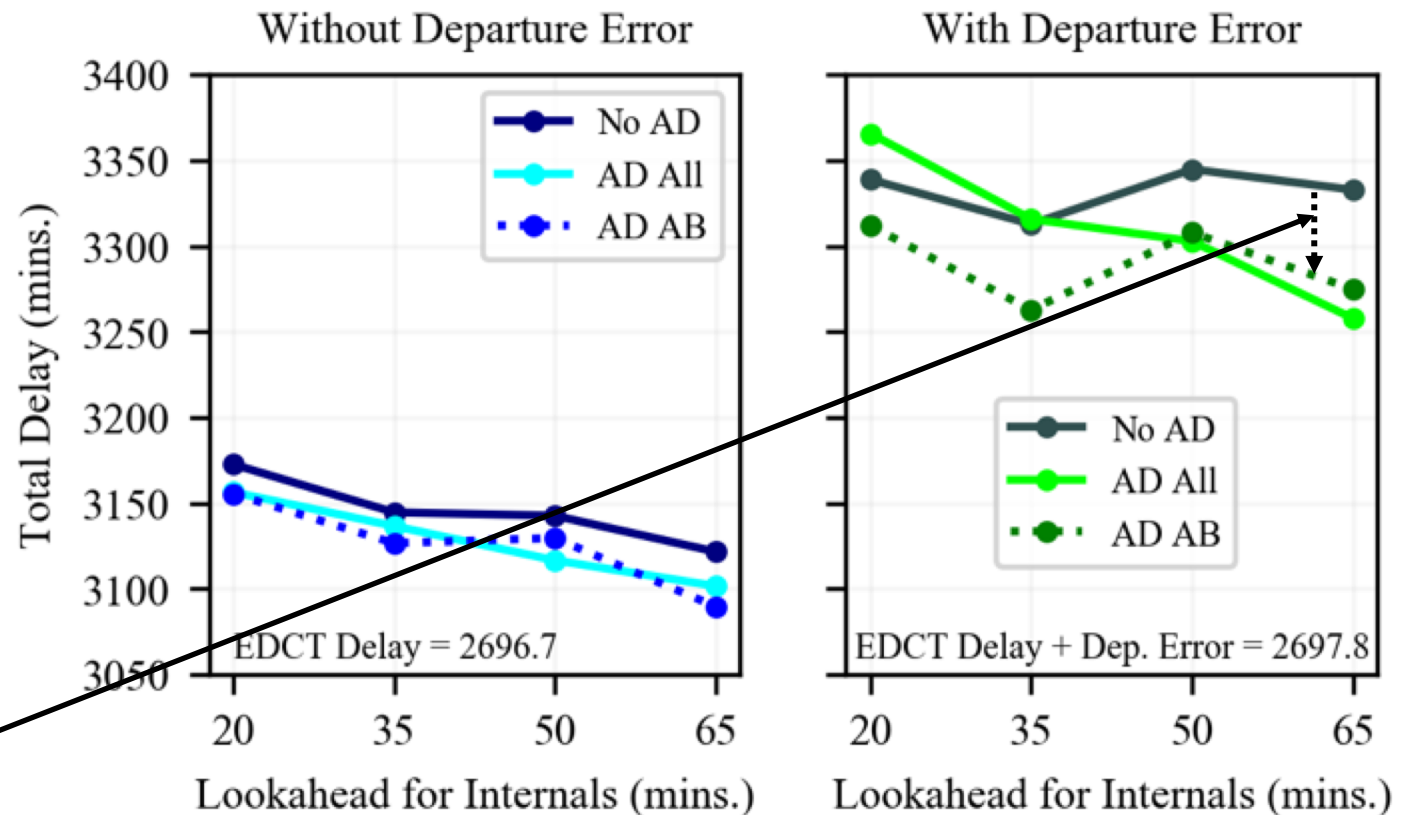
Total Delay Sensitivity to Internals Lookahead

- Currently, at 20 minutes lookahead before scheduled departure time, internals are added to TBFM schedule and assigned additional ground delay if needed

- Increasing lookahead for internals gives them more opportunities for finding earlier time slots among non-frozen flights

  Accrued delay prioritization impact on total delay slightly improved by increasing lookahead, particularly with departure error

Increasing lookahead for internals decreased total delay (shown for TBH, but true for both freeze horizon types)

Delay Standard Deviation Sensitivity to Internals Lookahead

As internal lookahead increases, standard deviation of total delay decreases, in particular with departure error

Accrued delay prioritization decreased standard deviation under all lookahead sizes and its impact on standard deviation improved by increasing lookahead, particularly with departure error
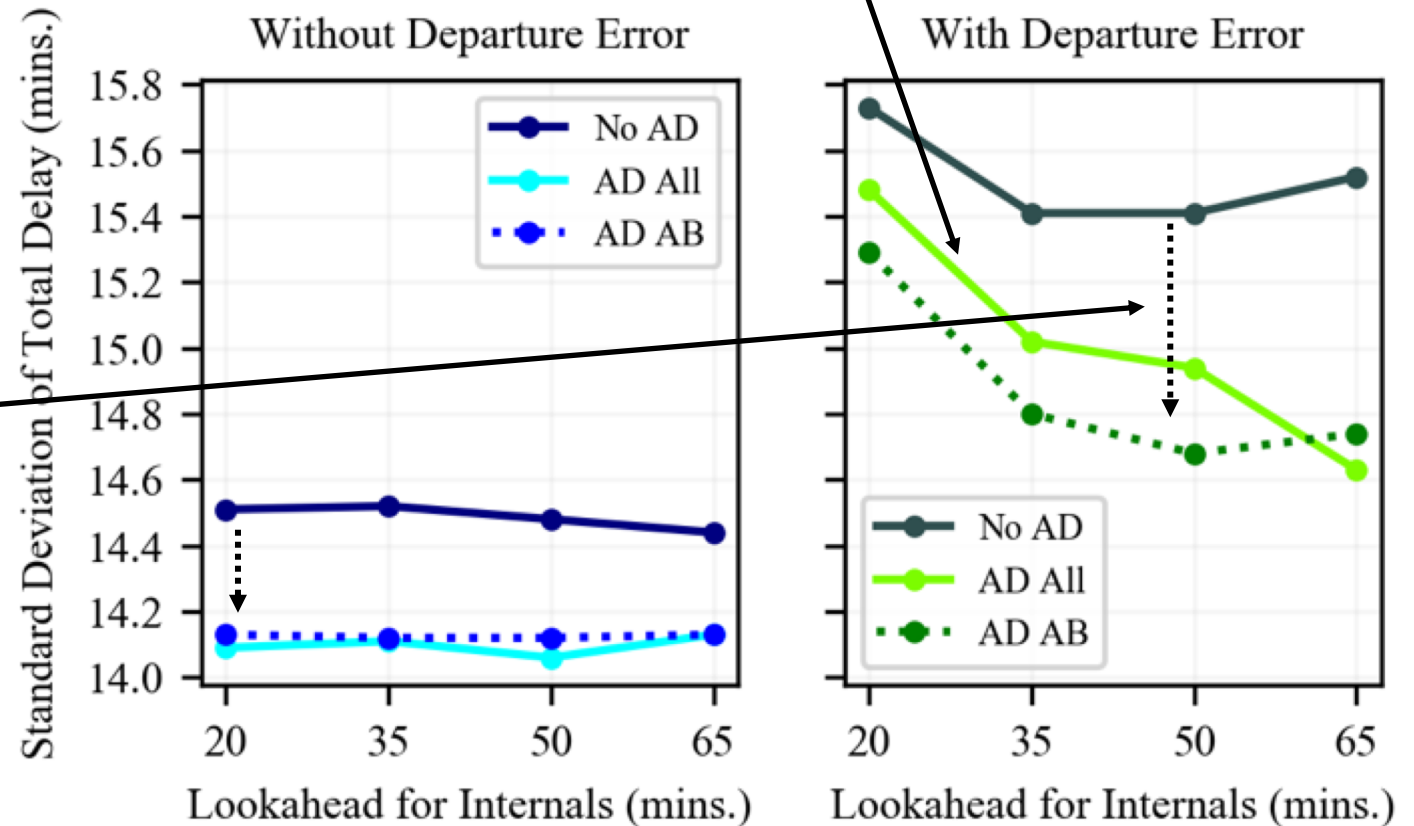
Accrued delay prioritization reduces delay

- "No AD" entries are baseline total delays
- "AD All" and "AD AB" entries are change in total delay when prioritizing with respective schemes

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%

Accrued delay prioritization reduces standard deviation of delay

- "No AD" entries are baseline standard deviations of total delay
- "AD All" and "AD AB" entries are change in standard deviation when prioritizing with respective schemes

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%