

Distributed Schemes for Integrated Arrival Departure Surface (IADS) Scheduling

NRA Year Two Final Briefing

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Outline

- Research Motivation and Objectives
- ATD-2 Focus and NASA Direction/Feedback
- Recap of Year One Activities
- Discussion of Year Two Activities
 - Queue Management Analysis using Low Fidelity Simulation (Husni)
 - Queue Management Analysis using High Fidelity Simulation (Husni)
 - Integrated Scheduling between Surface and Airspace using Low Fidelity Simulation (Aditya)
 - SOSS ATL Model and Validation (Jason)
- Conclusions and Future Work

Research Motivation and Objectives

- Solutions to mitigate delays focused historically on components of the system and resulted in separate tools, for example:
 - Traffic Management Advisor for arrival metering at TRACON entry points
 - Departure metering to absorb delay at gate/ramp rather than on airport movement area
 - Departure precision release to merge in overhead streams, etc.
- Integration is needed in order to reap the benefits envisioned by the isolated systems
- NASA is undertaking major efforts to demonstrate and mature integrated packages of decision support tools
 - ATD-1 focused on integrated arrival management
 - ATD-2 focused on integrated departure management, in addition to ATD-1

Research Motivation and Objectives

- Identify gaps and needs for integrated scheduling
- Identify and model real-world cases
- Develop concepts and architectures for distributed scheduling
- Prototype concepts in Matlab environment
- Implement concepts in high fidelity fast-time simulation platform
- Conduct performance analysis of concepts

ATD-2 Focus

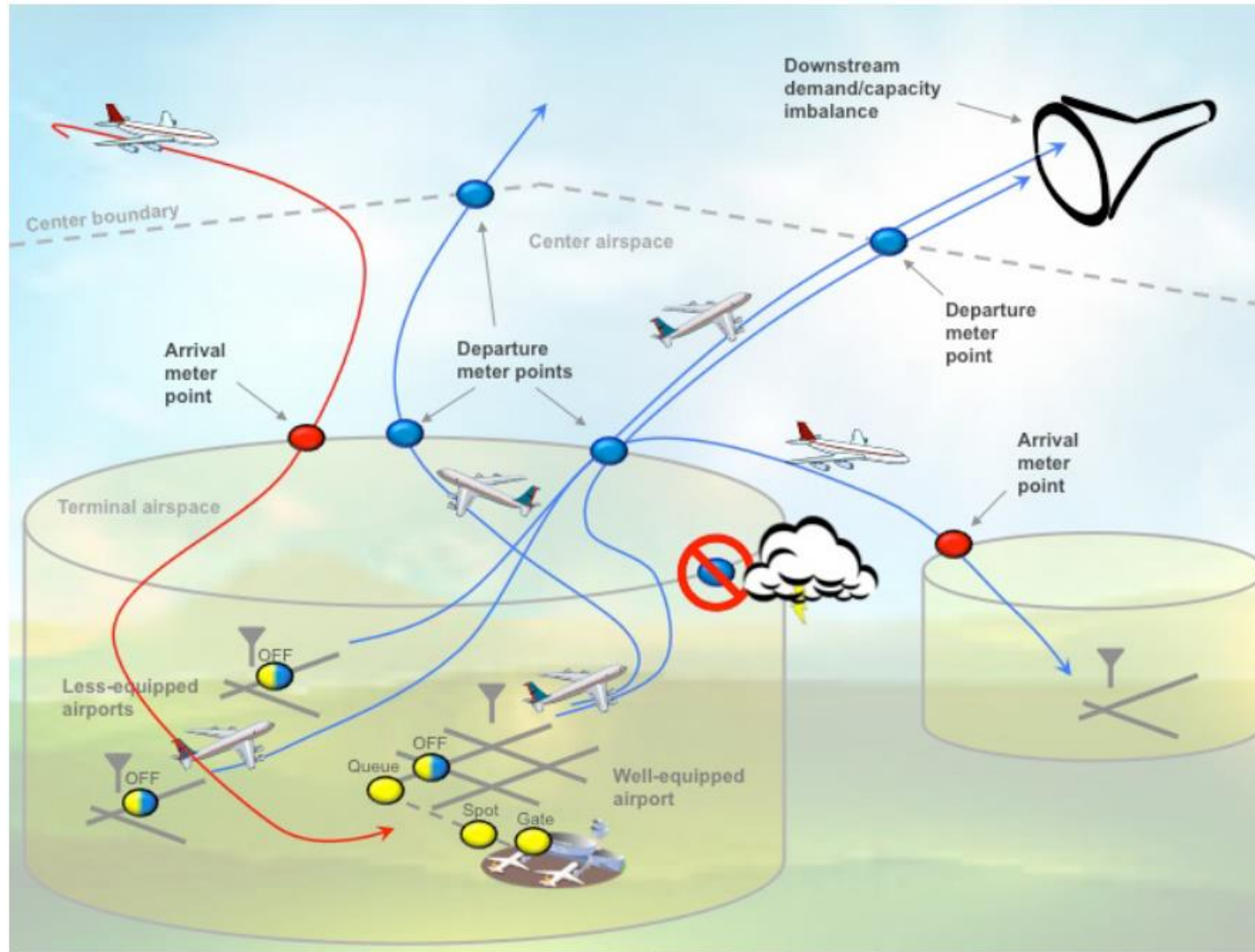


Figure taken from NASA ATD-2 team presentation

NASA's Feedback

- Sites: Focus on ATL and then CLT as sites for analysis
 - NY may be of interest later in project but not in near term
 - First year focused on ATL; second year focused on CLT
- Concepts: Focus on departure scheduling algorithms primarily
 - Consider arrival-departure interactions from departures' perspective both at runways and gate resources
 - Investigate queue management approaches for metering at gate
 - Investigate interactions between strategic and tactical schedulers
 - Heuristic rather than optimization approaches
- SOSS: Develop ATL model in high-fidelity SOSS environment
 - Performed by ATAC
 - Started in year one and continued with validation in year 2

NRA Year 1 Activities and Outcomes

- Literature review report comparing integrated arrival-departure scheduling approaches
- Case selection report with emphasis on NY and ATL-CLT
- Algorithms and simulation analyses (year 1 report)
 - MATLAB statistical queuing and saturation analysis of surface and airspace resources using PDARS/ASDE-X or ASPM historical data (ATIO 2016)
 - MATLAB heuristic FCFS departure runway scheduler with limited arrival time modification (using DSAS approach) applied to ATL
 - MATLAB integrated surface-airspace scheduler with queue buffers to mitigate uncertainty applied to ATL (DASC 2015 in collaboration with NRA subtopic 1)
- Partial SOSS ATL model

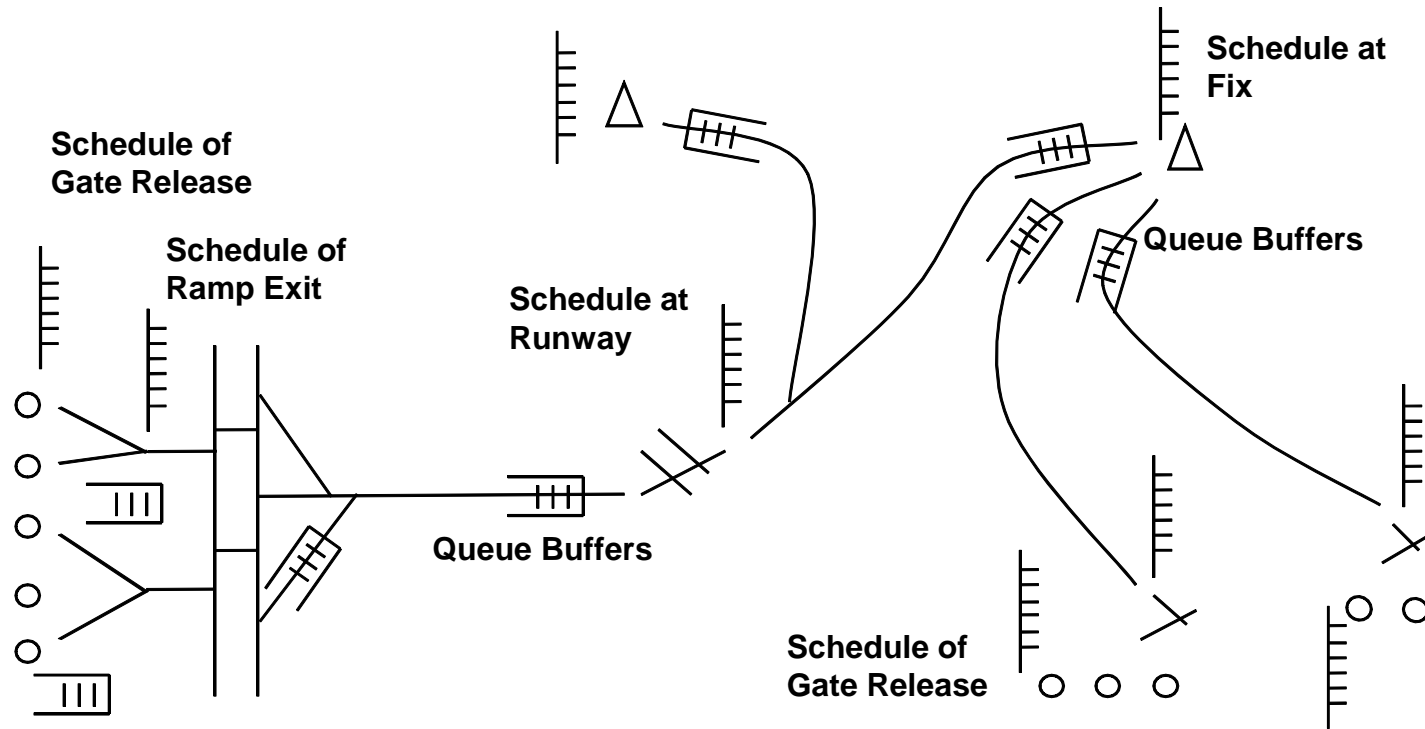
NRA Year 2 Activities and Outcomes

- Queue Management Analysis using Low Fidelity Simulation in MATLAB (Husni – DASC 2016)
- Queue Management Analysis using High Fidelity Simulation SOSS (Husni – submitted to ATIO 2017)
- Integrated Scheduling between Surface and Airspace using MATLAB Low Fidelity Simulation (Aditya – ATIO 2016)
- Complete and validated SOSS ATL model (Jason)

Queue Management Analysis - Outline

- Research Motivation
- Background on ATD-2 Concept and Analysis Assumptions
- Models and Simulation
 - Runway Scheduling and Metering Algorithms and
 - Associated Statistical Models
- Analysis and Results Applied at CLT Airport
 - Comparison of Control Strategies in Deterministic Scenario
 - Effects of Demand and Service Rate Uncertainties
- Conclusions and Future Work

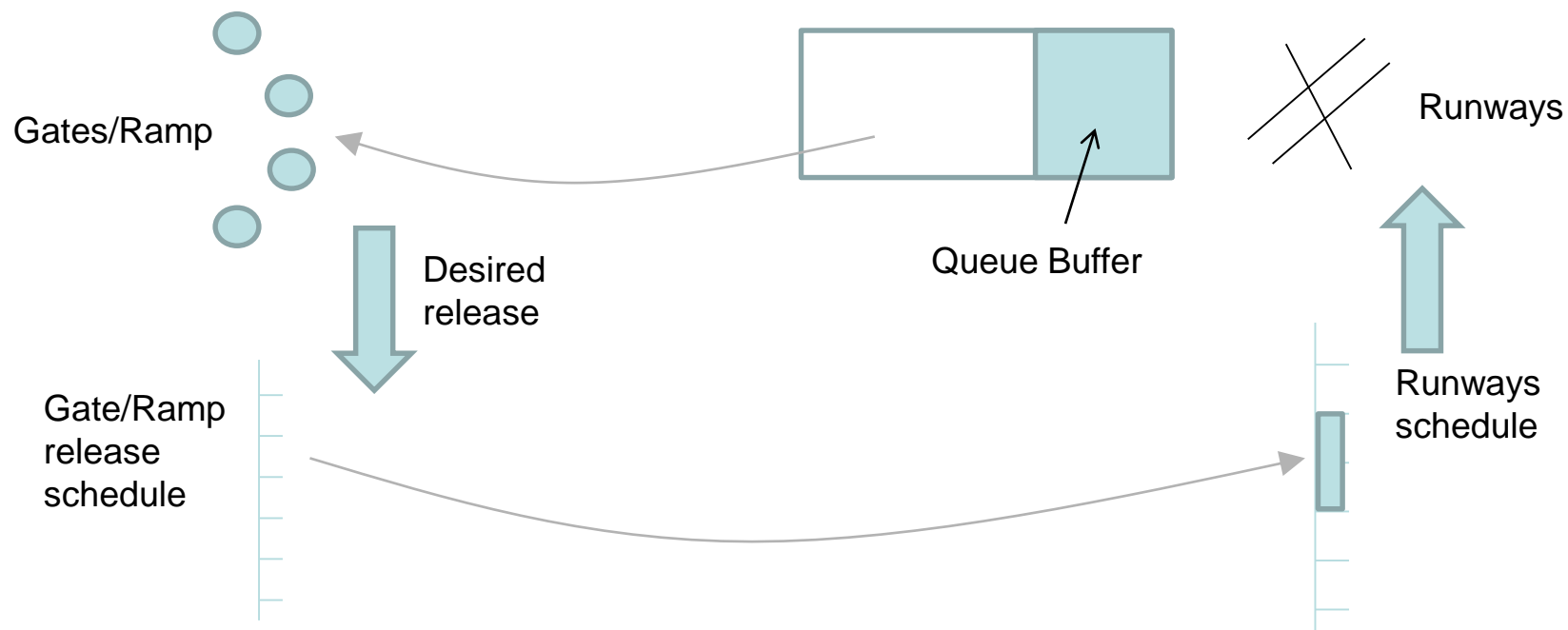
ATD-2 Concept – Metering and Queue Buffers



- Tradeoff: Maintain just enough queue buffers
 - Queue buffers are needed to maintain high throughput
 - Queue buffers are costly due to congestion, emissions, noise and fuel burn
 - e.g., JFK metering using buffer of six flights on airport surface was adjusted to twelve flights to ensure throughput and sequencing flexibility

ATD-2 Concept - Strategic and Tactical Scheduling

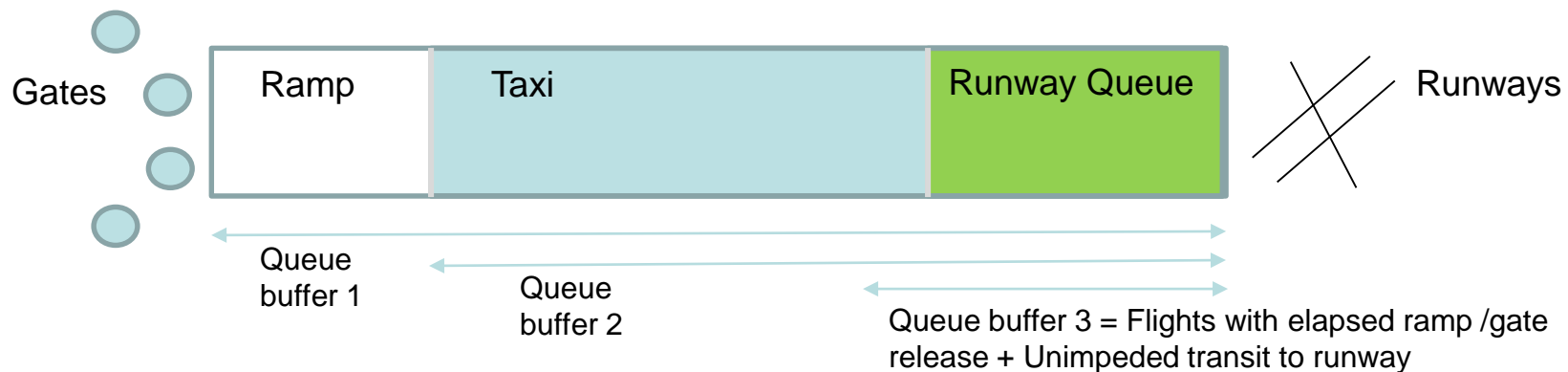
- Strategic scheduler meters departures at gates/ramp under high demand/congestion
 - Runs under high congestion only



- Tactical scheduler controls ramp/gate releases to meet metering and other scheduling restrictions
 - Runs continuously and refines strategic release times

Analysis and Associated Assumptions

- Key strategic scheduler parameter is target queue buffer size
 - Control queue buffers to minimum needed for maximizing throughput
 - Absorb remaining delay at gates/ramp with engines off

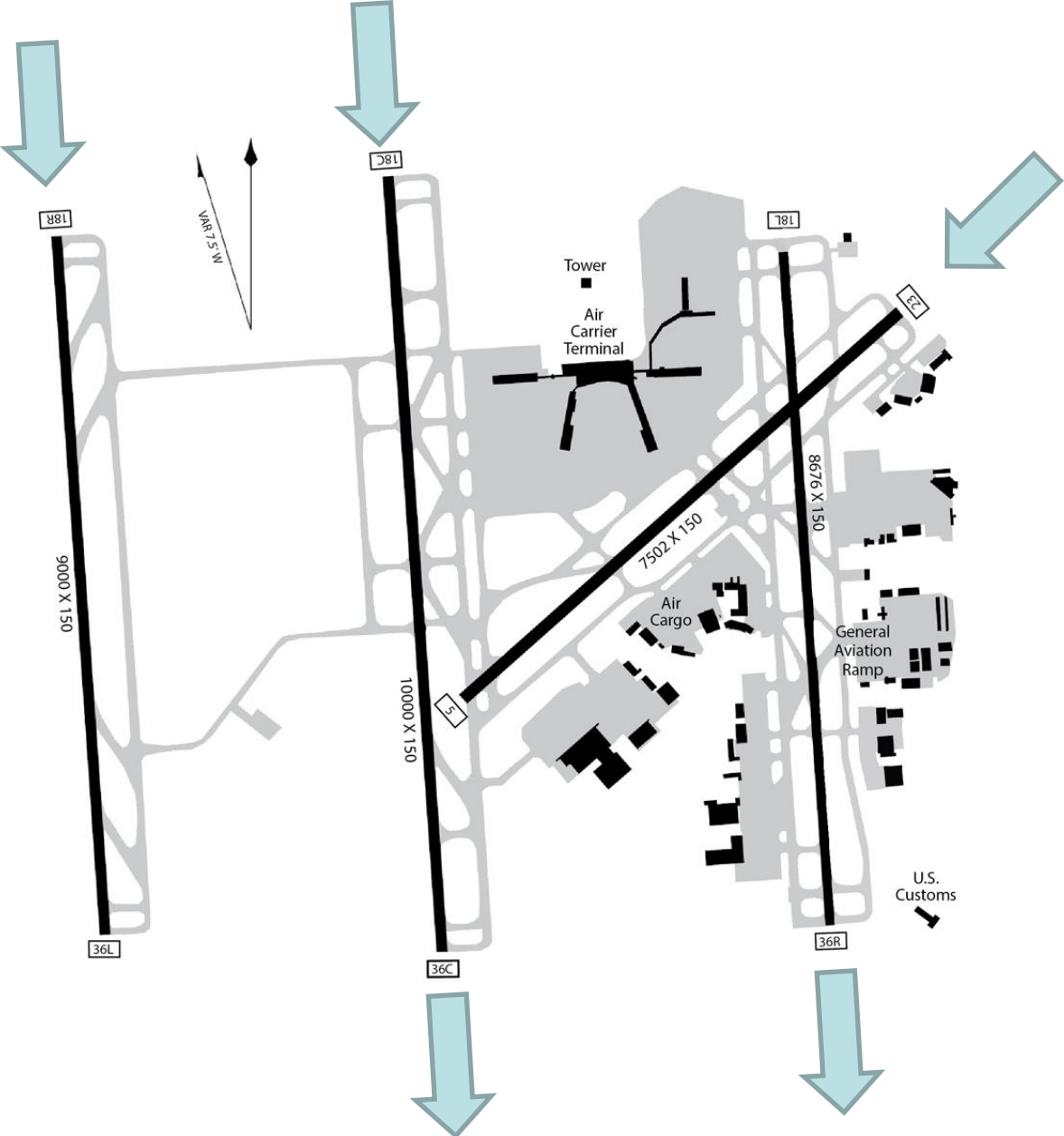


- Compared three metering control strategies / parameters
 1. Control number of flights that pushed back but did not take off
 2. Control number of flights that exited the ramp but did not takeoff
 3. Control number of flights that spent unimpeded transit time to the runway but did not take off

Analysis and Associated Assumptions

- Analysis: Compared the three metering control strategies / parameters
 1. Control number of flights that pushed back but did not take off
 2. Control number of flights that exited the ramp but did not takeoff
 3. Control number of flights that spent unimpeded transit time to the runway but did not take off
 - in terms of tradeoff between throughput and delay allocation
 - under deterministic and stochastic scenarios
- No tactical loop to adjust strategic release times
 - Tactical scheduler releases flights at strategic release times
 - Enables testing strategic scheduler impact on conformance to runway schedule
- Arrivals as constraints to departure scheduling at runways and gates

CLT Airport Diagram



Fast Time Simulation

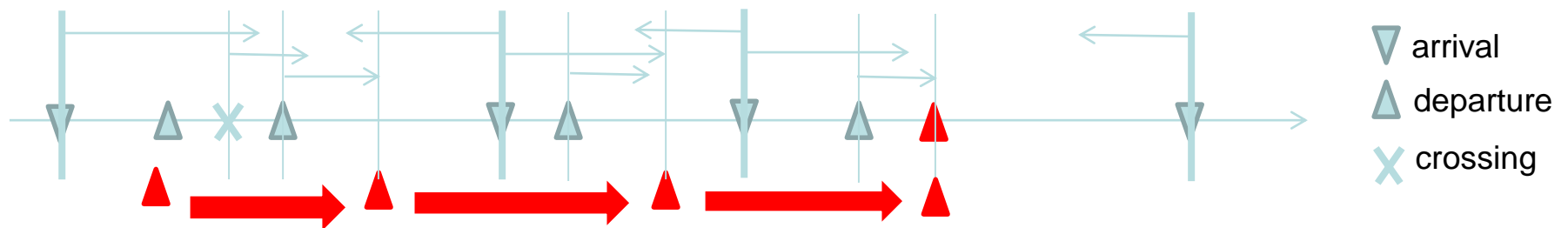
- Every fifteen minutes performs following steps
 1. Estimate demand for runway usage
 - Arrivals assumed to land at their actual landing times (from PDARS/ASDE-X)
 - Runway crossings assumed ready to cross at actual landing times plus mean unimpeded transit from landing to runway crossing point
 - Departures assumed ready for takeoff at estimated pushback time plus mean unimpeded transit from gate to spot (estimated ramp exit time) plus mean unimpeded transit from spot to runway
 - Deterministic scenarios: Pushback and ramp exit times estimated at actual pushback time (from ASPM) and actual ramp exit time (from ASDE-X) respectively
 - Non-deterministic scenarios: Pushback estimated at flight plan pushback time (from ASPM)
 2. Generate runway schedule over horizon set to remainder of day
 - Using mean separation time between runway operations
 3. Apply metering algorithm over time horizon set to remainder of day
 - Using one of three control strategies

Fast Time Simulation

- Every fifteen minutes performs following steps
 4. Update simulation over fifteen minutes
 - Pushback flights at later of actual pushback time (from ASPM) and metered pushback time (from scheduler)
 - Exit ramp at later of actual ramp exit time (from ADSE-X) and metered ramp exit time
 - Update transit times to runway
 - Deterministic scenarios: used same transit time values assumed by the scheduler
 - Non-deterministic scenarios: used random samples from transit time distributions to deviate from scheduler assumption
 - Compute runway takeoff times by running runway scheduler
 - Deterministic scenarios: used same runway separation values assumed by the scheduler
 - Non-deterministic scenarios: used random samples from separation distributions to deviate from scheduler assumption
 - Remove takeoffs that are due

Runway Scheduling Algorithm

- Inputs:
 - Actual arrival times (from ASDE-X) to fit departures and runway crossings in between
 - Required spacings: arrival→departure, arrival→crossing, departure→arrival, crossing→arrival, departure→crossing, crossing→departure, departure→departure, and crossing→crossing
 - Departure demand: expected departure times
 - Runway crossing demand: expected runway crossing time
- Logic:
 - For each departure and runway crossing operation in FCFS order according to expected operation times
 - Find earliest gap between arrivals that satisfies all separation requirements (using means of distributions)
 - Consider all dependent runways (e.g., 18C and 23 arrivals for 18C departure)



Metering Algorithm

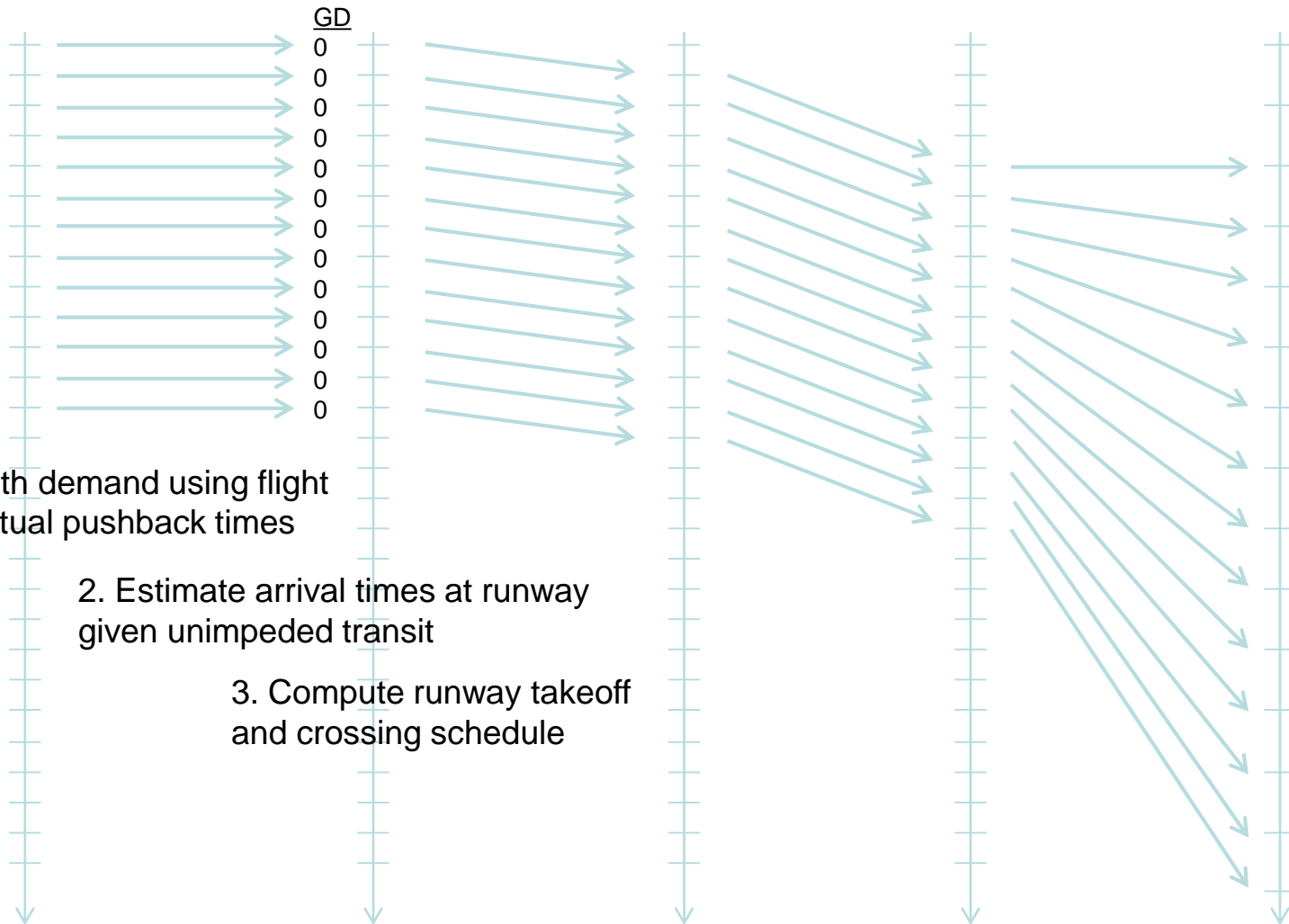
Demand at gate

Scheduled
release from
gate

Scheduled
release from
ramp

Scheduled
arrival at
runway

Scheduled exit
from runway



Metering Algorithm

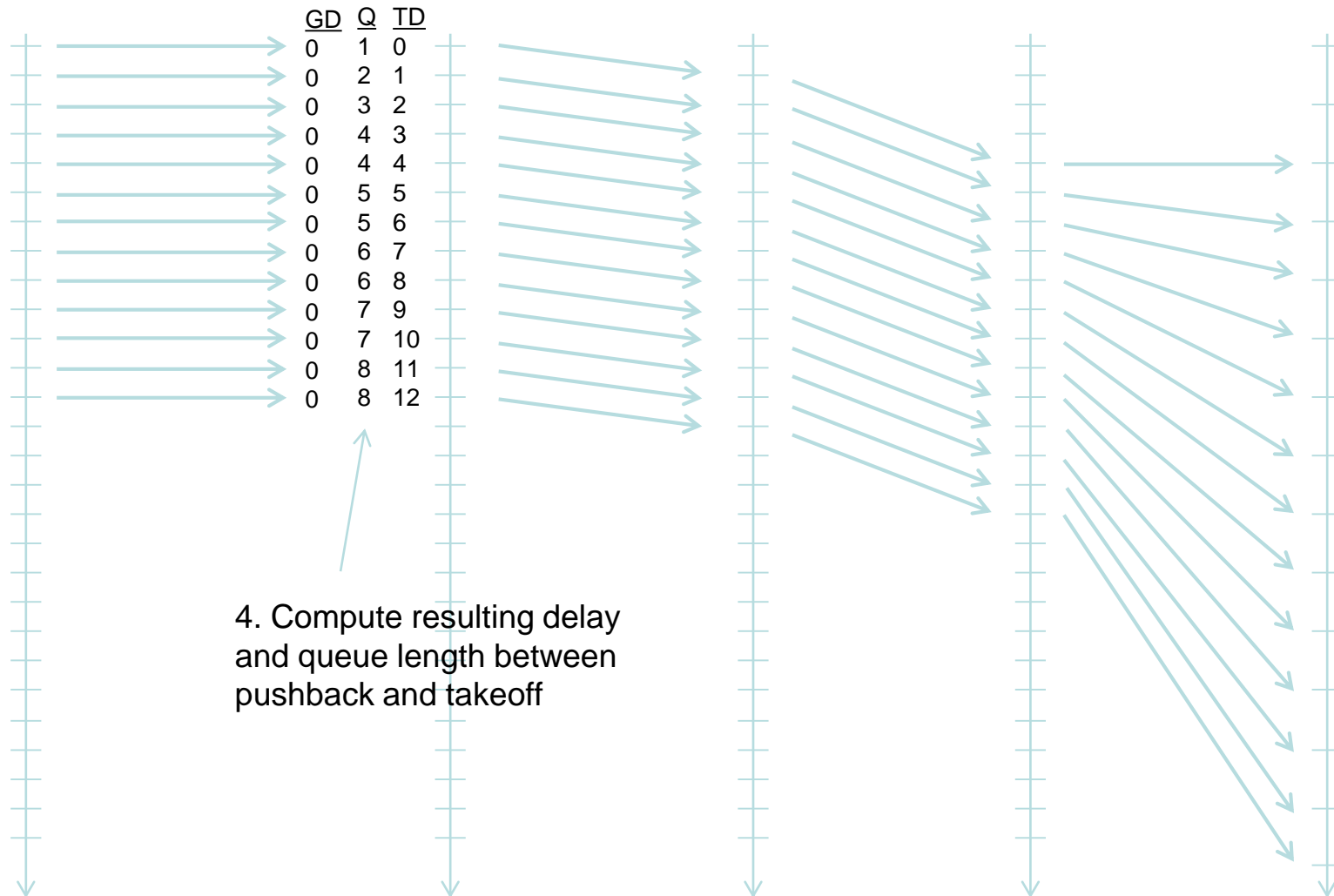
Demand at gate
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| <u>GD</u> | <u>Q</u> | <u>TD</u> |
|-----------|----------|-----------|
| 0 | 1 | 0 |
| 0 | 2 | 1 |
| 0 | 3 | 2 |
| 0 | 4 | 3 |
| 0 | 4 | 4 |
| 0 | 5 | 5 |
| 0 | 5 | 6 |
| 0 | 6 | 7 |
| 0 | 6 | 8 |
| 1 | 6 | 8 |
| 2 | 6 | 8 |
| 3 | 6 | 8 |
| 4 | 6 | 8 |

6. Compute corresponding
metering delay at gate

5. Apply metering with
maximum queue length
between pushback and takeoff

Metering Algorithm

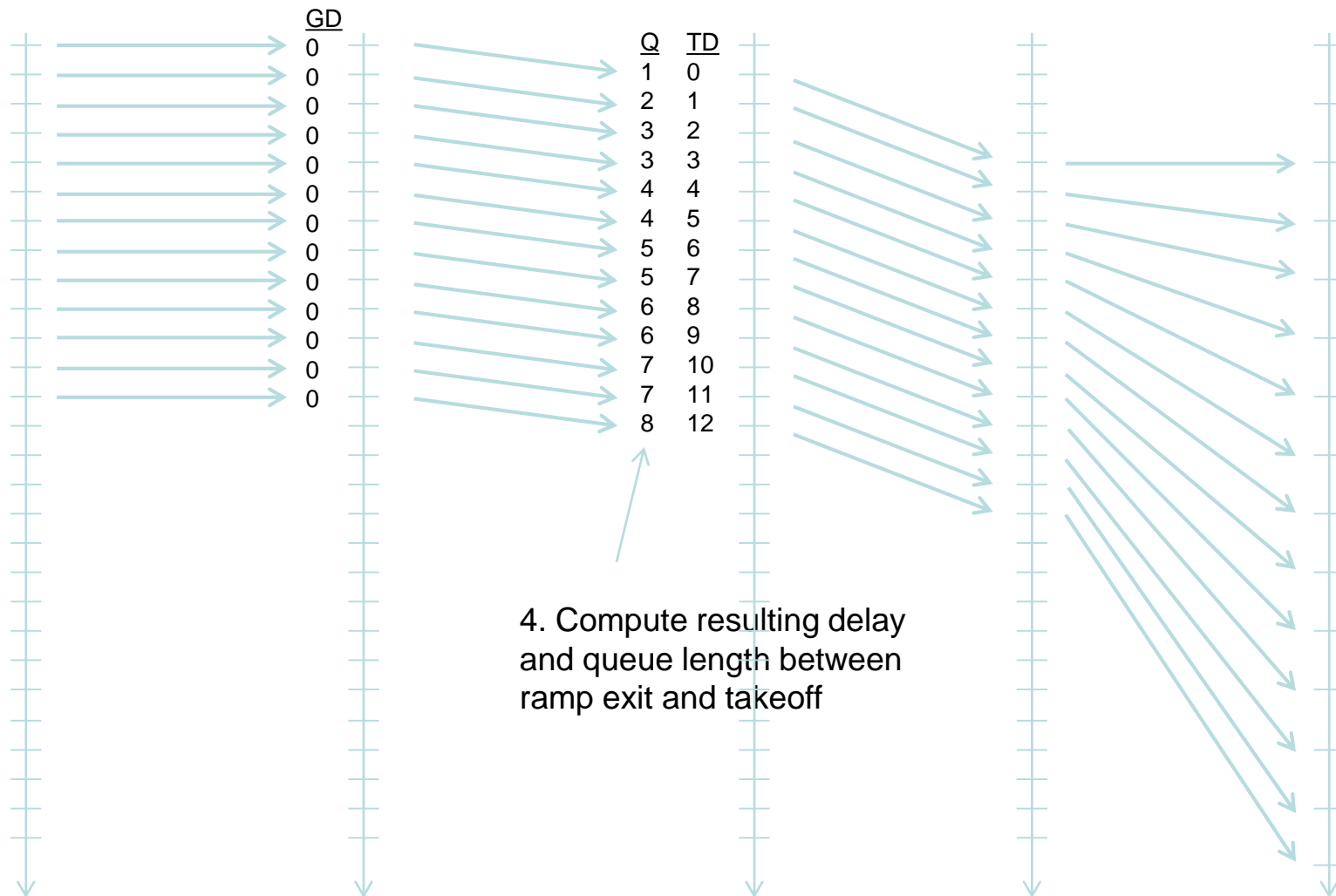
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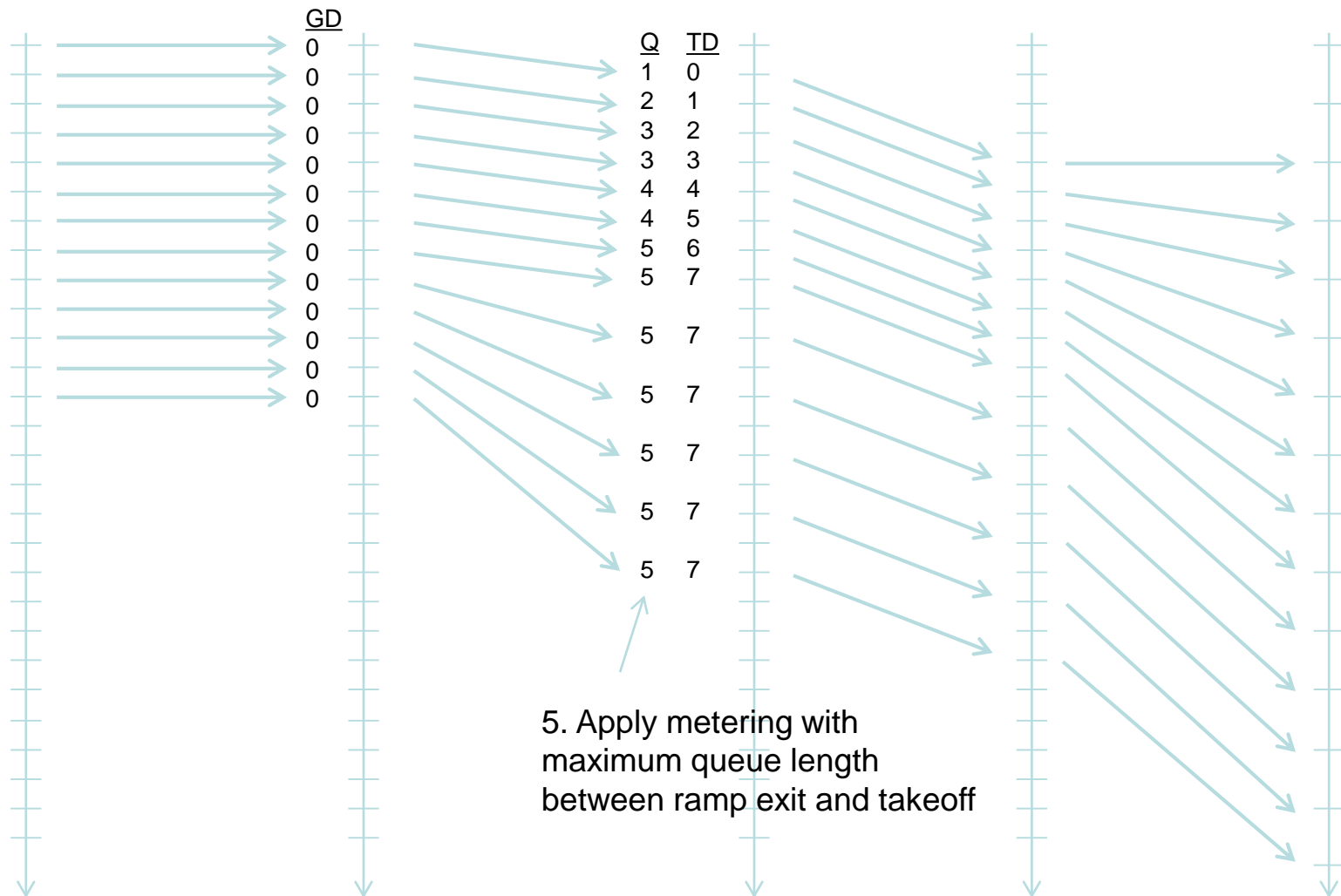
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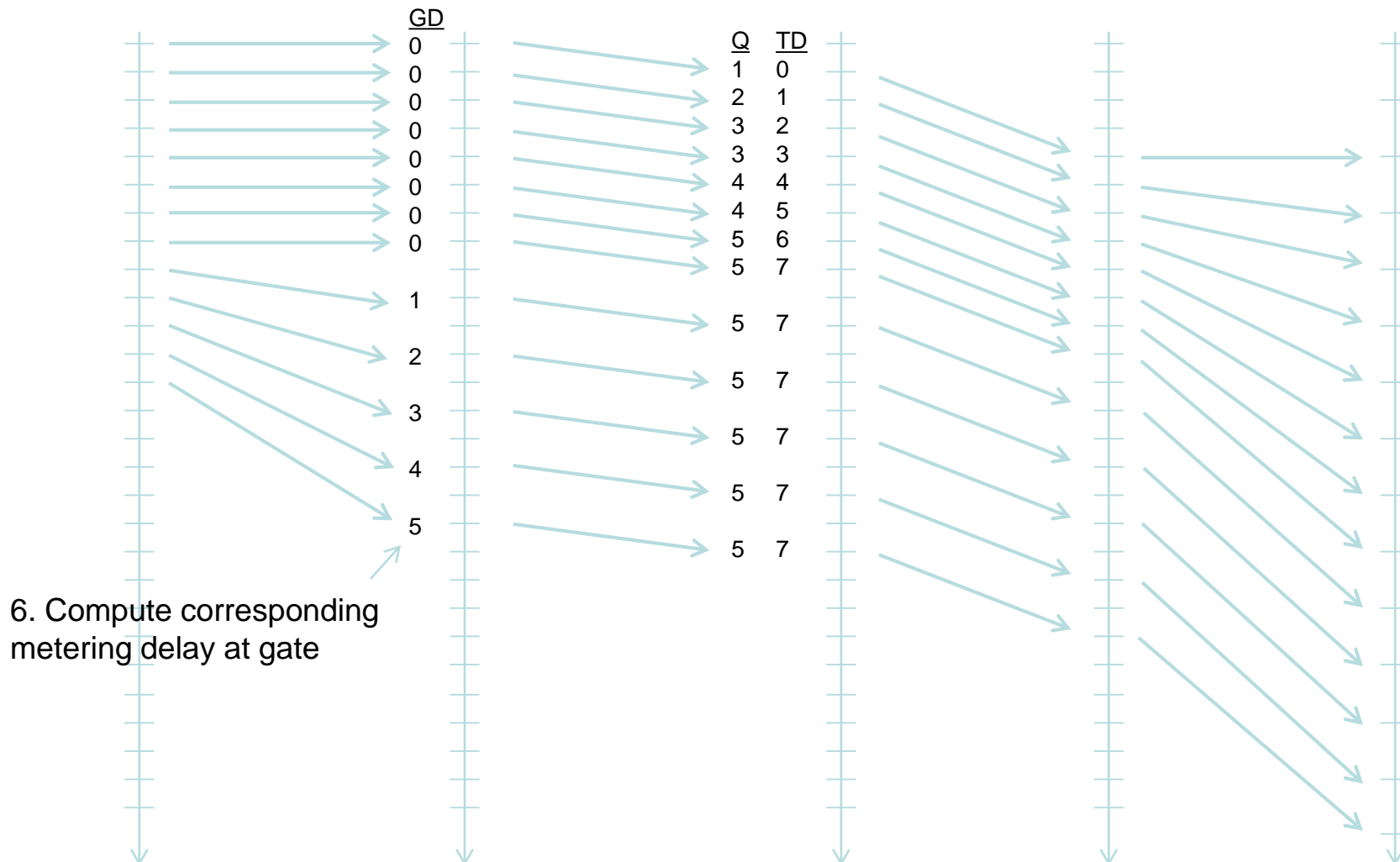
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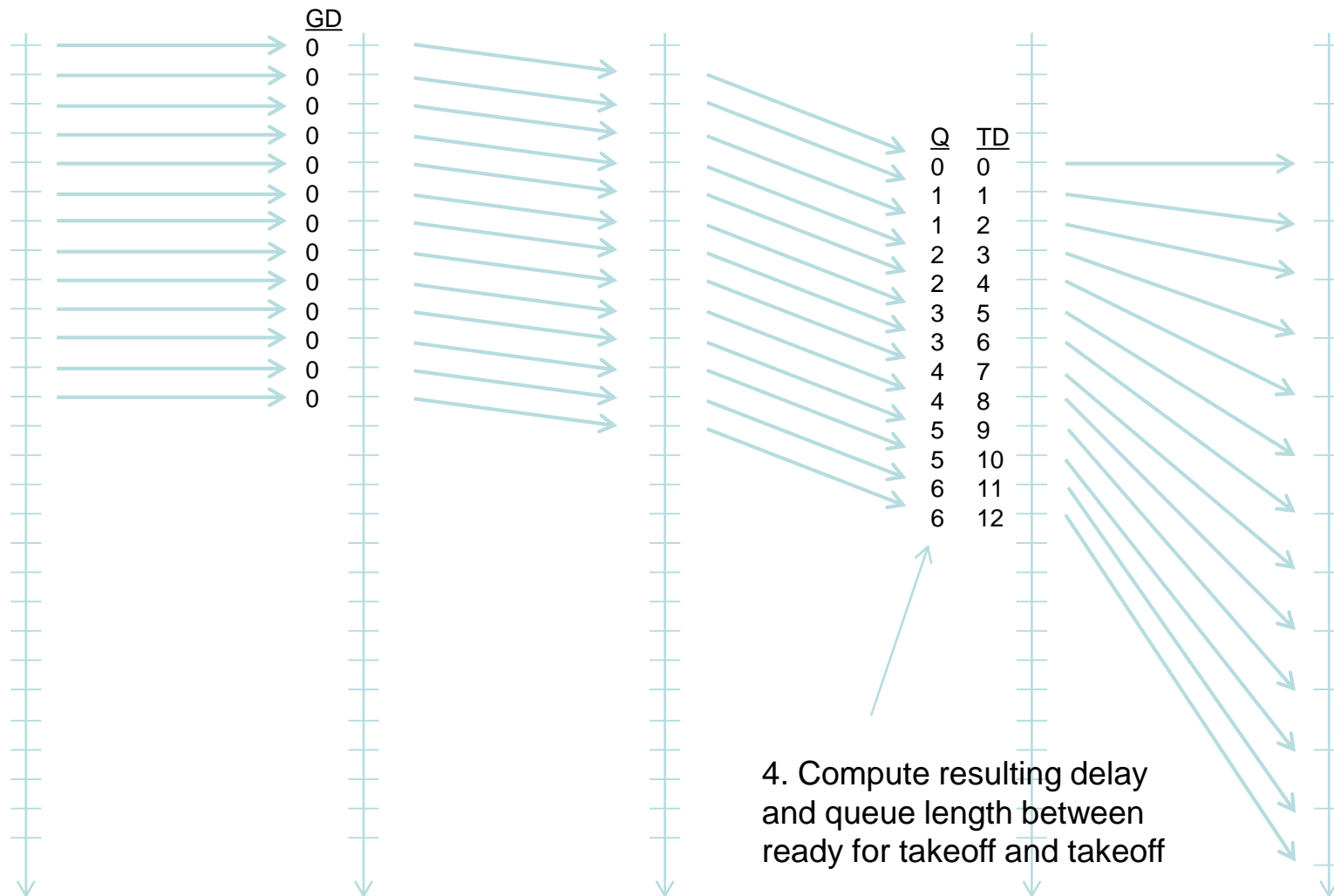
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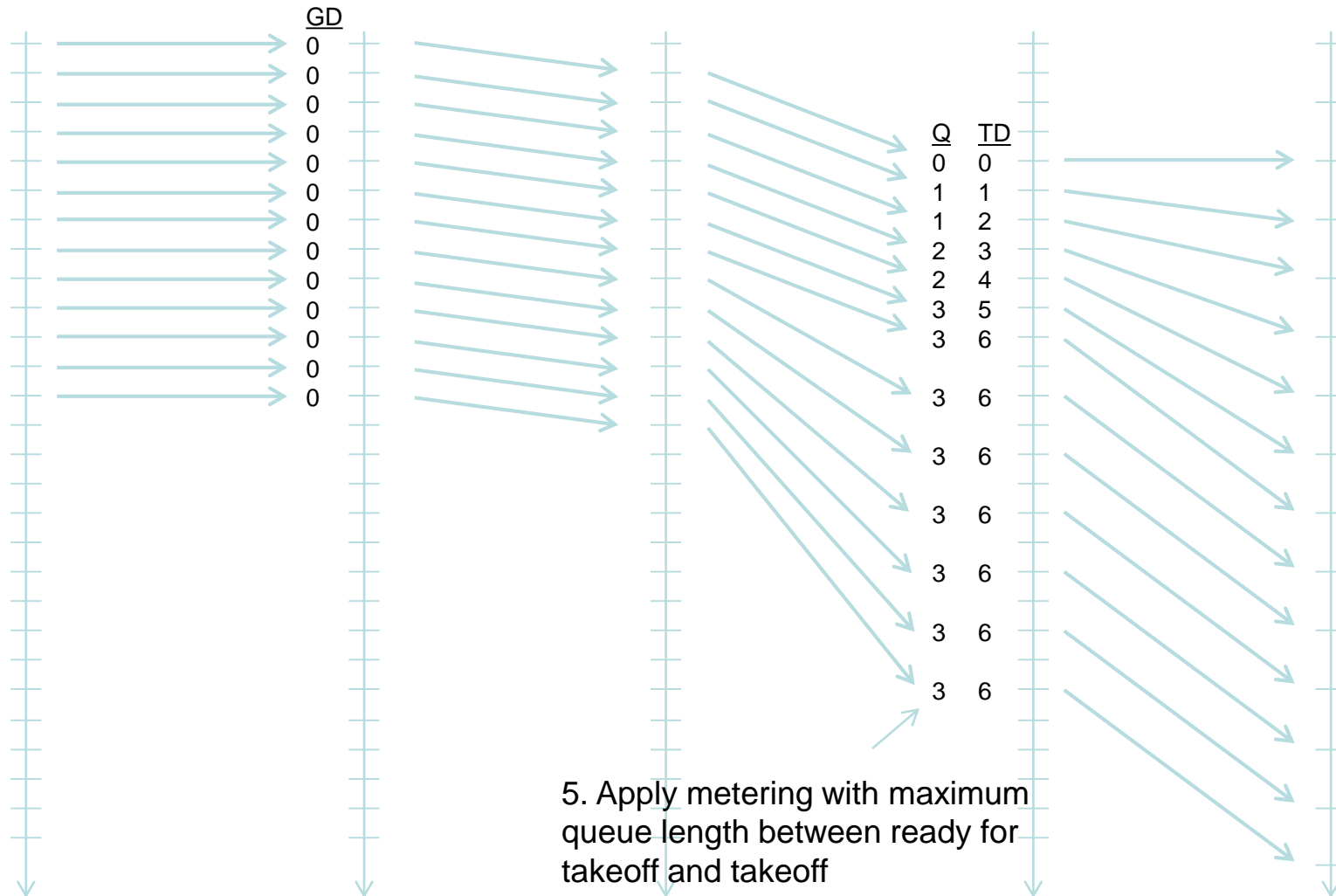
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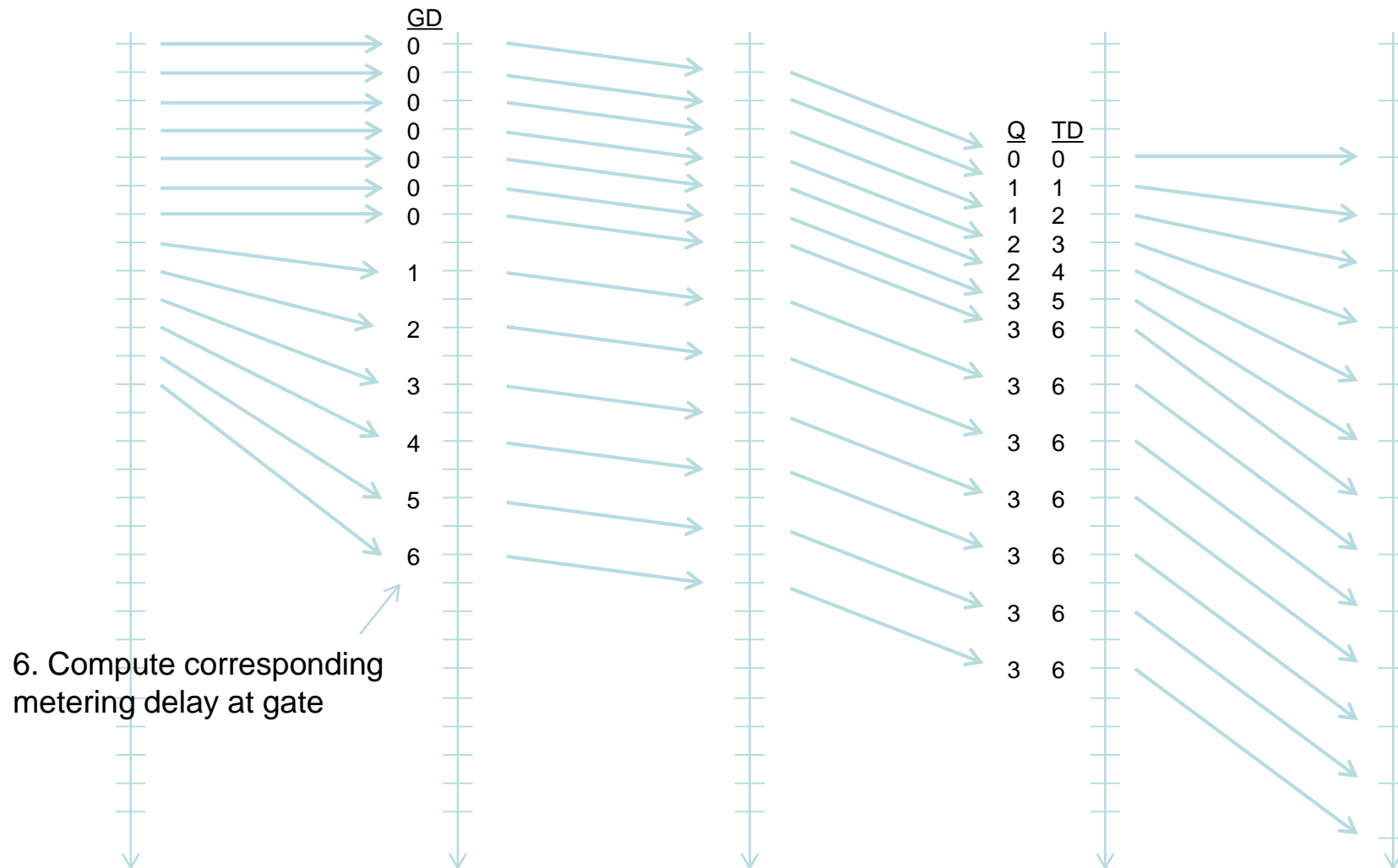
Demand at gate
(flight plan
pushback time)

Scheduled
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gate

Scheduled
release from
ramp

Scheduled
arrival at
runway

Scheduled exit
from runway



Metering Algorithm

- Gate constraints applied to departure metering delay at gate
 - Assuming actual arrival times at gates from ASDE-X
 - Estimate the gate demand at a candidate time as the sum of arrivals and departures that would still be at their gate at that time
 - Set the desired gate release time to the earliest time at which the gate demand drops below the threshold gate capacity value
- Gate capacity estimated using ASPM historical data
 - Maximum number of gates occupied at same time based on historical data of one year (2012)
 - 97 gates at CLT assumed available to all users interchangeably
- Tail numbers matched between arrivals and departures for estimating gate occupancy
- Two hour gate occupancy assumed for flights with no tail number matching (assuming towing off the gate beyond two hours)

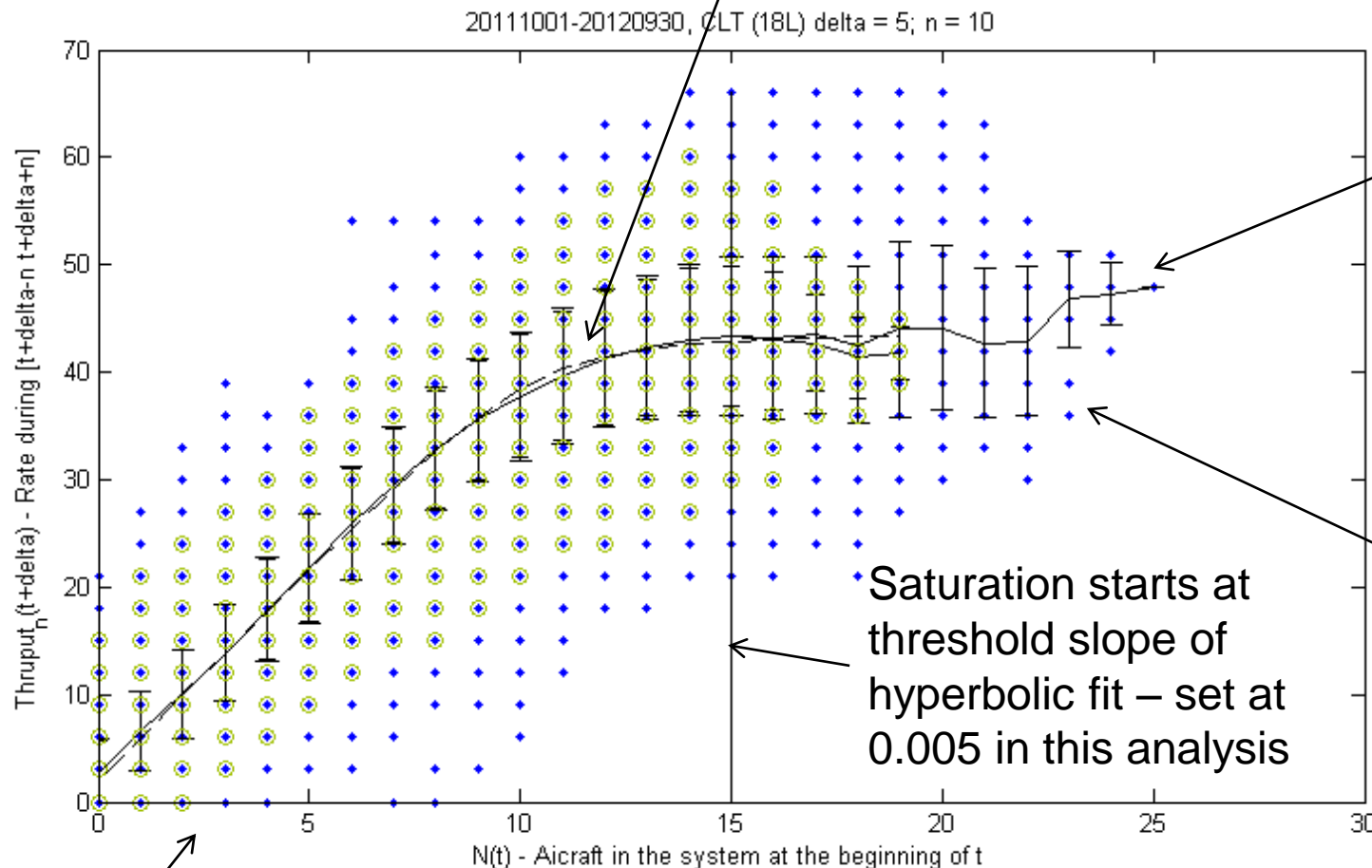
Statistical Models

- Statistical models of historical data used to identify
 - Queue buffer size as queue size that was just enough to cause throughput saturation in historical data
 - Separation between runway operations
 - Unimpeded transit times
- Used one year of data (10/1/2011 – 9/30/2012)
- Combined Aviation System Performance (ASPM) and Airport Surface Detection Equipment (ASDE-X) data
 - ASPM: Pushback time, takeoff time, landing time, parking time, runway configuration, and meteorological conditions
 - ASDE-X: Ramp exit time, takeoff time, landing time, and runway
 - Ninety nine percent matched to within ten minute takeoff time difference

Throughput Saturation Model

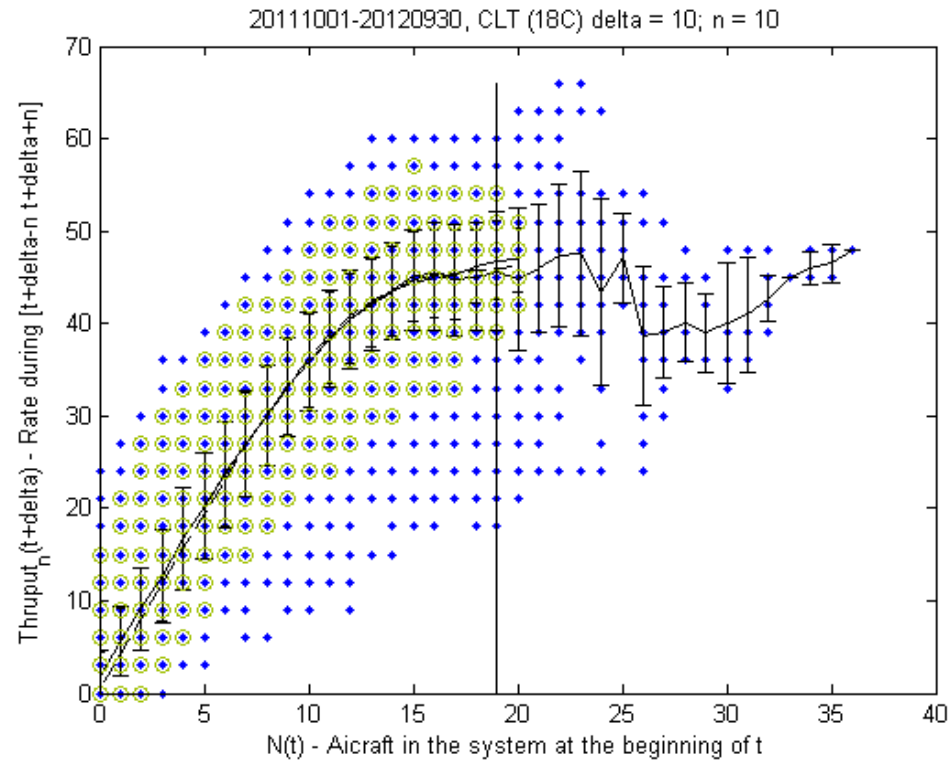
Throughput is number of takeoffs in time window of $2n$ at $t+\delta$

Dashed line: Hyperbolic curve with horizontal asymptote fitted to average throughput



Queue measured as departures due to takeoff at t but did not yet, e.g.:
 for parameter 1, $N(t) = \{ \text{flights } i \text{ with } \text{pushback}(i) \leq t < \text{takeoff}(i) \}$

Queue Buffers at Throughput Saturation

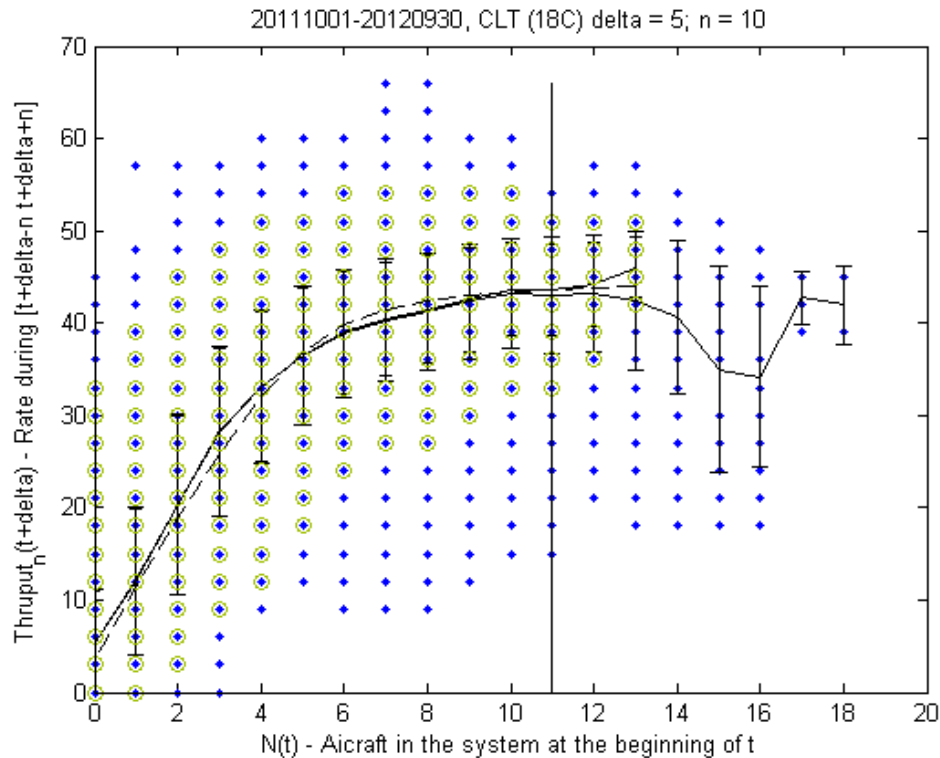


Parameter 1:

$N(t) = \{ \text{flights } i \text{ with } \text{pushback}(i) \leq t \text{ and } \text{takeoff}(i) > t \}$

Nineteen departures needed to cause throughput saturation for runway 18C

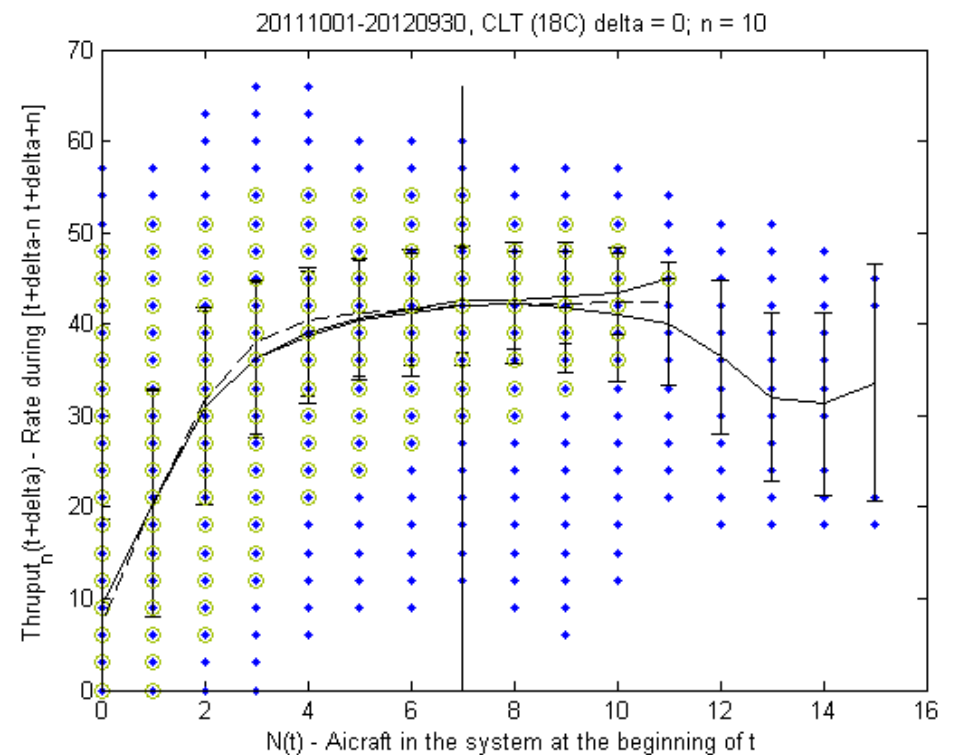
Queue Buffers at Throughput Saturation



Parameter 2:

$$N(t) = \{ \text{flights } i \text{ with } \text{rampexit}(i) \leq t \text{ and } \text{takeoff}(i) > t \}$$

Eleven departures needed to cause throughput saturation for runway 18C



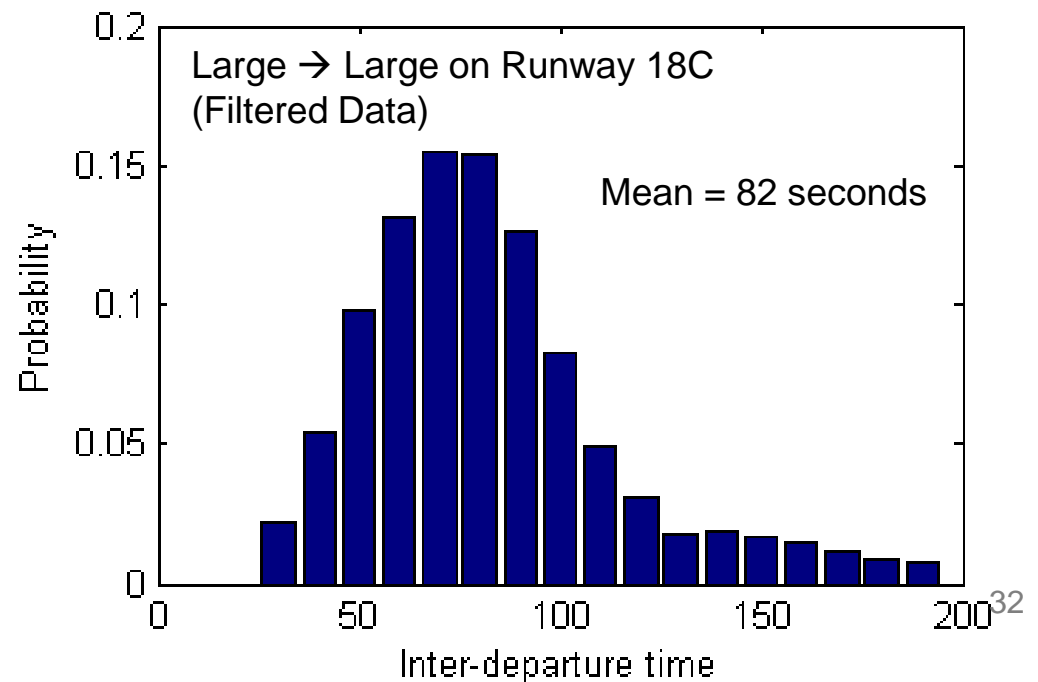
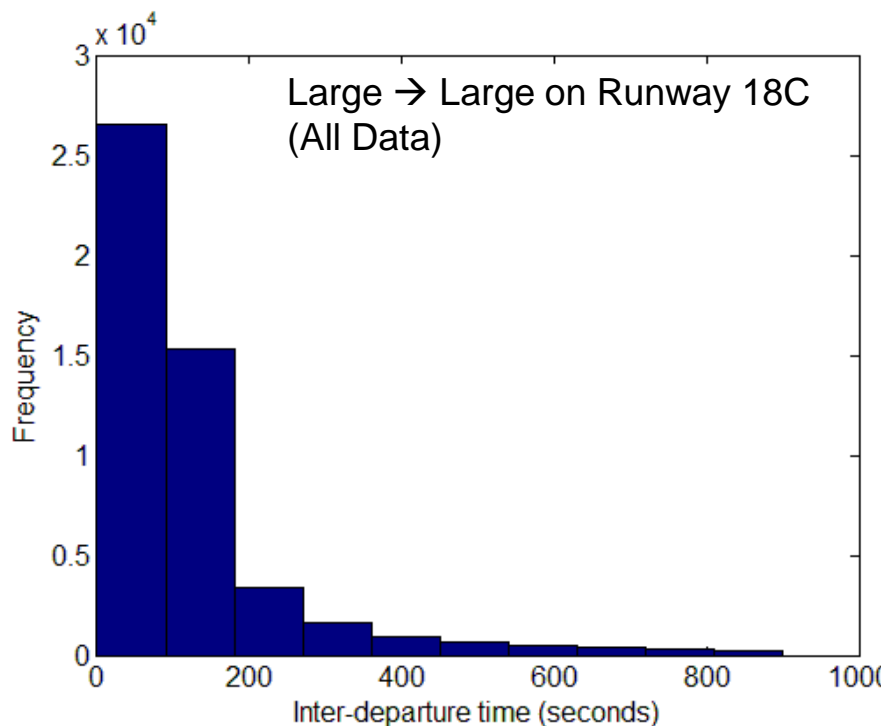
Parameter 3:

$$N(t) = \{ \text{flights } i \text{ with } \text{rampexit}(i) + \text{unimpeded_transit}(i) \leq t \text{ and } \text{takeoff}(i) > t \}$$

Seven departures sufficient to cause throughput saturation for runway 18C

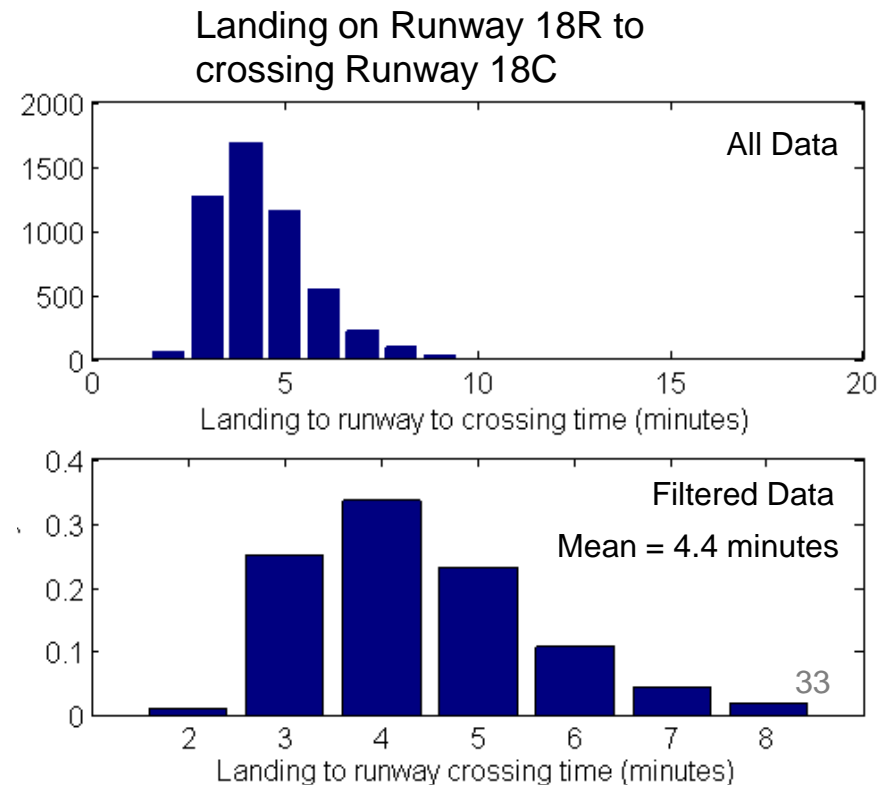
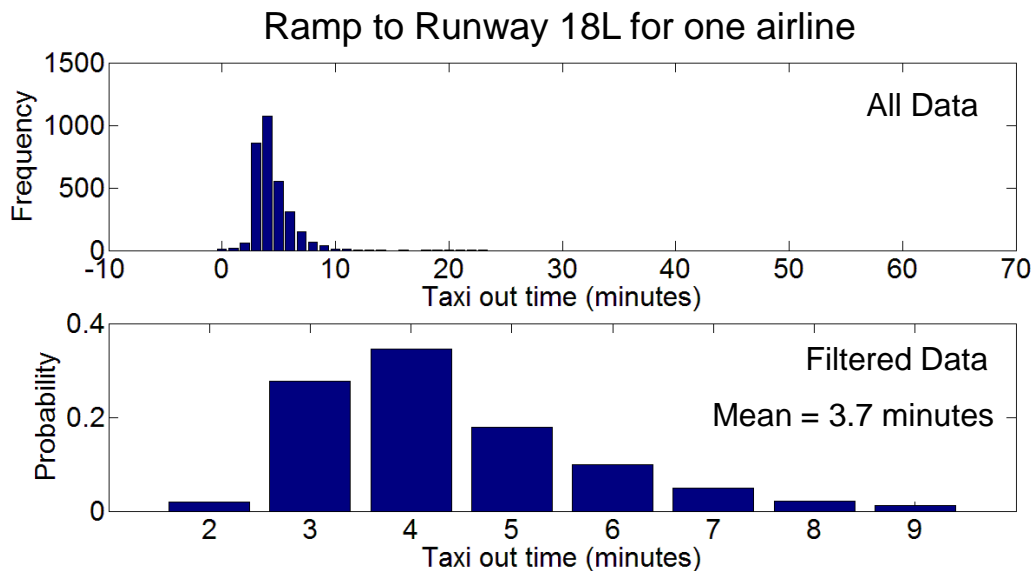
Runway Service Rate Model

- Statistical models generated for all relevant pairs of operations
 - Separation of runway crossing behind and after arrival for each crossing point
 - Separation of runway crossing behind and after departures for each crossing point
 - Separation between successive crossings for each crossing point pair
 - Separation of departure behind and after arrival per weight class pair for each runway
 - Separation between successive departures per weight class pair for each runway



Unimpeded Transit Time Model

- Statistical models generated for unimpeded transit
 - From pushback (ASPM Out time) to takeoff (ASDE-X takeoff) per runway and airline
 - From ramp exit (ASDE-X) to takeoff (ASDE-X) per runway and airline
 - From landing (ASDE-X) to runway crossing (ASDE-X) per runway and runway crossing point



Unimpeded Transit Time Model

for gate-to-runway:

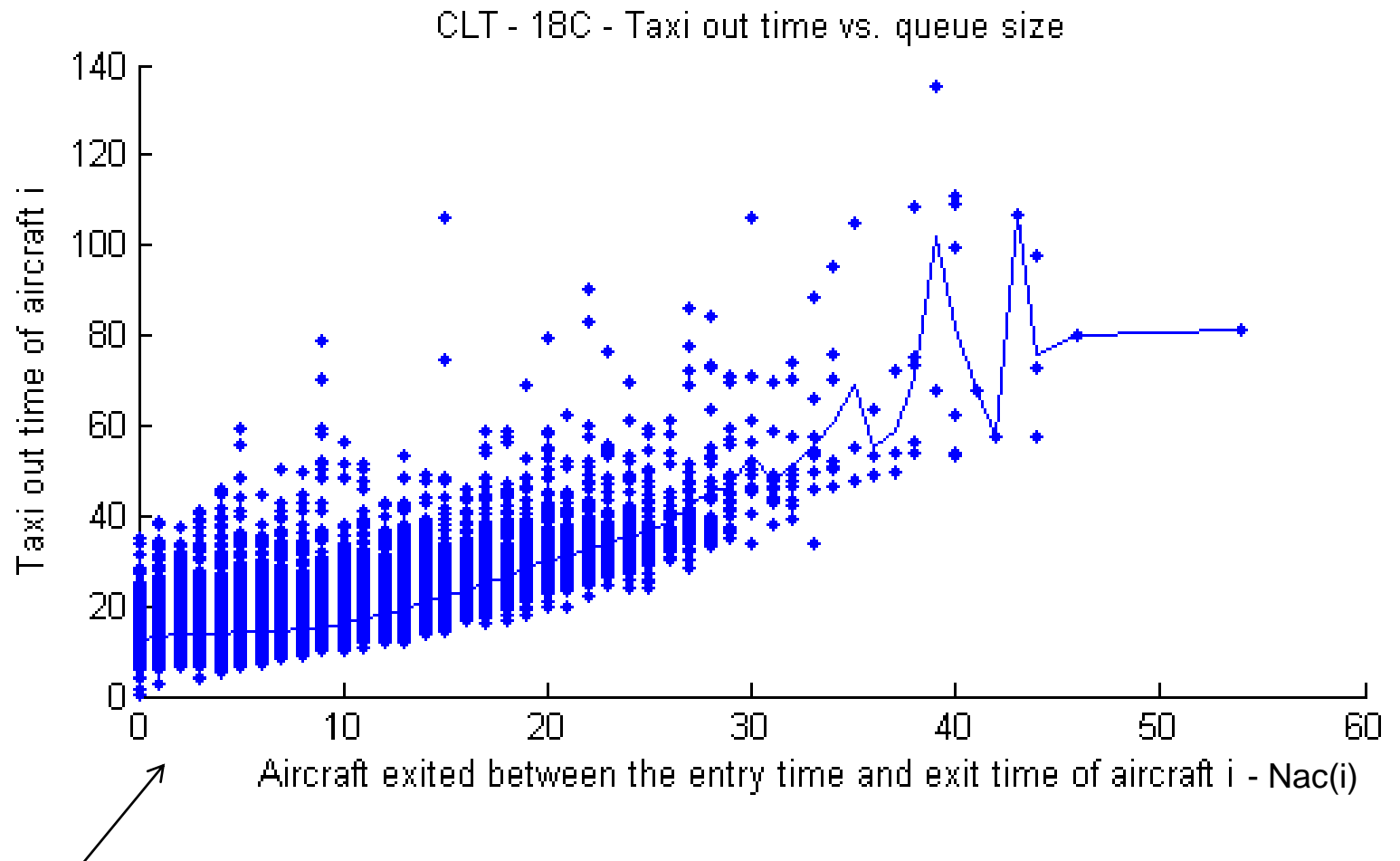
taxi out(i) =
takeoff(i) -
pushback(i)

for ramp-to-runway:

taxi out(i) =
takeoff(i) - ramp
exit(i)

for land-to-cross:

Taxi out =
crossing(i) -
landing(i)

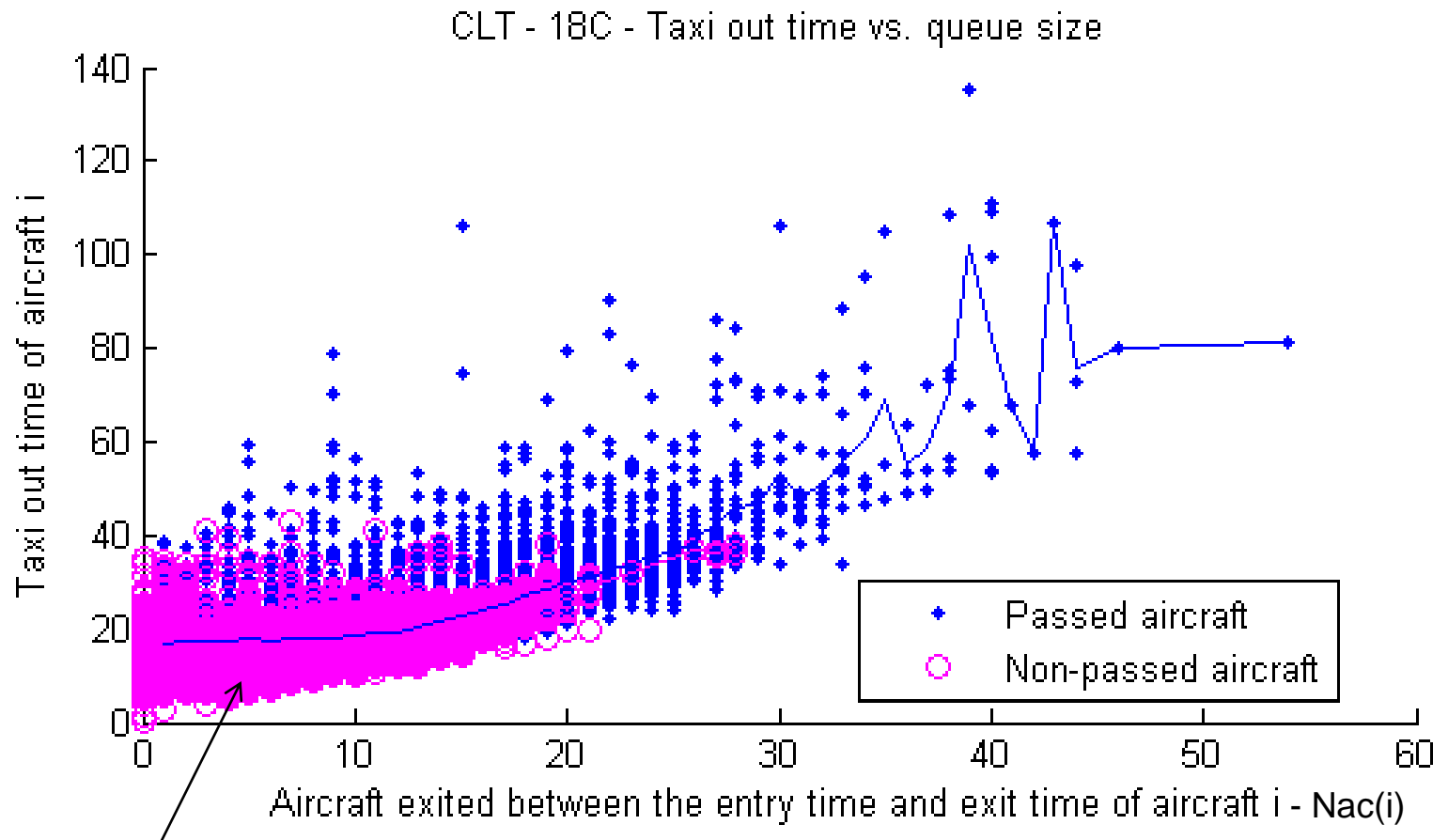


for gate-to-runway: $N_{ac}(i) = \{ \text{flights } j \text{ with } \text{pushback}(i) \leq \text{takeoff}(j) < \text{takeoff}(i) \}$

for ramp-to-runway: $N_{ac}(i) = \{ \text{flights } j \text{ with } \text{ramp exit}(i) \leq \text{takeoff}(j) < \text{takeoff}(i) \}$

for land-to-cross: $N_{ac}(i) = \{ \text{flights } j \text{ with } \text{landing}(i) \leq \text{crossing}(j) < \text{crossing}(i) \}$

Unimpeded Transit Time Model



To reduce non-queuing restriction impacts removed passed flights:

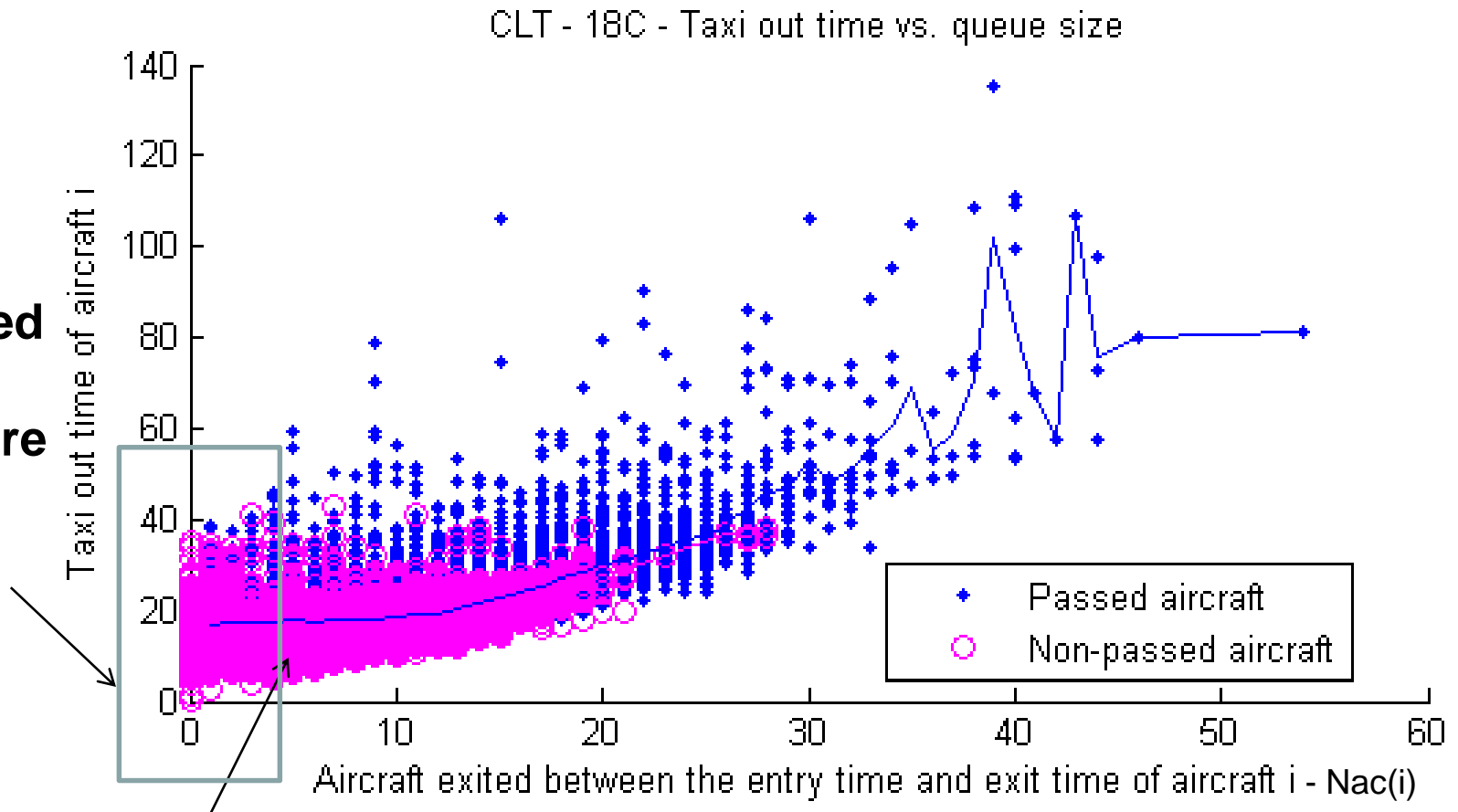
for gate-to-runway: $N_{ac}(i) = \{ \text{flights } j \text{ with } \text{pushback}(i) \leq \text{takeoff}(j) < \text{takeoff}(i) \text{ and } \text{pushback}(j) \leq \text{pushback}(i) \}$

for gate-to-runway: $N_{ac}(i) = \{ \text{flights } j \text{ with } \text{rampexit}(i) \leq \text{takeoff}(j) < \text{takeoff}(i) \text{ and } \text{rampexit}(j) \leq \text{rampexit}(i) \}$

for land-to-cross: $N_{ac}(i) = \{ \text{flights } j \text{ with } \text{landing}(i) \leq \text{crossing}(j) < \text{crossing}(i) \text{ and } \text{landing}(j) \leq \text{landing}(i) \}$

Unimpeded Transit Time Model

To reduce queuing impacts used low queue values before correlation starts



To reduce non-queuing restriction impacts removed passed flights:

for gate-to-runway: $N_{ac}(i) = \{ \text{flights } j \text{ with } \text{pushback}(i) \leq \text{takeoff}(j) < \text{takeoff}(i) \text{ and } \text{pushback}(j) \leq \text{pushback}(i) \}$

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for land-to-cross: $N_{ac}(i) = \{ \text{flights } j \text{ with } \text{landing}(i) \leq \text{crossing}(j) < \text{crossing}(i) \text{ and } \text{landing}(j) \leq \text{landing}(i) \}$

Analysis Scenarios

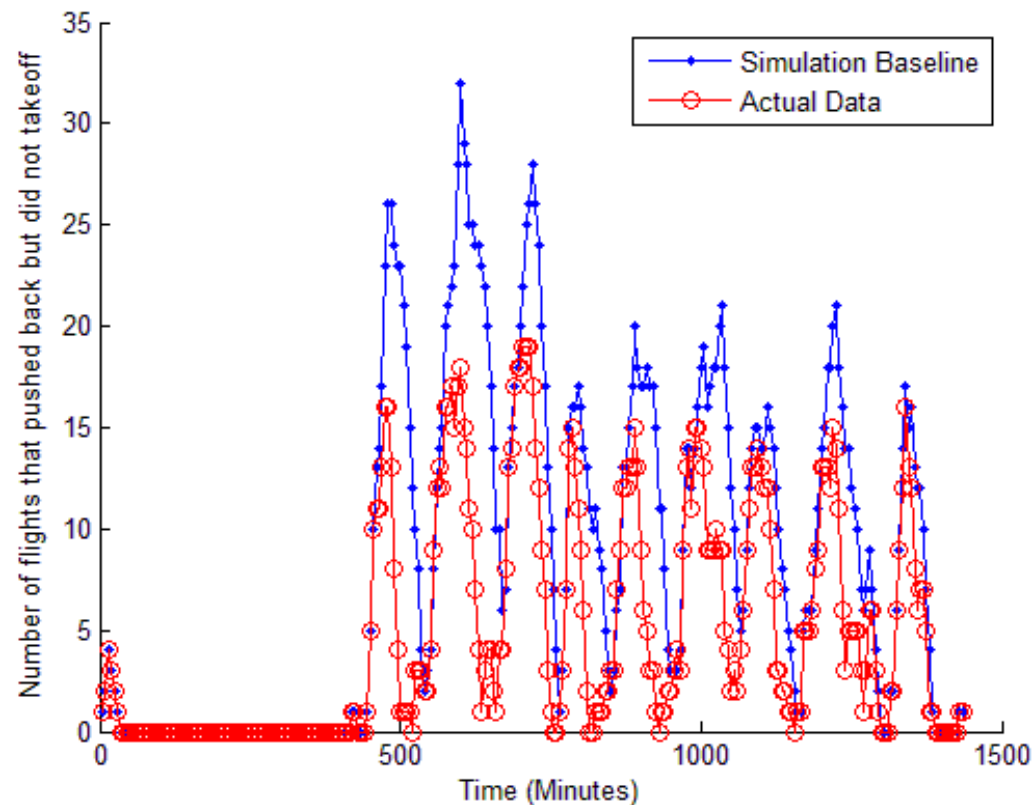
- Simulated July 17, 2012 at CLT in South runway configuration
- Scenarios

| Scenario | Deterministic No metering (baseline) | Deterministic Metering | Metering under Uncertainty | Metering under Uncertainty |
|--|---|-----------------------------------|---|---|
| Metering | Off | On | On | On |
| Demand Uncertainty | Off | Off | On | Off |
| Transit & Runway Separation Uncertainty | Off | Off | Off | On |

- Metrics
 1. Reduction in congestion due to metering
 2. Delay that was absorbed at the gate due to metering
 3. Change in flight takeoff time due to metering measures overall delay and hence runway throughput

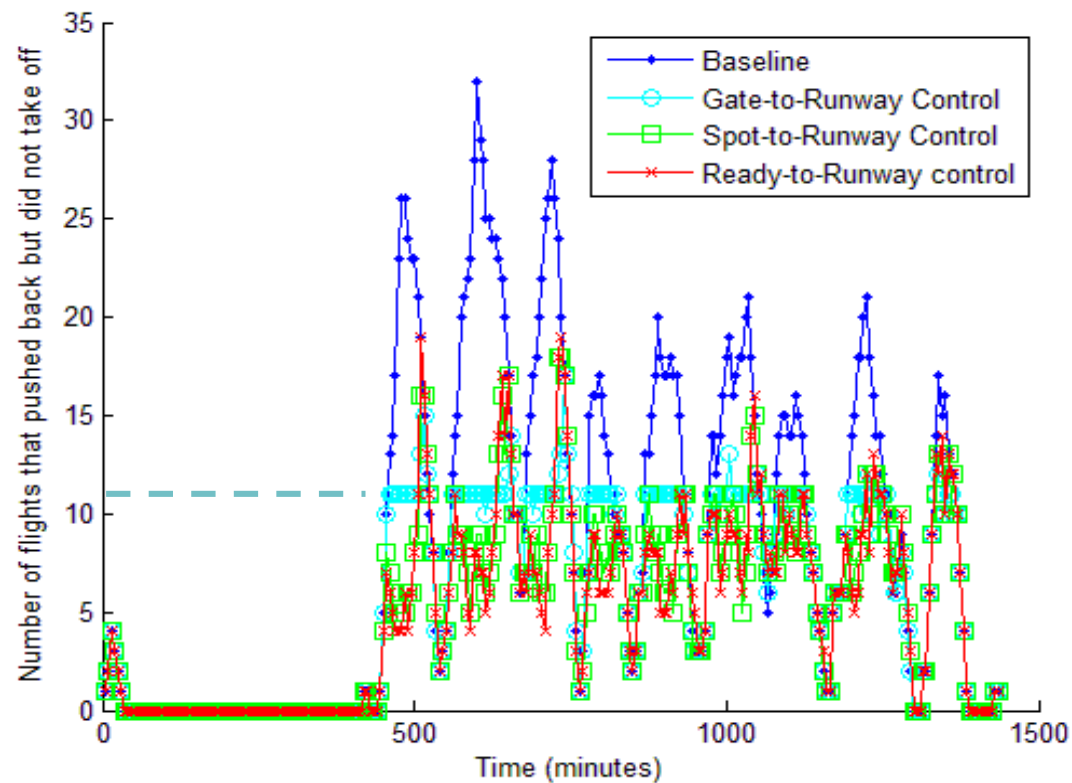
Model Validation

- Simulation overestimated congestion level relative to actual data for at least some of departure peaks
 - Further calibration of runway separation and transit times needed for model validation
 - Numbers reported do not reflect validated benefits



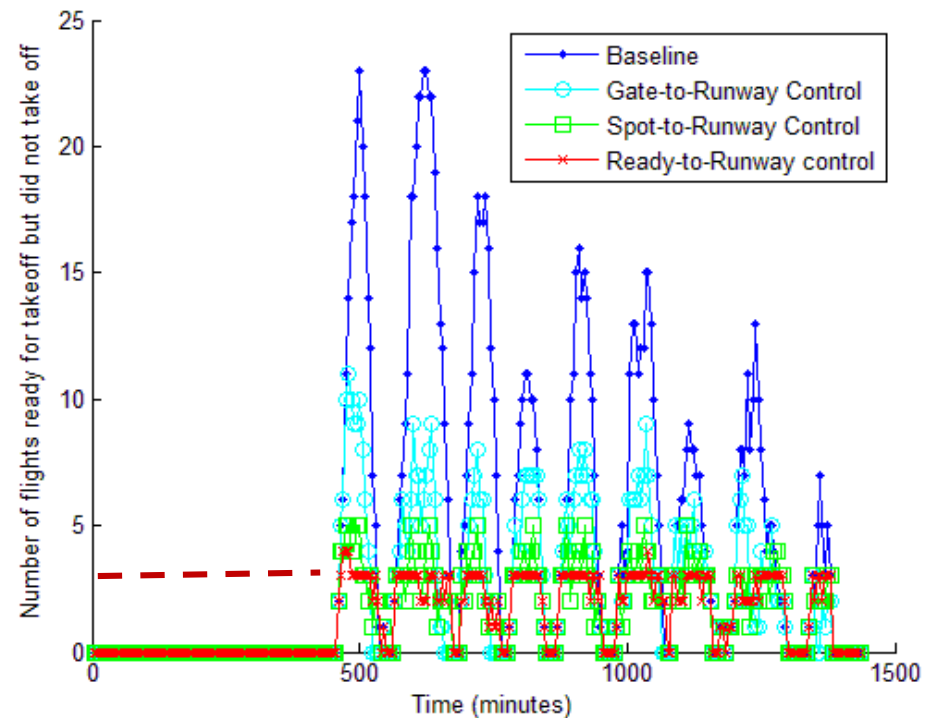
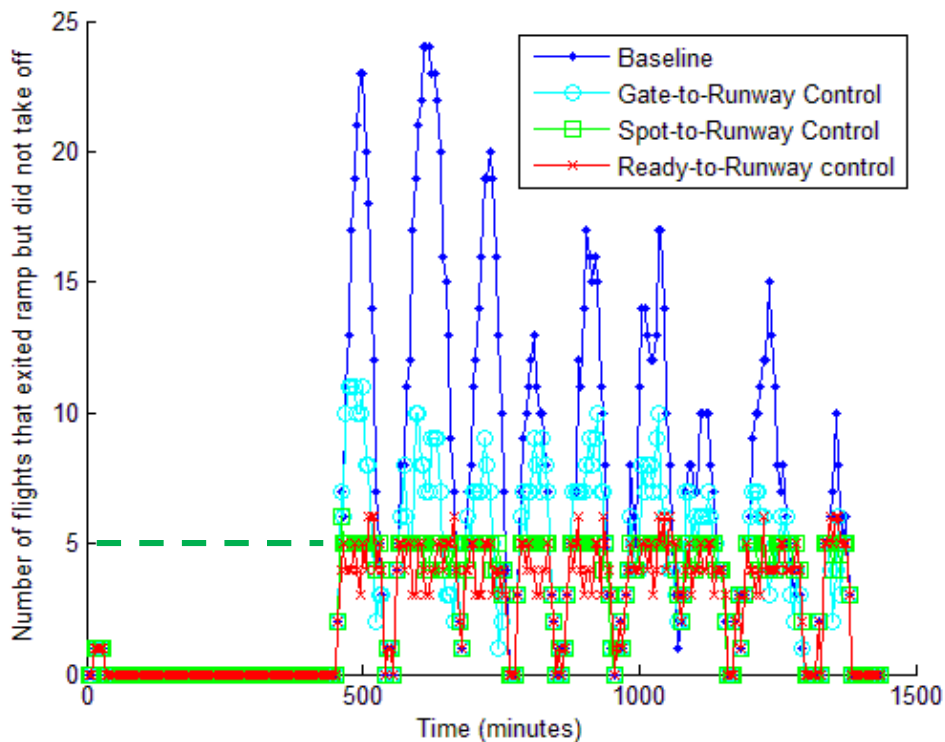
Metering Effect on Queuing Parameters

- Deterministic scenario
- Each strategy controls corresponding queuing parameter explicitly and the other queuing parameters implicitly



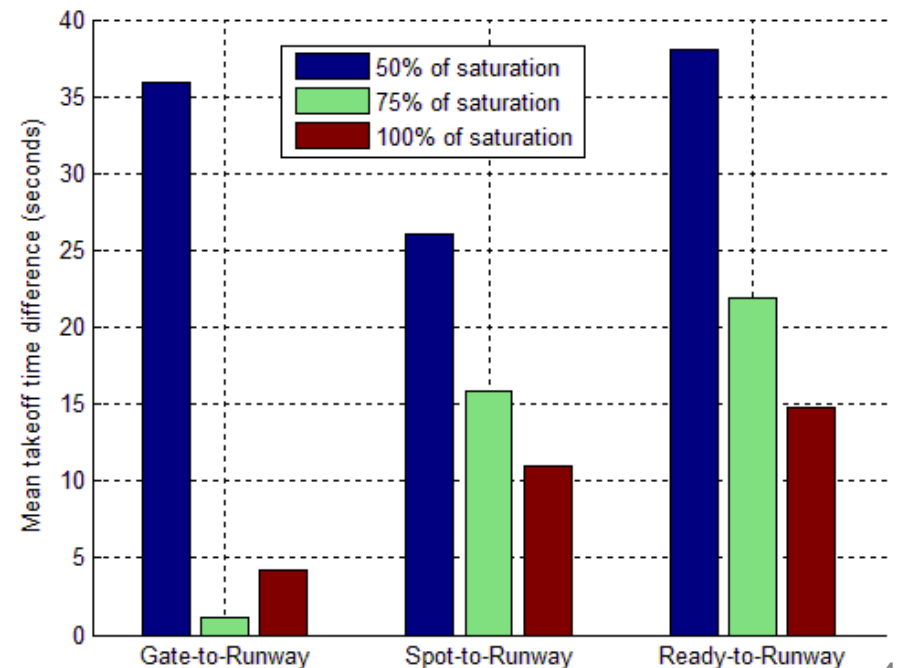
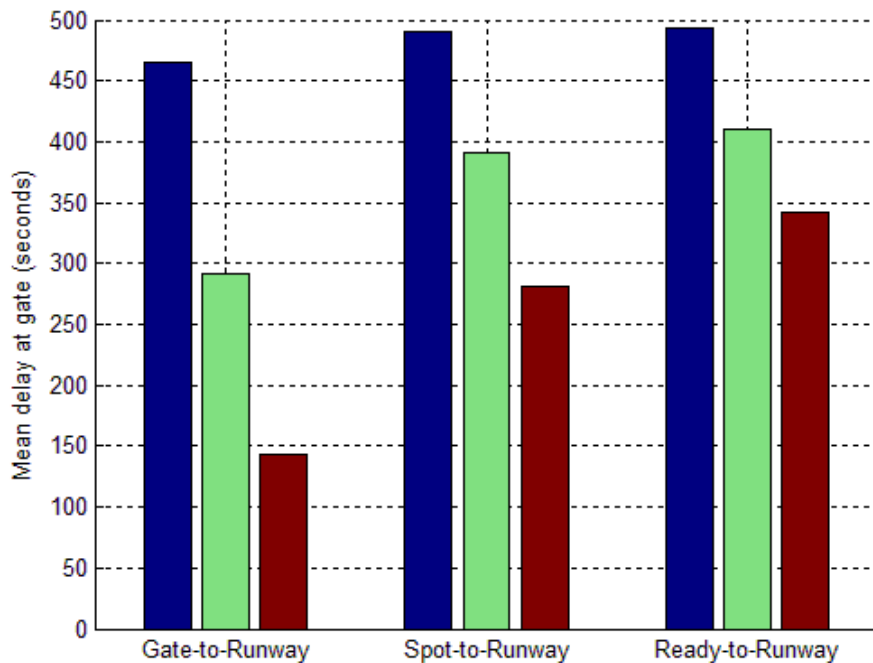
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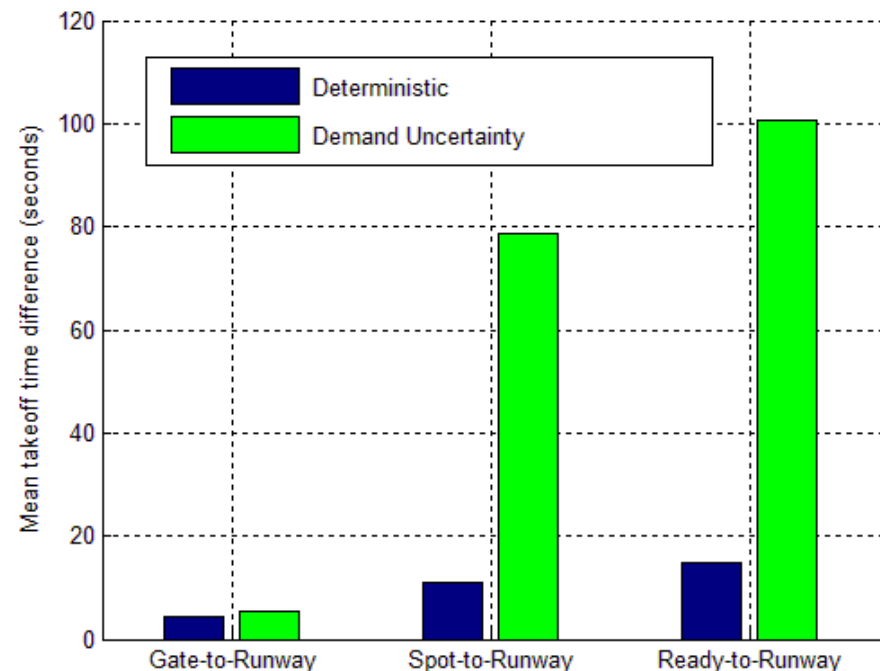
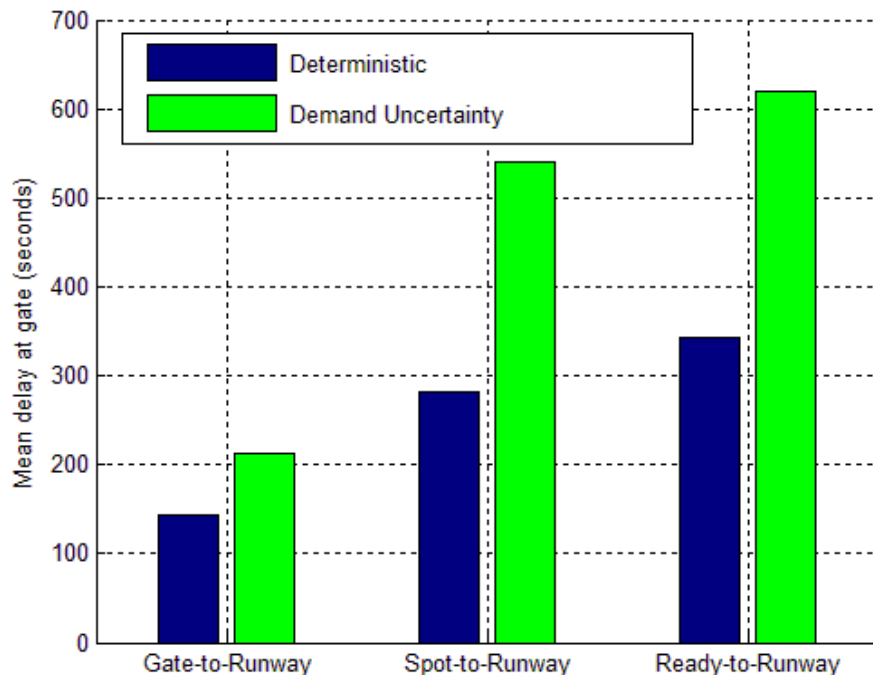
Effect of Queue Buffer Size

- Deterministic scenario
- Smaller queue buffer results in more gate delay but more takeoff delay
 - Buffer at 100% of throughput saturation needed for takeoff delay less than 5 seconds
- Gate-to-runway control strategy more effective at maintaining runway throughput



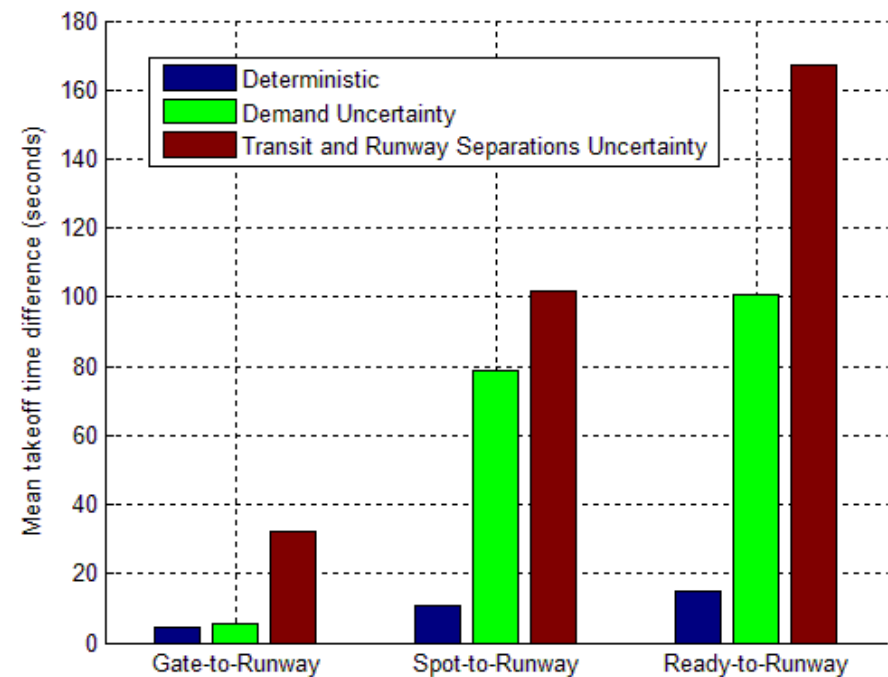
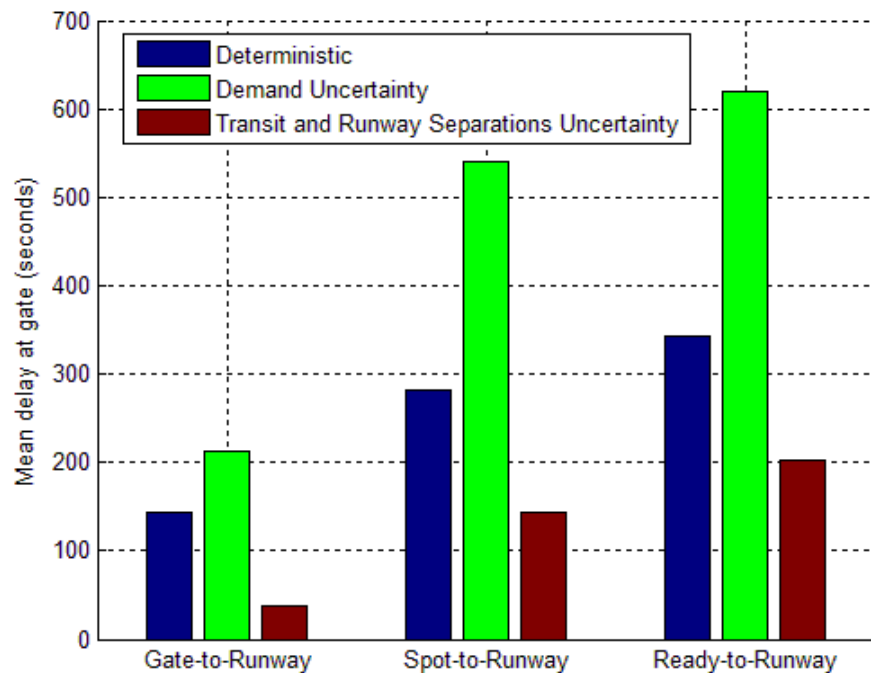
Effect of Demand Uncertainty

- Demand uncertainty modeled is extreme:
 - Modeled by scheduler using flight plan pushback time to estimate runway demand
- Only Gate-to-Runway strategy able to withstand demand uncertainty
 - Significant gate delay with minimal impact on takeoff time
- Queue buffers at 100% of throughput saturation level



Effect of Service and Transit time uncertainties

- Model:
 - Scheduler assumed means of runway separation and unimpeded transit time distributions while simulation update randomly sampled from distribution
- Impact more severe than demand uncertainty
 - Gate delay small relative to deterministic and demand uncertainty cases
 - Caused large takeoff time delay



Conclusions

- Challenge to apply departure metering without negative impact on runway take off time and throughput
 - What is an acceptable impact on takeoff time, 5 seconds, 40 seconds?
 - Requires analysis of impact on arrival times and network effects
- Reducing uncertainty is important for effective departure metering with less impact on runway throughput
 - Better demand information
 - Better modeling of transit and service times
 - Tactical control to close loop on deviations from runway schedule
- It is not sufficient to maintain queue buffer at runway end
 - Need queue buffers between gate and runway to maintain continuity of traffic flow

High Fidelity Simulation Analysis Outline

- Motivation and Background
- Approach
- Models and Simulation
- Analysis and Results
 - Model performance
 - Queue management (Metering) effects
 - Gate blocking effects
- Observations and Future Extentions

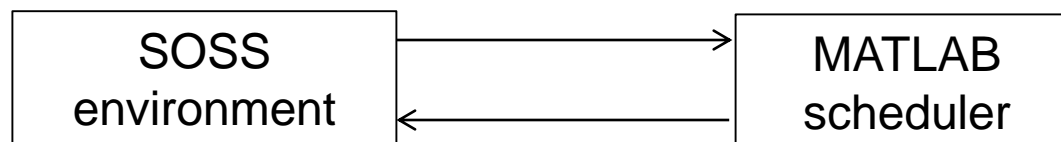
High Fidelity Simulation Analysis

Motivation and background

- Objective: Assess feasibility of some aspects of ATD-2 concept in high fidelity simulation environment
- Applied strategic queue management to CLT airport
- Looked at performance of queue management in terms of tradeoff between departure gate holding and arrival gate blocking
- Used NASA's SOSS as the high fidelity simulation environment

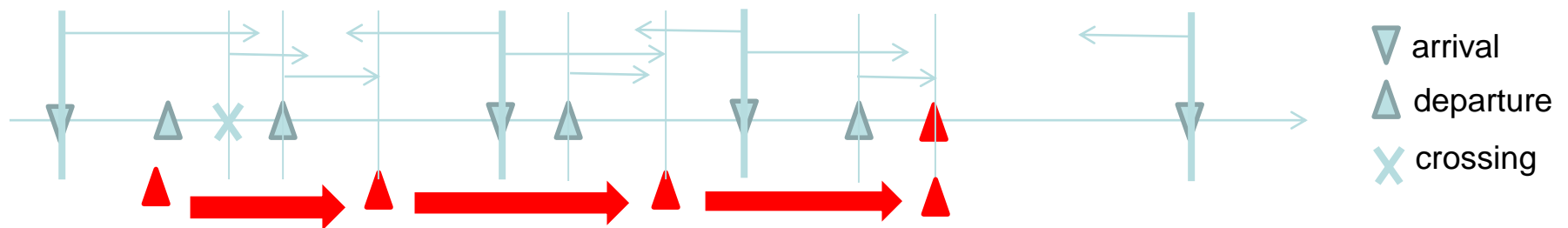
High Fidelity Simulation Analysis Approach

- Used SOSS as high fidelity simulation environment
- Used MATLAB scheduling algorithms already tested in low fidelity MATLAB simulation (DASC 2016)
 - Modified MATLAB algorithms to interface with SOSS
- Connected MATLAB scheduler to SOSS using MATLAB scripts provided by ATAC
 - Slight modifications to accommodate new SOSS version



High Fidelity Simulation Analysis Runway Scheduling Algorithm

- Inputs:
 - Landing demand: Expected arrival landing times from SOSS
 - Takeoff demand: Expected takeoff times using flight current state plus unimpeded transit time from SOSS
 - Runway crossing demand: expected runway crossing time using current flight state plus unimpeded transit time from SOSS
 - Required separations: Using separation requirements from SOSS
- Logic (same as DASC 2016):
 - For each departure and runway crossing operation in FCFS order according to expected operation times
 - Find earliest gap between arrivals that satisfies all separation requirements (using means of distributions)
 - Consider all dependent runways (e.g., 18C and 23 arrivals for 18C departure)



High Fidelity Simulation Analysis

Metering Algorithm

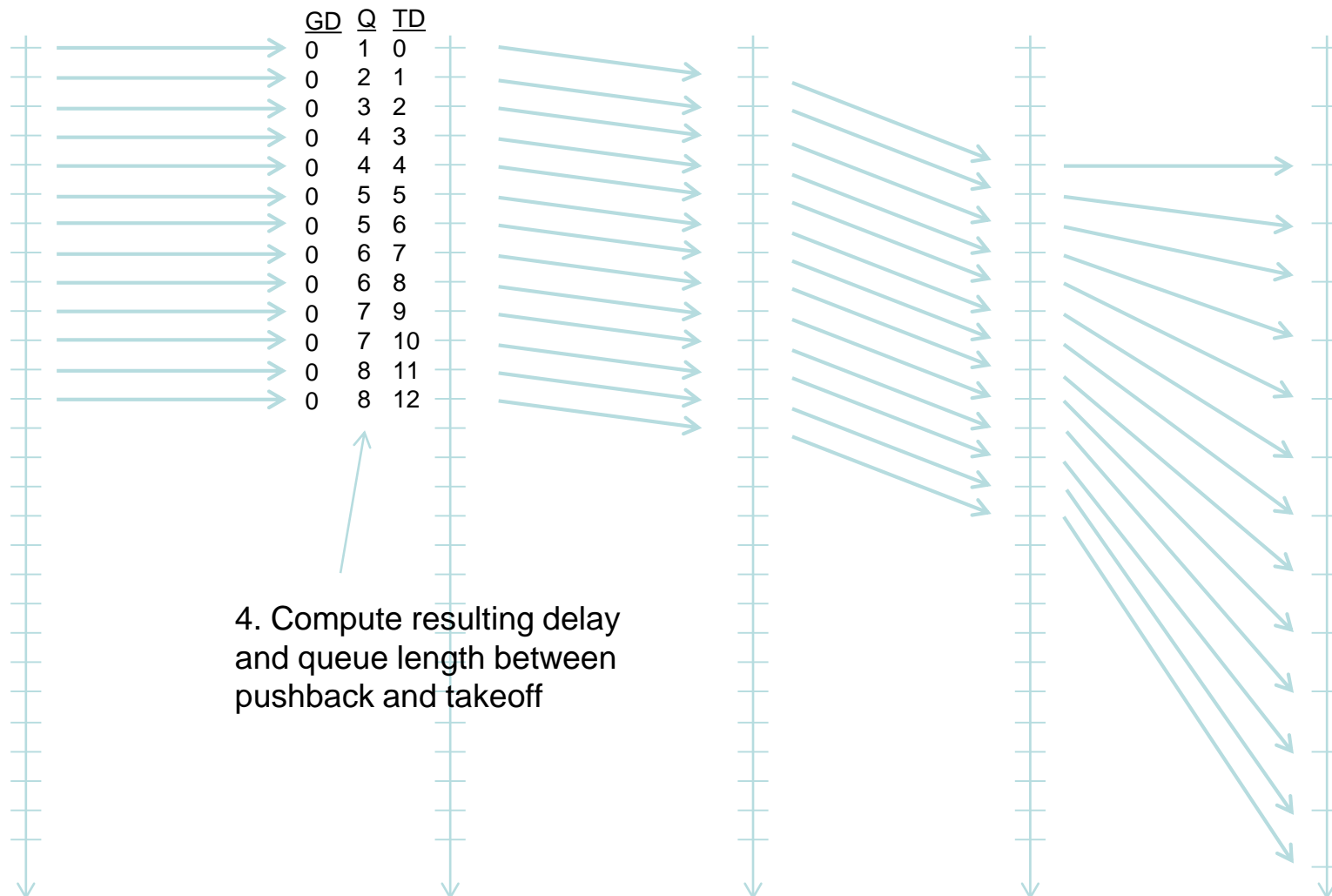
Demand at gate
(flight plan
pushback time)

Scheduled
release from
gate

Scheduled
release from
ramp

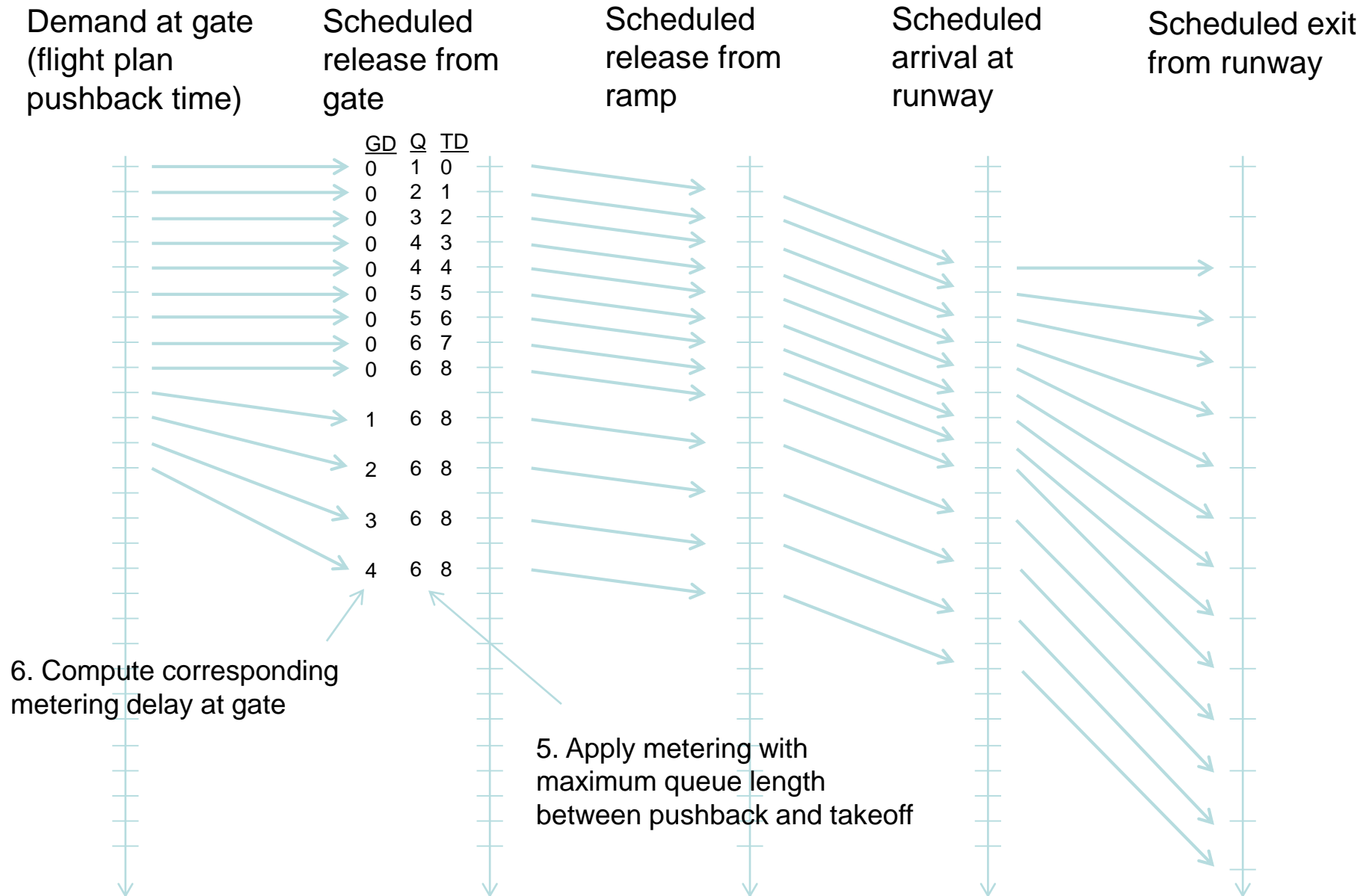
Scheduled
arrival at
runway

Scheduled exit
from runway



High Fidelity Simulation Analysis

Metering Algorithm



High Fidelity Simulation Analysis Metering Algorithm

- Gate constraints applied to departure metering delay at gate
- Assumed gate assignment known to the scheduler as given by SOSS
- Departure is released from gate a certain time buffer before the estimated arrival time at the gate but never earlier than the departure pushback ready time
- Gate blocking time buffer varied in analysis to determine the value needed to minimize the delay on arrivals

High Fidelity Simulation Analysis

Experiment Scenarios

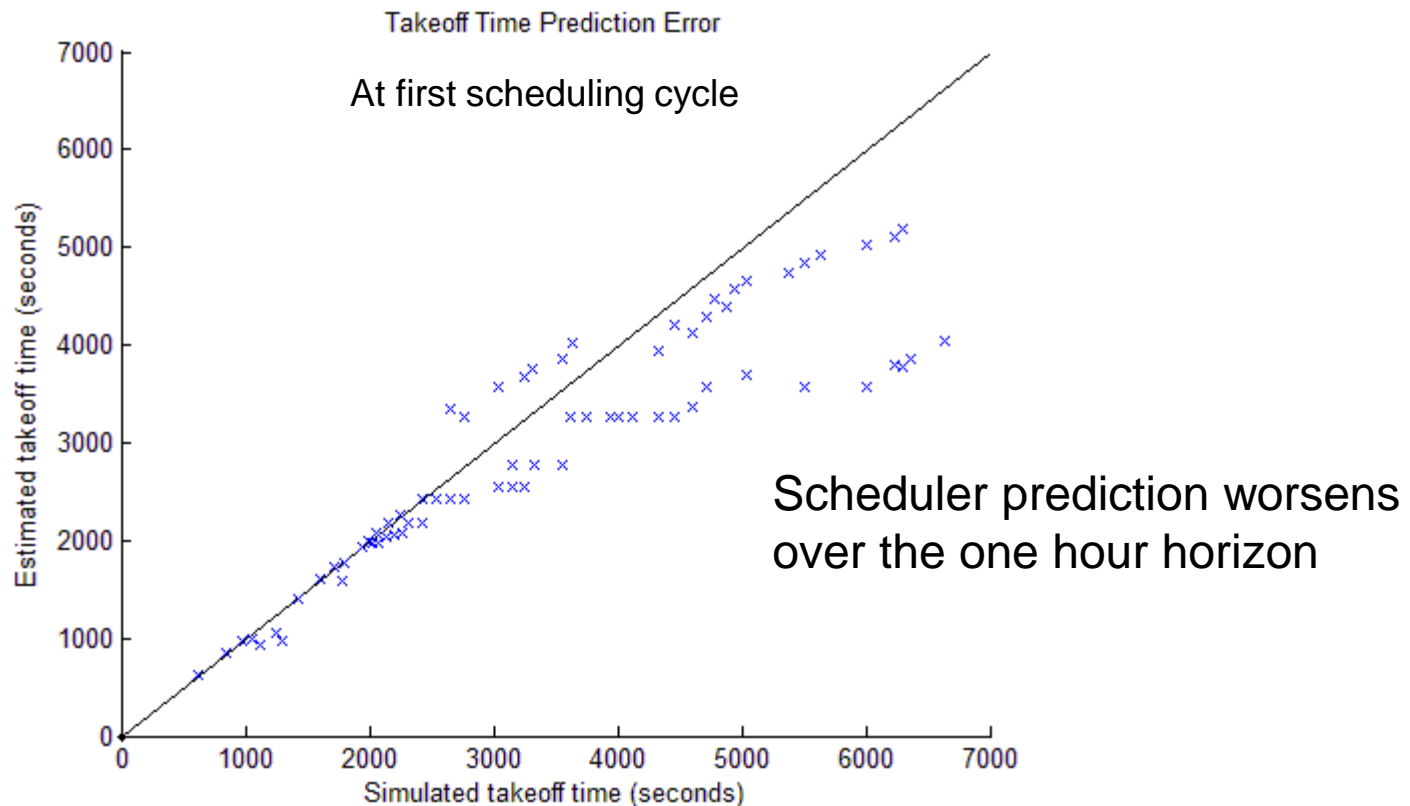
- Simulated 4 hours on 3/11/2016 at CLT in South runway configuration, 199 departures, 175 arrivals (provided by NASA)
- Scenarios

| Scenario | Run 1 | Run 2 | Run 3 | Run 4 | Run 5 |
|-----------------------------------|--------------|--------------|--------------|--------------|--------------|
| Metering | Off | On | On | On | On |
| Gate release buffer | Off | Off | 1 min | 2 min | 3 min |
| Queue buffer (18C/18L) | Off | 15/12 | 15/12 | 15/12 | 15/12 |
| Frequency/horizon | Off | 5/60 min | 5/60 min | 5/60 min | 5/60 min |

- Metrics
 1. Reduction in congestion due to metering
 2. Delay that was absorbed at the gate due to metering
 3. Change in takeoff time measures overall delay and throughput
 4. Taxi in delay to measure impact on arrivals due to gate blocking

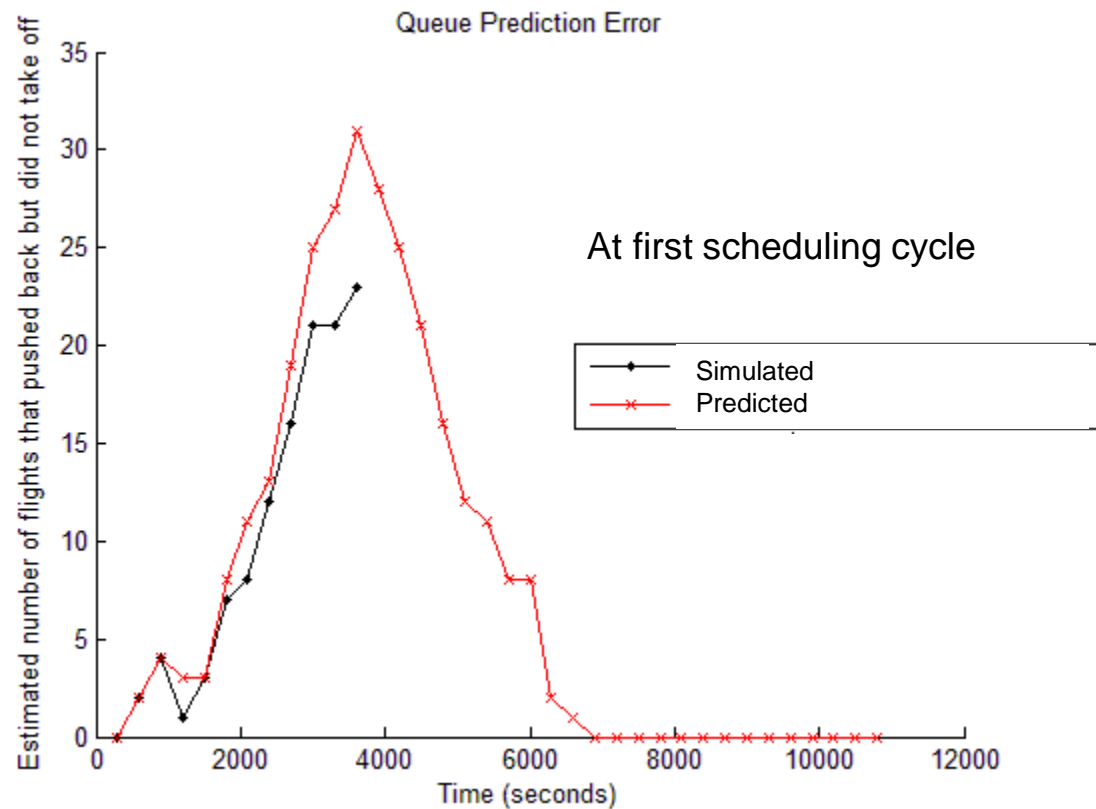
High Fidelity Simulation Analysis Results and Observations

- Prediction performance
 - Takeoff time estimates are earlier than SOSS takeoff times
 - Scheduler uses SOSS separation criteria and unimpeded transit times, but does not account for other delays due to interactions on the surface



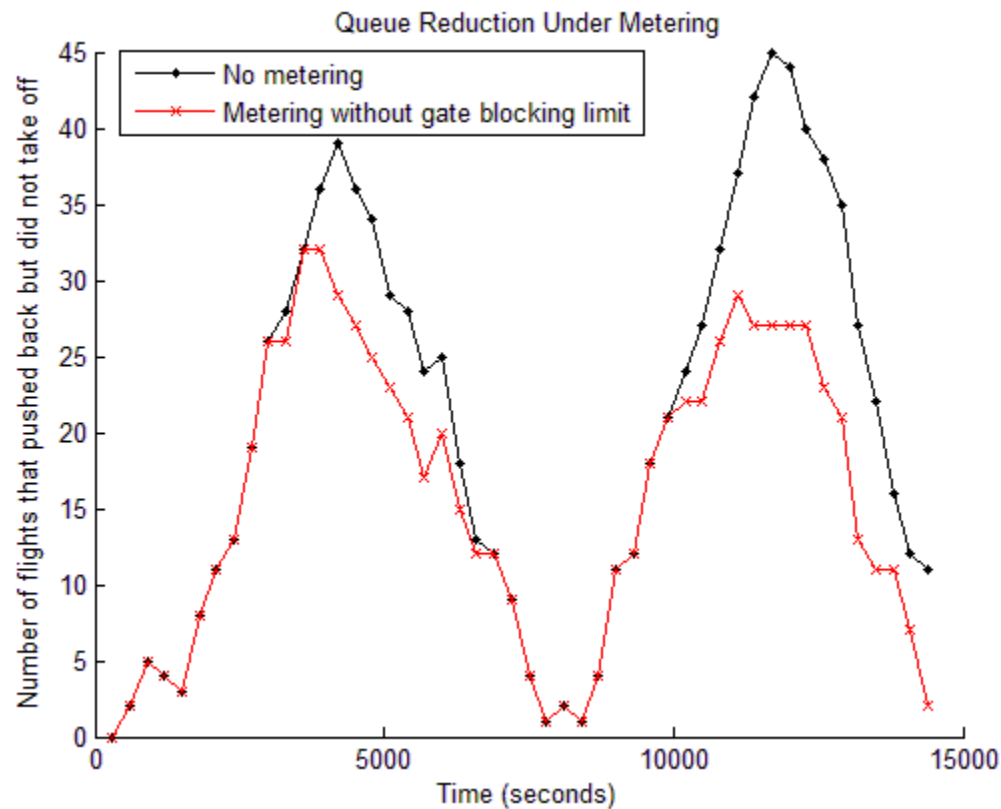
High Fidelity Simulation Analysis Results and Observations

- Prediction performance
 - Queue under predicted by scheduler leading to conservative metering delays



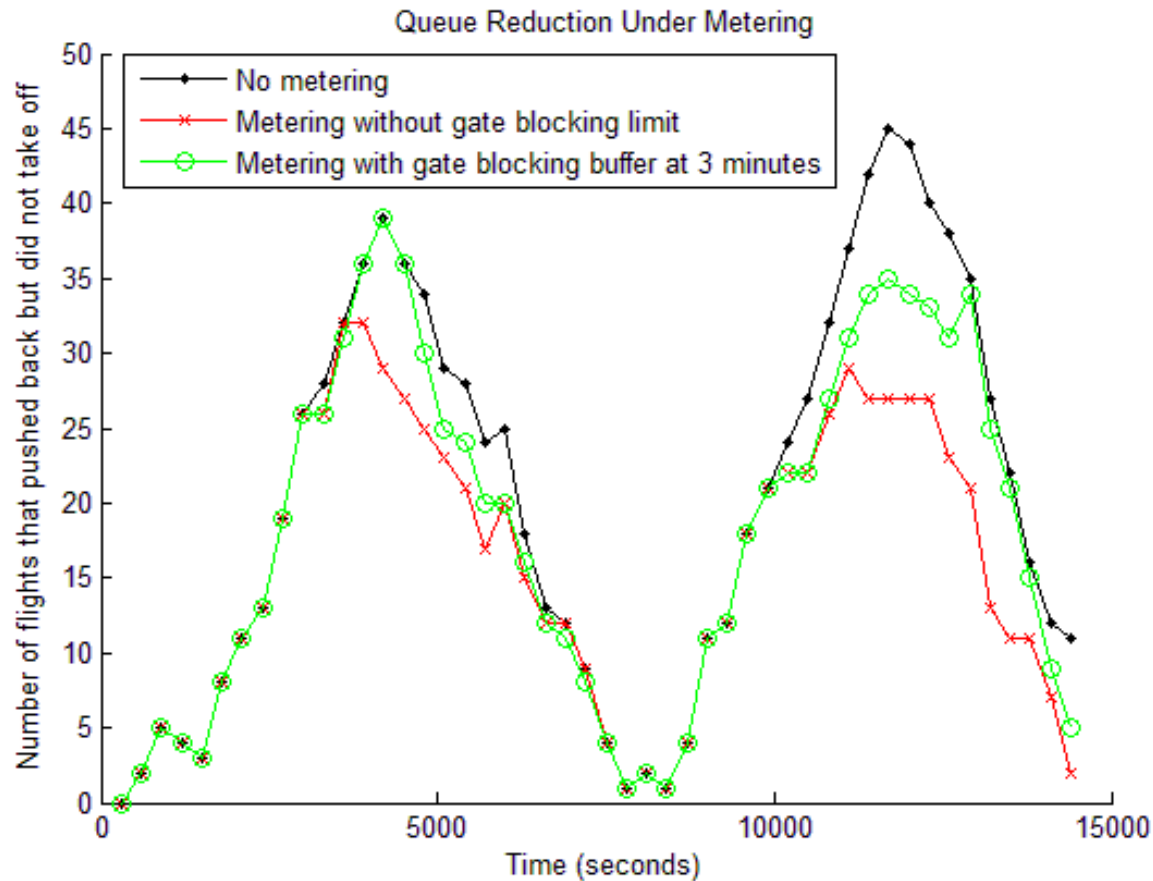
High Fidelity Simulation Analysis Results and Observations

- Metering queue control
 - Number of flights that pushed back but did not take off effectively reduced to threshold value (15 for 18C and 12 for 18L)



High Fidelity Simulation Analysis Results and Observations

- Metering queue control with gate blocking limit
 - Gate blocking limit reduced amount of metering



High Fidelity Simulation Analysis Results and Observations

- Metering queue control with gate blocking limit
 - Gate holding delay decreases with gate blocking limit

| | Average Gate Delay (Metered /All) | Total Gate Delay | Average Takeoff Delay | Total Takeoff Delay | Average Taxi-in Delay | Total Taxi-in Delay | Number Metered Flights | Number Blocked Flights |
|----------------------------------|-----------------------------------|------------------|-----------------------|---------------------|-----------------------|---------------------|------------------------|------------------------|
| No metering | 0 | 0 | 19.3 | 3835 | 1.7 | 293 | 0 | 0 |
| Metering w/o gate blocking limit | 8.4/3.25 | 588 | 18.9 | 3413 | 4.2 | 701 | 70 | 11 |
| Metering with 1 min gate buffer | Gridlock | | | | | | | |
| Metering with 2 min gate buffer | 6.7/2.8 | 545 | 19.7 | 3826 | 2.2 | 391 | 86 | 1 |
| Metering with 3 min gate buffer | 5.9/2.5 | 475 | 19.6 | 3776 | 1.6 | 281 | 86 | 1 |

High Fidelity Simulation Analysis Results and Observations

- Metering queue control with gate blocking limit
 - Queue buffer sufficient to keep takeoff time difference very small

| | Average Gate Delay (Metered /All) | Total Gate Delay | Average Takeoff Delay | Total Takeoff Delay | Average Taxi-in Delay | Total Taxi-in Delay | Number Metered Flights | Number Blocked Flights |
|----------------------------------|-----------------------------------|------------------|-----------------------|---------------------|-----------------------|---------------------|------------------------|------------------------|
| No metering | 0 | 0 | 19.3 | 3835 | 1.7 | 293 | 0 | 0 |
| Metering w/o gate blocking limit | 8.4/3.25 | 588 | 18.9 | 3413 | 4.2 | 701 | 70 | 11 |
| Metering with 1 min gate buffer | Gridlock | | | | | | | |
| Metering with 2 min gate buffer | 6.7/2.8 | 545 | 19.7 | 3826 | 2.2 | 391 | 86 | 1 |
| Metering with 3 min gate buffer | 5.9/2.5 | 475 | 19.6 | 3776 | 1.6 | 281 | 86 | 1 |

High Fidelity Simulation Analysis Results and Observations

- Metering queue control with gate blocking limit
 - Taxi in delay decreases when gate blocking limit is applied

| | Average Gate Delay (Metered /All) | Total Gate Delay | Average Takeoff Delay | Total Takeoff Delay | Average Taxi-in Delay | Total Taxi-in Delay | Number Metered Flights | Number Blocked Flights |
|----------------------------------|-----------------------------------|------------------|-----------------------|---------------------|-----------------------|---------------------|------------------------|------------------------|
| No metering | 0 | 0 | 19.3 | 3835 | 1.7 | 293 | 0 | 0 |
| Metering w/o gate blocking limit | 8.4/3.25 | 588 | 18.9 | 3413 | 4.2 | 701 | 70 | 11 |
| Metering with 1 min gate buffer | Gridlock | | | | | | | |
| Metering with 2 min gate buffer | 6.7/2.8 | 545 | 19.7 | 3826 | 2.2 | 391 | 86 | 1 |
| Metering with 3 min gate buffer | 5.9/2.5 | 475 | 19.6 | 3776 | 1.6 | 281 | 86 | 1 |

High Fidelity Simulation Analysis Results and Observations

- Metering queue control with gate blocking limit
 - Releasing departure three minutes before estimated arrival at gate sufficient to eliminate taxi in delay

| | Average Gate Delay (Metered /All) | Total Gate Delay | Average Takeoff Delay | Total Takeoff Delay | Average Taxi-in Delay | Total Taxi-in Delay | Number Metered Flights | Number Blocked Flights |
|----------------------------------|-----------------------------------|------------------|-----------------------|---------------------|-----------------------|---------------------|------------------------|------------------------|
| No metering | 0 | 0 | 19.3 | 3835 | 1.7 | 293 | 0 | 0 |
| Metering w/o gate blocking limit | 8.4/3.25 | 588 | 18.9 | 3413 | 4.2 | 701 | 70 | 11 |
| Metering with 1 min gate buffer | Gridlock | | | | | | | |
| Metering with 2 min gate buffer | 6.7/2.8 | 545 | 19.7 | 3826 | 2.2 | 391 | 86 | 1 |
| Metering with 3 min gate buffer | 5.9/2.5 | 475 | 19.6 | 3776 | 1.6 | 281 | 86 | 1 |

High Fidelity Simulation Analysis

Results and Observations

- Taxi in delay of arrival flights that experienced gate blocking
 - Arrivals with nominal arrival at gate larger than departure arrival at gate and less than departure release from gate (in run 2: metering with gate blocking)

| Arrival | No Metering | Metering with gate blocking | Metering with 2 min gate buffer | Metering with 3 min gate buffer |
|---------|-------------|-----------------------------|---------------------------------|---------------------------------|
| PDT4934 | 2.8 | 11.28 | 1.75 | 1.75 |
| AAL790 | 5.3 | 11.9 | 4.92 | 4.92 |
| AAL2053 | 4.7 | 11.50 | 4.86 | 4.86 |
| AAL850 | 0.30 | 15.19 | 2.44 | 1.19 |
| AAL657 | 0.06 | 2.588 | 0.057 | 0.057 |
| AAL826 | 0.61 | 23.28 | 28.84 | 8.15 |
| AAL887 | 0.05 | 20.86 | 25.02 | 4.37 |
| JIA5091 | 1.44 | 10.4 | 1.44 | 1.60 |
| AAL1989 | 1.29 | 22.96 | 3.64 | 3.64 |

High Fidelity Simulation Analysis

Results and Observations

- Gate delay of departures that blocked arrivals at gate
 - Arrivals with nominal arrival at gate larger than departure arrival at gate and less than departure release from gate (in run 2: metering with gate blocking)

| Departure | No Metering | Metering with gate blocking | Metering with 2 min gate buffer | Metering with 3 min gate buffer |
|-----------|-------------|-----------------------------|---------------------------------|---------------------------------|
| PDT4847 | 0 | 9.541 | 0 | 0 |
| AAL1965 | 0 | 16.92 | 0 | 0 |
| AAL1910 | 0 | 13.26 | 0 | 0 |
| AAL1756 | 0 | 26.77 | 13.20 | 12.2 |
| AAL521 | 0 | 14.56 | 12 | 11 |
| AAL1814 | 0 | 30.66 | 36.23 | 15.53 |
| AAL850 | 0 | 23.25 | 4.02 | 3.01 |
| JIA5210 | 0 | 33.28 | 24.33 | 24.52 |
| AAL876 | 0 | 36.78 | 9.92 | 12.82 |

High Fidelity Simulation Analysis Results and Observations

- Run 3 did not complete because of gridlock that occurred on the taxiway caused by metered departure AAL1965 and blocked arrival AAL790
- Gridlock could be avoided with better taxi management
- Observations on SOSS
 - Taxi routing and sequencing logic leads to gridlock and taxi delays even if the number of flights in the system is low
 - Can lead to unfair comparison between simulation runs
 - Flight tail number can be obtained from ASPM and matched between arrivals and departures for better gate occupancy modeling

High Fidelity Simulation Analysis

Future Extensions

- Assess gate blocking under uncertainties
 - In unimpeded taxi times and runway service rate
 - In knowledge about gate assignment and gate arrival times (can be manipulated by user gaming)
 - Assumptions about user swapping of gates between flights
- Vary other parameters to accommodate uncertainty
 - Strategic scheduler frequency and time horizon
 - Tactical scheduling at higher frequency
 - Queue buffer values

Future Work

- Leverage models and simulation in benefit assessment of ATD-2
- Extend analyses to
 - Assess different schemes of interaction between strategic and tactical schedulers
 - Assess performance under different uncertainty conditions
- Leverage insights gained from fast time simulations in ATD-2 demonstration efforts

High Fidelity Simulation Analysis Results and Observations

- Metering queue control with gate blocking limit
 - Gate holding delay, takeoff time difference, and taxi in delay

| | Average Gate Delay | Total Gate Delay | Average Takeoff Delay | Total Takeoff Delay | Average Taxi-in Delay | Total Taxi-in Delay | Number Metered /total Flights | Number Blocked Flights |
|----------------------------------|--------------------|------------------|-----------------------|---------------------|-----------------------|---------------------|-------------------------------|------------------------|
| No metering | 0 | 0 | 19.3 | 3835 | 1.7 | 293 | 0/199 | |
| Metering w/o gate blocking limit | 8.4/3.25 | 588 | 28.3/18.9 | 1980/3413 | 4.2 | 701 | 70/181 | |
| Metering with gate buffer 60 | | | | | | | | |
| Metering with gate buffer 120 | 6.7/2.8 | 545 | 29.5/19.7 | 2394/3826 | 2.2 | 391 | 86/194 | |
| Metering with gate buffer 180 | 5.9/2.5 | 475 | 29.2/19.6 | 2338/3776 | 1.6 | 281 | 86/193 | |