Development of Methods of Increasing Terminal Flexibility and Control Authority

Option Year 1 Final Report

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Contents

1 Introduction

This is the Option Year 1 final report for of the NASA-sponsored research project titled "Methods of Increasing Terminal Airspace Flexibility and Control Authority," covering the period from October 1, 2015 through September 30, 2016. The focus of this contract is to develop a What-if Analysis Tool for planning Departure Management Programs (DMP) at airports. This report summarizes the work conducted throughout the contract year, with a focus on the implementation of the What-if Analysis Tool and its application to traffic and weather scenarios at Charlotte Douglas International Airport (CLT).

1.1 Background and Motivation

The FAA Surface Collaborative Decision Making (CDM) Concept of Operations calls for DMPs to manage airport departure traffic congestion [FA2012]. DMPs specify Target Movement Area Entry Times (TMATs) for departures. TMATs are specified to meter the rate of departure entries into the movement area of the airport. DMPs are implemented for bounded time periods when runway queue lengths or airport traffic congestion are predicted to exceed a Target Departure Queue Length (TDQL). The TDQL may be specified as the optimum queue length to maximize runway throughput under given airport operating conditions [NA2011]. The What-if Analysis Tool evaluates airport traffic performance and congestion levels under forecast operating conditions to determine the need for a DMP, the start and stop times for the DMP, and other DMP parameters. A what-if analysis capability for planning DMPs is described at a high level in the FAA's Surface CDM Concept of Operations, and specified further in findings from a series of Human-In-The-Loop (HITL) evaluations of the FAA Surface CDM Concept of Operations [ME2012, ME2013].

The What-if Analysis Tool is intended to support the NASA Airspace Technology Demonstration (ATD)-2 traffic management system for airports. The ATD-2 system comprises traffic scheduling and management technologies and operations to enable departures to absorb delay at the gate, taxi unimpeded on the airport surface, spend minimum time in the departure runway queue, and climb continuously to cruise altitude [NA2015]. DMPs provide the ATD-2 system with strategic TMATs for departures to enter the movement area, and may suggest gate pushback times for departures to begin taxiing out to their assigned runways from their gates [NA2016]. In turn, the ATD-2 traffic management tools, such as the NASA Spot and Runway Departure Advisor (SARDA) for optimizing runway departure sequences and schedules and determining the appropriate departure sequence and schedule at each movement area entry point (spot) to meet the runway departure sequence and schedule [JU2011][NA2016], must accommodate the TMATs in scheduling departure takeoffs at the runways of the airport and the departure entries into the movement area of the airport.

The DMP is planned and then implemented by a Departure Reservoir Coordinator (DRC) position [FA2012]. Previous experiments to develop the FAA Surface CDM Concept of Operations identified the need for a What-if Analysis Tool to improve DMP planning and management. Stakeholders participating in the experiments called for a trial and error capability to assess the impact of changes in departure restrictions, airport surface operations, traffic schedule or DMP parameters. Changes in airport operations include changing the configuration or capacities, or closure, of airport runways or taxiways or terminal airspace departure fixes. Changes in the traffic include changing runways and fixes assigned to flights, substituting flights, changing the estimated off-block time and changing the gating plan. Changes in the DMP include extending or terminating the DMP and evaluating different queue lengths.

The ATD-2 What-if Analysis Tool and relationship to the ATD-2 airport arrival, departure, and surface traffic management system is illustrated in Figure 1-1.

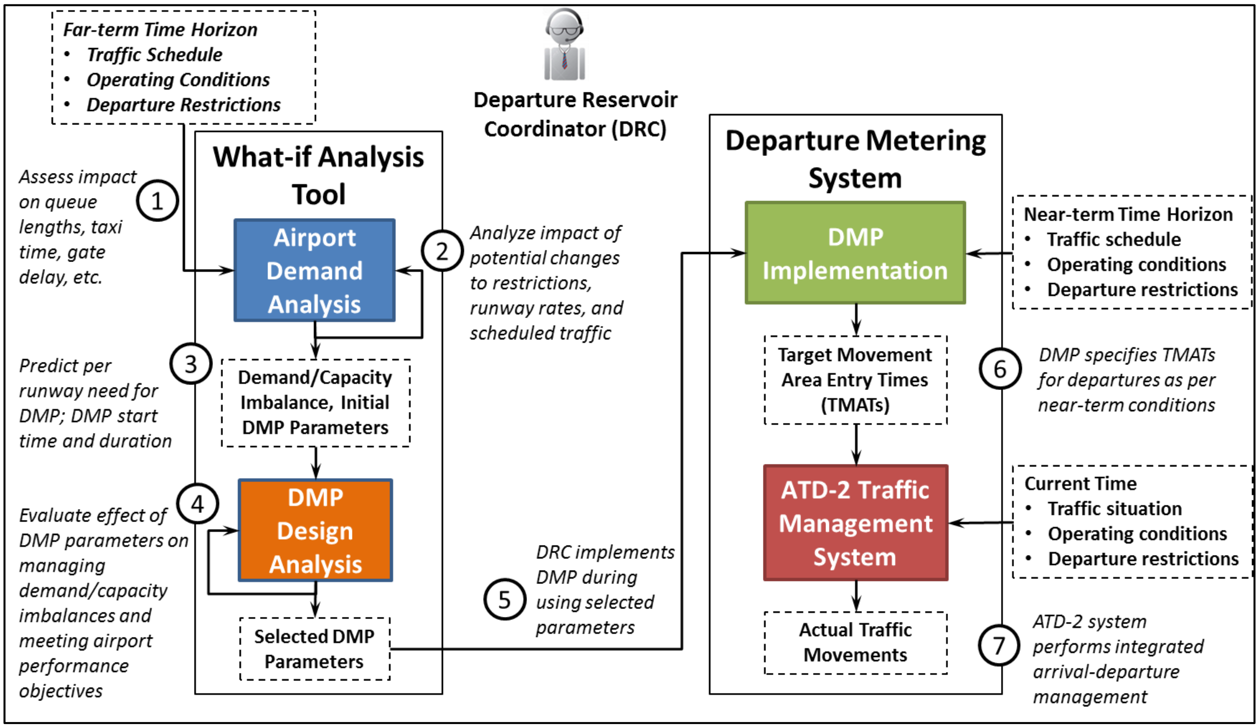


Figure 1-1. Relationship between ATD-2 Departure Metering and the What-if Analysis Tool.

The figure shows how the What-if Analysis Tool supports the implementation of DMPs. The DMPs specify TMATs which are constraints into the ATD-2 Traffic Management System for planning and management of airport arrival, departure and surface traffic.

As indicated in the figure, what-if analysis comprises airport demand analysis and DMP design analysis. The DRC conducts airport demand analysis to estimate airport departure, arrival and surface traffic over a forecast time horizon of operating conditions. If estimated traffic levels are excessive and performance targets such as throughput and taxi times are not met, the DRC may consult with aircraft operators and other stakeholders to consider the implementation of a DMP. In turn, the DRC conducts DMP design analysis to explore the implementation of a DMP to manage traffic levels and performance. If the need for a DMP is confirmed, then the DRC conducts DMP design analysis to determine start and stop times, target queue lengths, unscheduled demand buffers and other parameters for the DMP. DMP design analysis may be done iteratively to account for the uncertainties in the forecast operating conditions and aircraft operator responses in specifying DMP parameters.

A key aspect to the what-if analysis is implementation of DMPs to proactively minimize the negative impact of dynamic forecast weather and airport/traffic conditions on airport traffic performance. While this project focused on developing and demonstrating a tool for what-if analysis, work remains to develop methods for forecasting traffic flow restrictions, traffic conditions, and airport operating conditions from weather forecasts, and to use the What-if Analysis Tool to design DMPs to accommodate those forecasts. These predictions of future operating conditions, and estimations of their uncertainties, would be inputs to the What-if Analysis Tool. What-if analysis would be the basis for designing categorical (fix specific) DMPs along with other runway-specific DMPs or destination-specific Traffic Management Initiatives (TMIs) for departures subject to particular restrictions. Aircraft operators and other stakeholders would be involved in the what-if analysis and decision making process to determine the implementation of DMPs. Further discussion and examples are provided in Section 6.1.

1.2 Base Year Accomplishments

The Base Year effort established a proof of concept for the what-if analysis capability. The capability comprised an airport traffic simulation and an emulation of the ATD-2 scheduling tool for the ATD-2 development site, Charlotte Douglas International Airport (CLT). Primary DMP parameters to incorporate into the What-if Analysis Tool were identified by creating use cases for how the DRC would use the what-if analysis capability. Parameters included the DMP start and stop times, the TDQL, and Unscheduled Demand Buffer (UDB). The Base Year developed a What-if Analysis Tool prototype and conducted an initial evaluation of the what-if analysis use cases. The evaluations explored the impact of the DMP parameters on the performance of ATD-2 scheduling of departure traffic.

1.3 Option Year 1 Objectives

The objectives of Option Year 1 are to enhance the fidelity of the What-if Analysis Tool and evaluate the capability under a broader set of traffic and weather conditions. The specific tasks to support these objectives are:

1. Refine Modeling of Charlotte Airport. Enhance the modeling of the Charlotte Douglas International Airport (CLT) surface and airspace to allow a wider range of traffic and weather scenarios to be represented, while maintaining a fidelity that is suitable for performing what-if analyses in real-time.

2. Expand Departure Metering Program Modeling. Enhance the modeling of Departure Metering Programs (DMPs) to allow a wider range of traffic and weather scenarios and DMP parameters to be represented, while maintaining a fidelity that is suitable for performing what-if analyses in real-time.

3. Expand Traffic and Weather Scenarios. Identify candidate traffic and weather condition situations impacting CLT operations and departure rates. Create traffic and weather impact scenarios for evaluating the what-if analysis capability.

4. Characterize Departure Metering Program Parameters. Design and conduct what-if analysis evaluations to identify candidate DMP and airport operational parameters and characteristics for individual traffic and weather scenarios.

1.4 Option Year 1 Accomplishments

The accomplishments for Option Year 1 are summarized in the following sections.

1.4.1 Charlotte Modeling Refinements

The Option Year 1 accomplishments for Charlotte Modeling Refinements are summarized below.

- Investigated CLT surface operations and documented in the project deliverable "Charlotte Airport Modeling Refinements" report [AT2016-1].
- Implemented modeling and simulation of airport departures and arrivals into What-if Analysis Tool.
- What-if Analysis Tool inputs a traffic schedule file in a format compatible with the NASA Surface Operations Simulator and Scheduler (SOSS) airport surface traffic simulation software [WI2012].
- What-if Analysis Tool employs automated node-link modeling of individual airport runway, spot, gate and terminal airspace arrival and departure fix nodes, and connecting links, for airport runway configurations inherent in CLT traffic files. Verified spots and runways, and associated taxi routes, for CLT south flow runway configuration models by analyzing ASDE-X surveillance system data from several dates in 2009.
- What-if Analysis Tool models of gate-spot and spot-runway link transit times were derived from data output from SOSS simulations of CLT from previous project. What-if Analysis Tool models of terminal airspace transit times from data from high fidelity departure flight simulations completed during base year of project [AT2015].
- Verified that the what-if analysis traffic simulation results comply with modeling parameters of input node service rate, node queue length limit and link transit time. Compared departure and arrival throughput rates and taxi times from what-if analysis to FAA Aviation System Performance Metrics (ASPM) data for entire day of CLT traffic on August 8, 2014.
- Implemented modeling of traffic flow Miles-In-Trail (MIT) restrictions for flights to individual departure fixes in specified time window in What-if Analysis Tool. Implemented modeling of in-trail spacing applied by controllers at runway to satisfy MIT restrictions at fix. Verified modeling enforces in-trail spacing for departures subject to restrictions as per user-specified restriction parameters.
- Implemented in What-if Analysis Tool preliminary gate utilization models to coordinate use of airport gates among departures and arrivals in traffic demand set, while adhering to scheduled times and gate occupancy times.

- Developed for future implementation detailed models of CLT surface traffic interaction points among runways, taxiways and ramp routes for south and north flow runway configurations. Developed detailed, parameterized, realistic node-link models of taxi routes incorporating the interaction points; developed separation matrix approach to managing the interactions; implemented modeling logic to simulate traffic as per the interactions.

1.4.2 DMP Modeling

The Option Year 1 accomplishments for departure management program modeling are summarized below.

- Summarized high-level specifications for DMP tool from [FA2012] and proposed point design solutions to address them in project deliverable "Departure Metering Program Modeling Enhancements" [AT2016-2].
- Implemented in What-if Analysis Tool time-based scheduling of departure pushback times to satisfy multiple constraints. Constraints include the Runway Departure Rates (RDRs) of individual runways, time-varying MIT restrictions at particular departure fixes, TDQLs for individual runways, single-aircraft terminal gate occupancy, and specified DMP start and end times. The departure scheduler leverages the Order of Consideration algorithm from the Dynamic Planner (DP) of the Traffic Management Advisor (TMA) [WO2000].
- Developed and implemented in What-if Analysis Tool method for feedback control of delivery rate of departures to individual runways to maintain Target Departure Queue Length (TDQL). The method adjusts the scheduled inter-flight spacing of departures to the runway node queue based on the current deviation from the TDQL.

1.4.3 Traffic and Weather Scenarios

The Option Year 1 accomplishments for traffic and weather scenarios are summarized below.

- Characterized traffic and weather at CLT throughout 2014 from historical data to identify and model operational scenarios of interest for what-if analysis. Identified good weather day 8 August 2014 for desired airport traffic schedule. Identified bad weather days in 2014 as "disturbance" scenarios to evaluate application of the What-if Analysis Tool.
- Developed methodology to model traffic and departure restrictions from historical operational data. Implemented methodology to generate traffic schedule input file for the What-if Analysis Tool and compatible with NASA's SOSS simulation software, and to generate departure fix MIT restriction files compatible with the What-if Analysis Tool for historical days of interest.

1.4.4 DMP Parameter Characterization

The Option Year 1 accomplishments for characterizing the DMP parameters are summarized below.

- Extended the What-if Analysis Tool with a Graphical User Interface (GUI) to configure and evaluate traffic performance under particular weather scenario, to design departure metering program parameters, and to evaluate traffic performance under departure metering program.
- Extended the What-if Analysis Tool to analyze the performance of airport departure and arrival traffic. Interfaces present per-runway traffic demand and resulting performance. Data are presented on a time-series basis for detailed understanding of trends and variability, and on an aggregate basis for comprehensive overview of traffic. Assessment of arrivals enables understanding of departure management program impacts on arrivals.
- Used the What-if Analysis Tool to evaluate airport traffic performance for historical traffic and weather scenario, and numerous hypothetical traffic and weather scenarios, and to assess impact of DMP in mitigating demand/capacity imbalance inherent in each scenario.

1.5 Outline of Report

The remainder of this report is structured as follows. Section 2 presents the enhancements to the what-if analysis tool, including the traffic simulation, DMP emulation and airport traffic performance metrics. The section also presents results of verifying the what-if analysis tool implementation, including modeling logic and parameter adherence, and comparison to FAA ASPM data. Section 3 presents the methodology for and results of selecting and modeling historical weather and traffic scenarios of interest for what-if analysis demonstrations for CLT. This section also discusses approaches to modeling notional traffic and weather scenarios and potential uncertainty values for the parameters defining traffic and weather scenarios. Section 4 presents methodology for and results of applying the what-if analysis tool to airport demand analysis and DMP analysis for a traffic and weather scenario at CLT in August 2014. Section 5 provides a guide for using the what-if analysis tool to perform airport demand analysis and DMP analysis. Section 6 presents recommendations for future work. Recommendations include exploration and development of what-if analysis operations for airport stakeholders to collaboratively forecast airport performance and plan DMPs, further developments of the tool, and additional traffic and weather scenarios for modeling.

2 What-if Analysis Tool Enhancements

The What-if Analysis Tool includes an airport-airspace simulation and a departure metering program emulation. In Option Year 1, enhancements were made to each. Enhancements to the airport-airspace simulation include increased fidelity modeling of the airport surface, modeling of arrivals and a practical approach to representing traffic flow restrictions at departure fixes. Enhancements to the DMP emulation include initial start and stop times for metering from demand/capacity assessment, a method to explicitly meet a target queue length for each runway, and practical methods for addressing departure fix traffic flow restrictions. The remainder of this section presents each of these enhancements in detail.

2.1 Airport Modeling and Traffic Simulation

A core capability of the What-if Analysis Tool is simulation of the movement of aircraft through the airport and terminal airspace. Simulation of traffic through the airport and airspace enables demand analysis to identify occurrences of traffic demand/facility capacity imbalance under forecast operating conditions, and enables DMP design analysis to design DMP programs to manage departures as per available capacity.

The What-if Analysis Tool uses node-link modeling to simulate the traffic flow through the airport and airspace. Node-link modeling uses nodes to represent physical points were the flow rate of traffic is limited, such as airport runways, terminal airspace metering fixes, or other points. Node-link modeling uses links to represent transit routes between the nodes, such as taxiways or air routes.

Data to create the node-link model for what-if analysis come from two distinct sources. The nodes and links modeling the airport surface are synthesized from the routes of the flights defined in the airport traffic schedule input to the What-if Analysis Tool. Parameters defining the service rates and queue length limits of the nodes, and the transit times of the links, are separate user inputs to the What-if Analysis Tool. Figure 2-1 presents the fundamental components of node-link modeling.

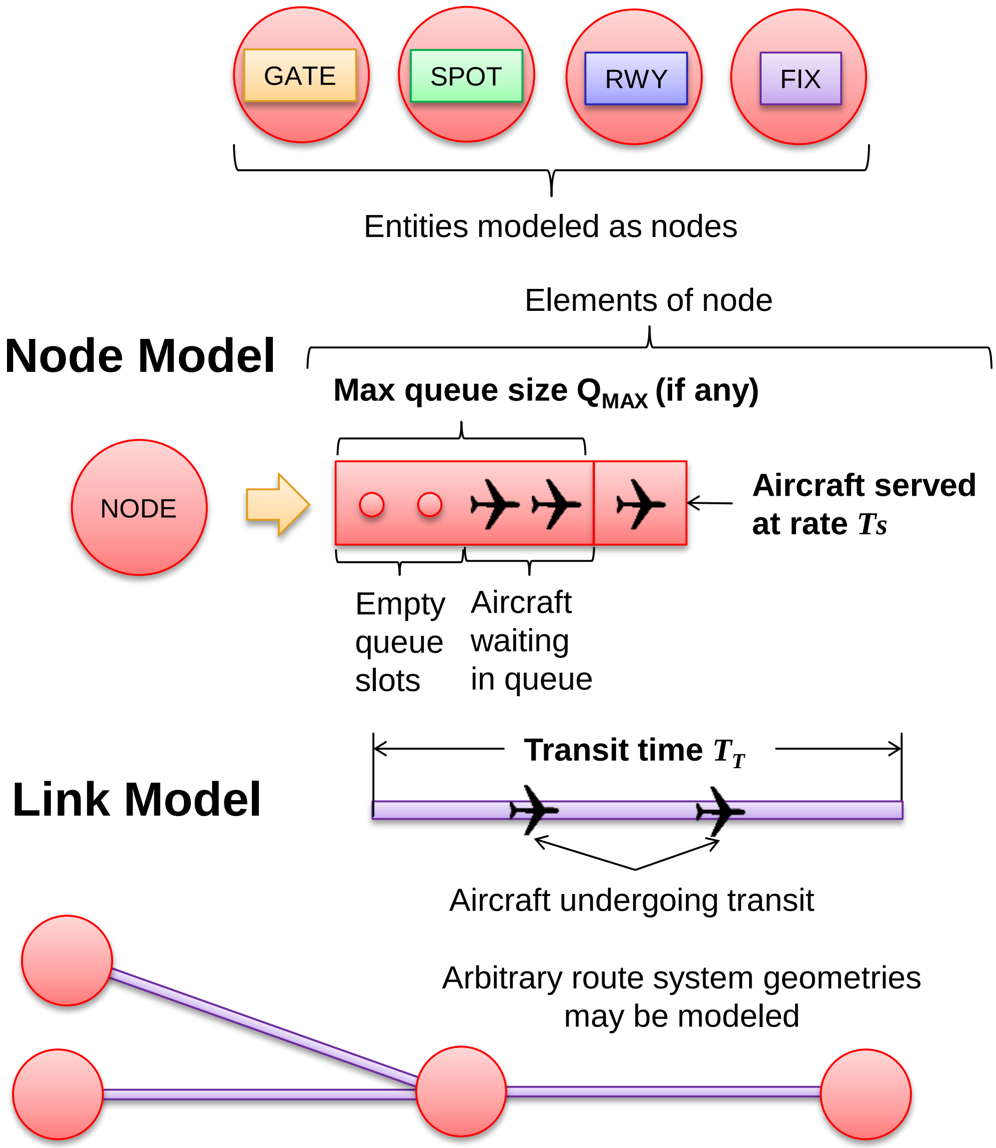


Figure 2-1. Fundamental Components to Node-Link Modeling of Airport and Airspace.

Nodes model points where traffic flow is constrained. At such points, if the arrival rate of traffic to the node exceeds the effective rate of traffic flow that can be met at the node, the aircraft form a queue as they wait for passage through the point [DE2003]. Such points include the runways of the airport, terminal gates or groups of gates, spots delineating the transition between the non-movement and movement areas of the airport, and other points of congestion such as points where runways or taxiways cross one another.

Parameters defining a node include a service time, T_s, and a queue size limit, Q_{max}. The service time represents the time for the node to process each flight, and corresponds to a maximum limit on the flow rate of traffic through the node. This can represent the time for the controller to clear the aircraft to take off or enter the movement area, the minimum in-trail separation with the previous flight to exit the node for safety, or other constraints. The queue size limit specifies the maximum number of aircraft that may be queued (i.e., waiting in line) to exit the node. In the What-if Analysis Tool, flights are processed by the node model in order of first-in, first-out. The time at which each flight is serviced is the later of its node entry time or the exit time of its node predecessor. The exit time of each flight is the time at which it is serviced plus the node service time to process the flight. Links model the transit of aircraft between pairs of nodes. Links are modeled as inter-node transit times, T_T, representing undelayed transit.

The Base Year What-if Analysis Tool implemented the following modeling of the airport surface and terminal airspace:

- The airport surface was modeled as a single departure node. The airspace was modeled as numerous departure fix nodes and a en route merge point node.
- Only movement of departure aircraft was modeled. Arrival traffic and its interactions with departure traffic were not modeled.
- The airport surface model comprised a single departure queue to represent aggregate airport departure capacity, not individual runway capacity.
- The airport surface model did not include intermediate traffic interaction points.
- The airport surface model represented link transit as taxi-out times for flights of individual airlines from Aircraft Situation Display to Industry (ASDI) data.
- The airspace modeled individual TRACON entry/exit points. The airspace modeled a proxy point for departures to merge into overhead traffic flow.

The Option Year 1 What-if Analysis Tool implements the following modeling of the airport and airspace:

- The airport surface is modeled as a collection of individual gate, spot and runway nodes. The airspace is modeled as numerous departure and arrival fix nodes.
    - A node for each airport gate models its occupancy time, and its length limit of one aircraft;
    - A node for each spot models the time for an aircraft to obtain clearance to enter the movement area.
    - A node for each departure and arrival runway models its capacity (and the effective time separation between operations it implies);
    - A node for each TRACON exit fix for departures and entry fix for arrivals models its restriction on traffic flow.
- Link transit times between nodes represent the undelayed transit time of the flight between those points.
- Movement of departure and arrival aircraft is modeled. Departure and arrival aircraft interact through shared resources of the airport and airspace, including gates and runways.

- A trajectory for a flight comprises a sequence of nodes, with the link between each node implied by each pair of nodes. For each node, the flight has an entry and exit time.
    - The entry time represents when the flight arrived to the node.
    - The exit time represents when the flight exited the node. The time difference between entry and exit represents any time the flight had to wait for flights queued ahead of it to pass through the node (i.e., queueing delay), and the service time of the node.
    - The time difference between the exit time of one node and the entry time of the next node is the transit time along the link connecting those nodes. Any additional time represents delay in entering the next node because the queue size limits of that node have been reached.

The benefits of the more detailed modeling of the airport surface and terminal airspace in Option Year 1, include understanding the characteristics of traffic flow to individual runways and how traffic flow restrictions impact the traffic of particular runways; designing and evaluating DMPs for individual runways; and understanding the impact of departure gate holding on arrival traffic flow and management when designing DMPs.

The next sections describe the inputs, airport and airspace modeling and traffic simulation of the What-if Analysis Tool.

2.1.1 Inputs

Inputs to the What-if Analysis Tool include a schedule of airport arrival and departure traffic and departure restrictions, described in the following subsections.

2.1.1.1 Scheduled Airport Traffic

Airport modeling is derived from the schedule of airport departures input to the What-if Analysis Tool. Each input flight has a distinct call sign, simulation entry time, and sequence of gate, spot, runway and fix defining its route.

2.1.1.2 Departure Restrictions

The What-if Analysis Tool currently models MIT restrictions for departures to a particular departure fix. Such restrictions call for successive aircraft transiting the fix to have in-trail separations meeting or exceeding the MIT restriction.

An input file specifies the departure fix, MIT separation value, start time, end time for each restriction. The What-if Analysis Tool supports specifying multiple, sequential restrictions for a single fix, and concurrent restrictions for multiple fixes.

What-if analysis modeling translates the MIT restriction to equivalent in-trail time spacing at the runway between successive departures to that fix. This modeling approach captures the impact of departure restrictions on airport traffic flow that can cause traffic congestion. To do this, a rule-of-thumb distance spacing of 20 MIT at the runway to meet 30 MIT at the departure fix used by controllers between departures taking off from the runway to meet departure fix spacing at the departure fix [LO2016]. This yields a distance ratio of 0.67 to convert MIT at the departure fix to MIT at the runway. The distance spacing at the runway is converted to equivalent time spacing through an assumed average takeoff speed of 150 knots [AI2016].

2.1.2 Node and Link Modeling

The current implementation of the What-if Analysis Tool synthesizes an airport surface model from the data contained in the input traffic schedule and user-defined parameters. This makes the What-if Analysis Tool adaptable to different airports, airport configurations and operating conditions. Future development proposes to implement more surface models of CLT capturing key interaction points among the runways, taxiways and ramp areas.

In the traffic file, each flight is assigned a gate, spot, runway, departure or arrival fix, and destination airport (for departures) or origin airport (for arrivals). These data comprise the route for each flight in the simulation. From these data, the node-link model is synthesized. The nodes are the distinct gates, spots, runways, fixes and destination/origin airports. The links are the couplings between the gates and spots, spots and runways and fixes, fixes and airports. The identities of the individual nodes and links are synthesized from the routes specified in the traffic demand set. In turn, user-specified, airport-specific default parameter values for node service rate and queue length limit, and inter-node transit time, are used to configure the airport model.

2.1.2.1 Identification

As an example, the following sequence of figures depict the individual gate, spot, runway and fix nodes, and their linkages, inherent among the departures defined in the *hitl6-training-advisory.list_data* traffic file furnished by NASA.

Figure 2-2 depicts the individual CLT terminal and spot nodes, and their linkages, among the departures listed in the file as per their specified routes. Terminals are presented in lieu of actual gates for brevity of presentation.

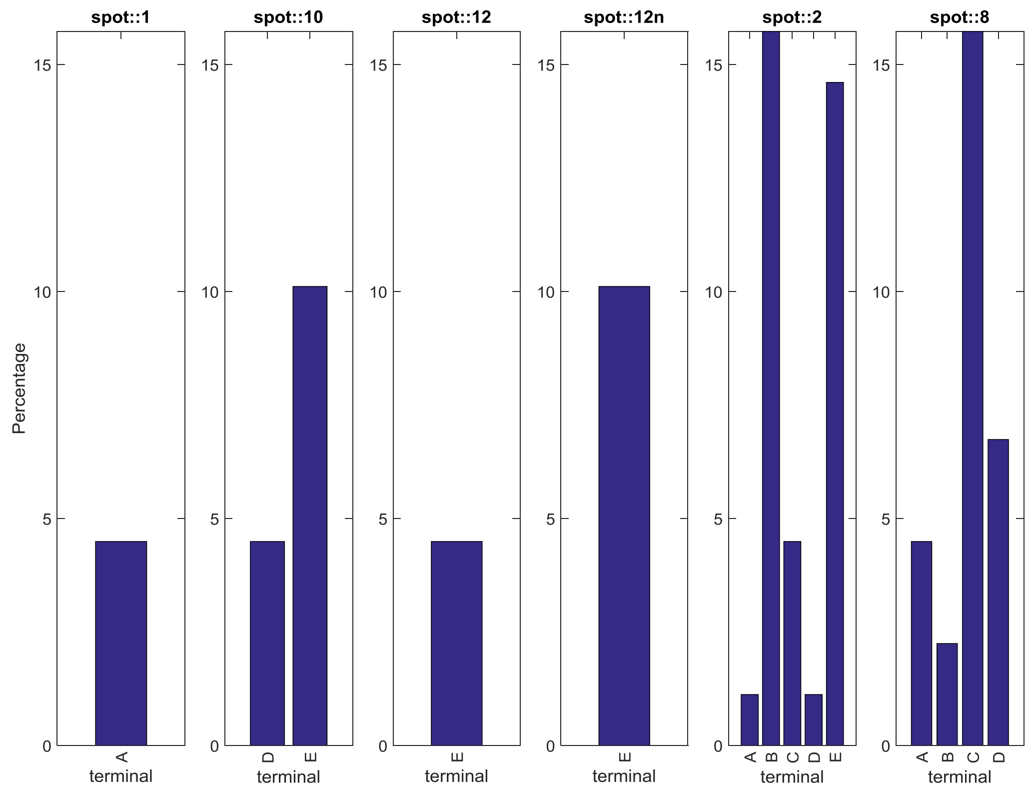


Figure 2-2. Distinct CLT Terminal and Spot Nodes, and their Linkages, Inherent in the Departure Flights Defined in the *hitl6-training-advisory.list_data* Input Traffic File.

The data in the figure indicate that, in the traffic demand set, the gate nodes are within terminals A, B, C, D and E. The spot nodes are spots 1, 10, 12, 12n, 2 and 8. The gate nodes of Terminal A are linked to spot nodes 1, 2 and 8; the gate nodes of Terminal B are linked to spot nodes 2 and 8; the gate nodes of Terminal C are linked to spot nodes 2 and 8; the gate nodes of Terminal D are linked to spot nodes 10, 2 and 8; and the gate nodes of Terminal E are linked to spot nodes 10, 12, 12n and 2.

Figure 2-3 depicts the individual CLT spot and runway nodes, and their linkages, among the departures listed in the file as per their specified routes.

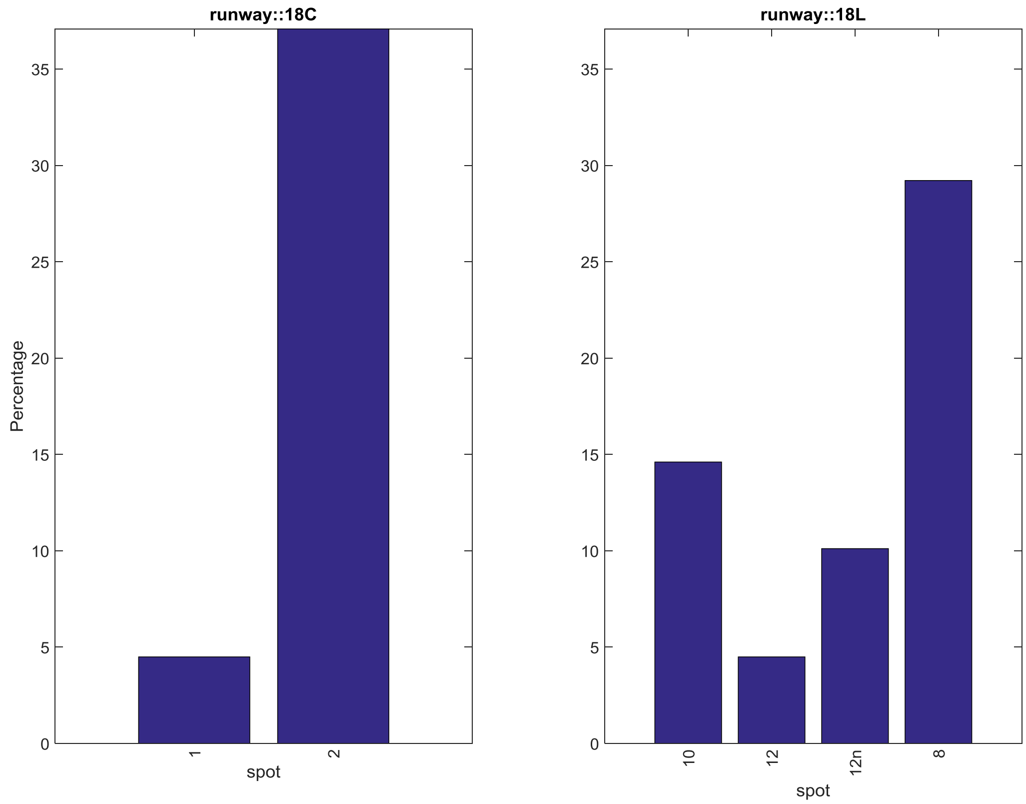


Figure 2-3. Distinct CLT Spot and Runway Nodes, and Their Linkages, Inherent in the Departure Flights Defined in the *hitl6-training-advisory.list_data* Input Traffic File.

The data in the figure indicate that, in the traffic demand set, the departure runway nodes are runways 18C and 18L. The spot nodes 1 and 2 are linked to the runway 18C node, and the spot nodes 10, 12, 12n and 8 are linked to the runway 18L node.

Figure 2-4 depicts the individual CLT runways and departure fixes, and their linkages, among the departures listed in the file.

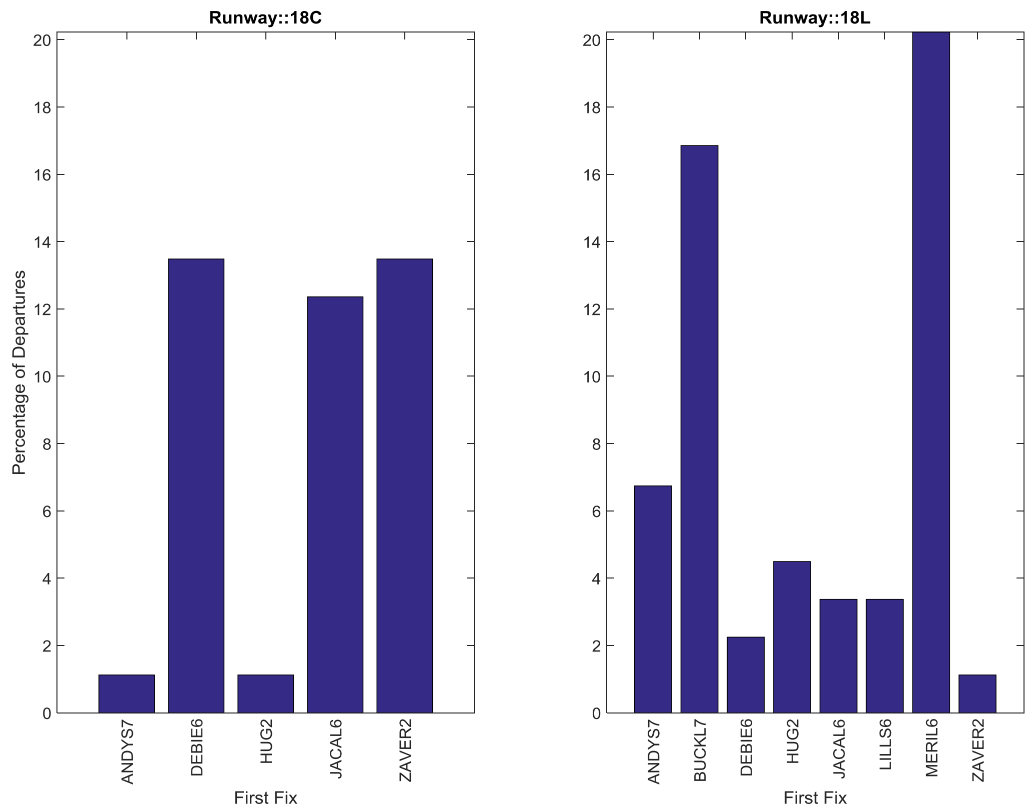


Figure 2-4. Distinct CLT Runway and Fix Nodes, and Their Linkages, Inherent in the Departure Flights Defined in the *hitl6-training-advisory.list_data* Input Traffic File.

The data indicate that the departure fix nodes are ANDYS, BUCKL, DEBIE, HUG, JACAL, LILLS, MERIL and ZAVER. The runway 18C node is linked to the ANDYS, DEBIE, HUG, JACAL and ZAVER departure fix nodes, and the runway 18L node is linked to the ANDYS, BUCKL, DEBIE, HUG, JACAL, LILLS, MERIL and ZAVER departure fix nodes.

The result is a network of distinct gate, spot, runway and departure and arrival fix nodes connected by links as per the gate-spot, spot-runway and runway-fix combinations inherent in the flights defined in the airport traffic input file. The histograms indicate not only the individual nodes and their linkages, but also the quantity of flights using each link.

Figure 2-5 depicts the individual CLT gate, spot and runway nodes and their linkages, as per the specified routes of the departures listed in the traffic input file. In the figure, instead of connecting individual gates to their associated spot nodes, gates are grouped into terminals A, B, C, D and E encircled by a dashed line, and the links from each gate group to its associated spots are shown.

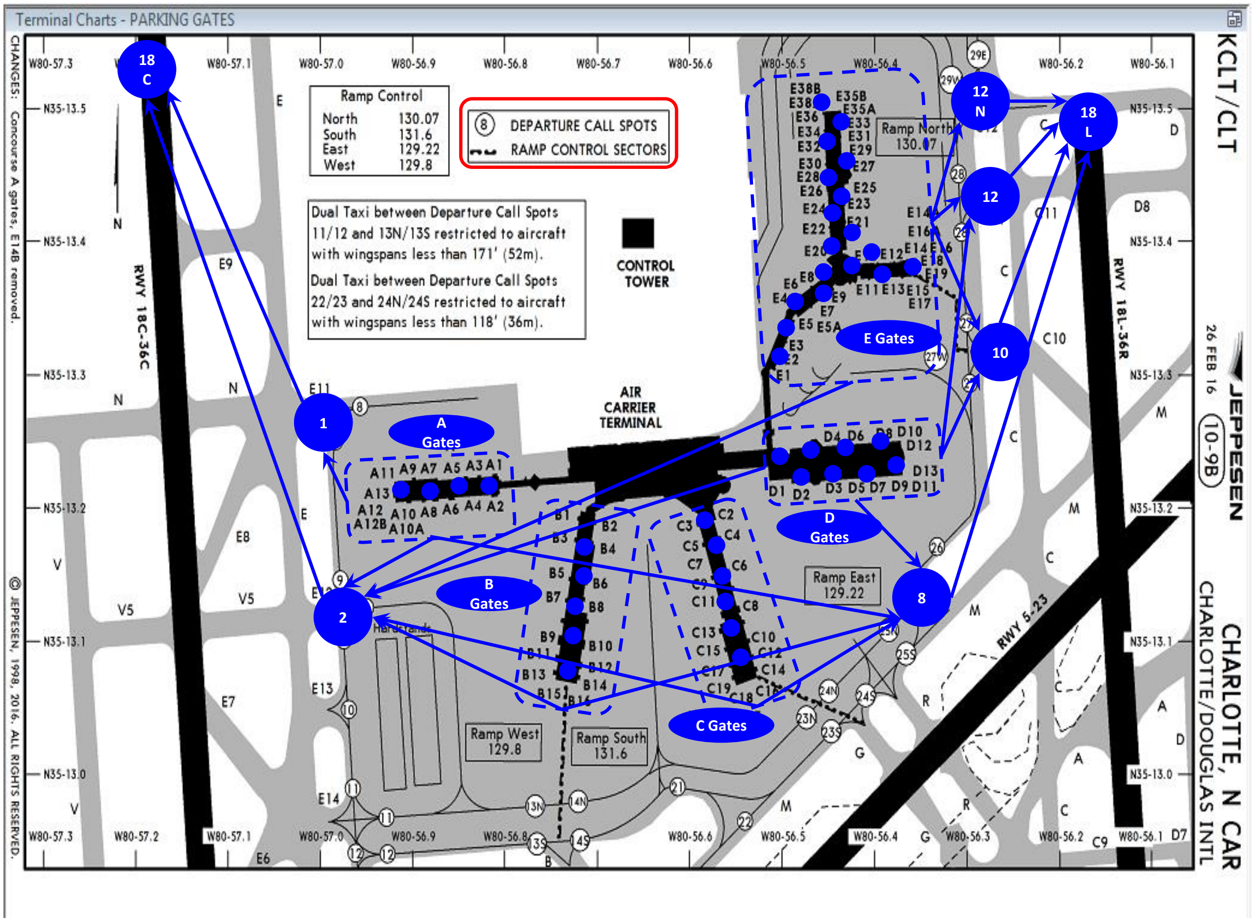


Figure 2-5. Gate, Spot and Runway Nodes and their Linkages Inherent in the Departure Flights. Defined in the *hitl6-training-advisory.list_data* Input Traffic File.

The figure reflects the links between individual gate and spot nodes, spot and runway nodes inherent in the traffic input file. Regarding the links between gate and spot nodes, the Terminal A gate nodes are linked to spot nodes 1, 2 and 8; the Terminal B gate nodes are linked to spot nodes 2 and 8; the Terminal C gate nodes are linked to spot nodes 2 and 8; the Terminal D gate nodes are linked to spot nodes 2, 8 and 10; and the Terminal E gate nodes are linked to spot nodes 2, 10, 12 an 12n. Regarding the links between spots and runways, spot nodes 1 and 2 are linked to the runway 18C node, and spot nodes 8, 10, 12 and 12n are linked to the runway 18L node.

Figure 2-6 depicts the individual CLT runway and departure fix nodes and their linkages, as per the specified routes of the departures listed in the traffic input file. In the figure, the node symbol for HUG is an empty circle, not a filled circle as for the others. This is because HUG is a departure procedure comprising numerous other waypoints; it is not a waypoint or navigational aid. Because it is indicated as a departure fix in the traffic input file, it is modeled as a fix. Refinement to the traffic file is required to capture the particular departure fix each flight assigned to the HUG departure procedure is actually transiting.

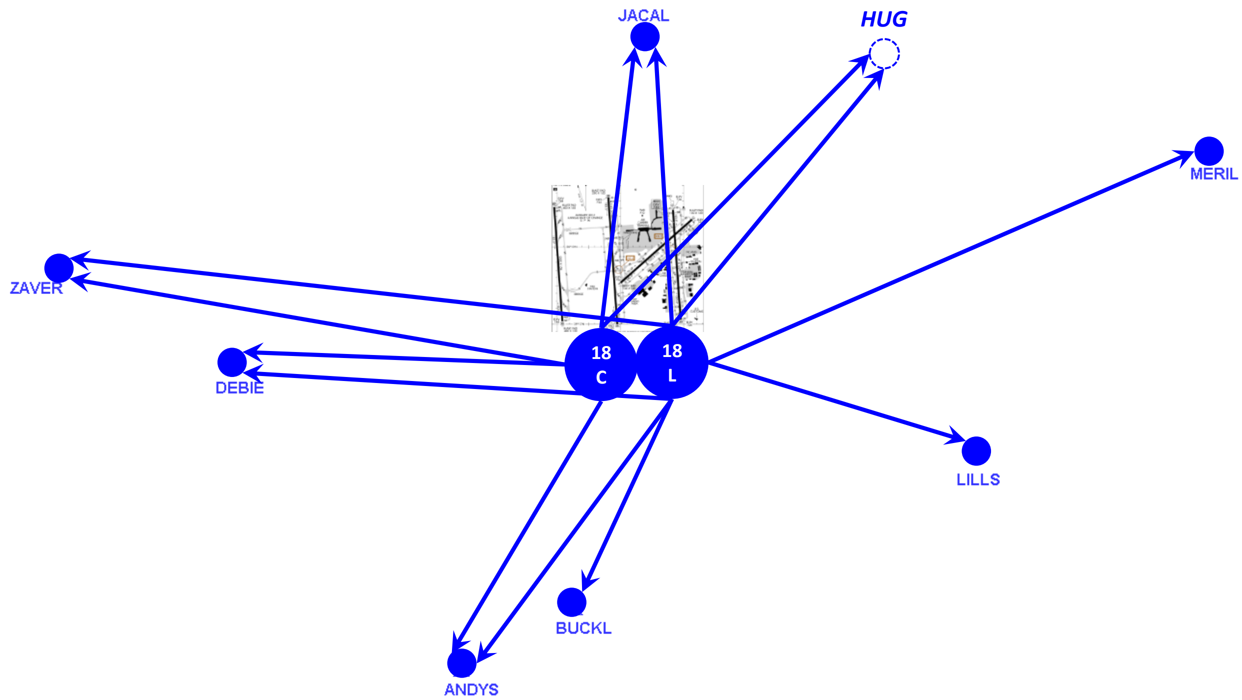


Figure 2-6. Runway and Departure Fix Nodes and their Linkages Inherent in the Departure Flights. Defined in the *hitl6-training-advisory.list_data* Input Traffic File.

The figure reflects the links between the individual runway nodes and the fix nodes inherent in the traffic input file. The runway 18C node is linked to fix nodes ANDYS, DEBIE, ZAVER, BUCKL and HUG. The runway 18L node is linked to fix nodes MERIL, LILLS, BUCKL, ANDYS, DEBIE, ZAVER, JACKAL and HUG.

A similar analysis of arrivals may be conducted to present the arrival fix, runway, spot and gate nodes, and their linkages, inherent in their routes specified in the *hitl6-training-advisory.list_data* traffic file furnished by NASA.

2.1.2.2 Parameterization

User-defined parameters define the default service rates and queue length limits of the nodes, and inter-node transit times of the links in the airport and airspace model. Distinct values are used for the service rates and queue length limits of each gate, spot, runway and fix category of nodes, and for each gate-spot, spot-runway and runway-fix category of links. Different values may be used for different nodes or links within each category of nodes or links of the airport surface to more accurately represent operating characteristics of the airport.

The current implementation uses standard service rate and queue length limit values for the gate, spot, runway and fix nodes and the gate-spot, spot-runway and runway-fix links. The current model of CLT uses node service rates of 2 minutes for runways, 1 minute for spots, 30 minutes for gates, and 2 minutes for arrival and departure fixes.

- The service rate for the gates of 30 minutes represents the time required for a departure flight to prepare for pushback, including loading baggage and passengers, maintenance, etcetera. The service rate for gates also represents for arrivals the time to unload passengers and baggage and other flight conclusion tasks. References [GO2009][WU2004][BO2008] might provide deeper insight into appropriate parameter values.
- The service rate for the spots of 1.0 minute represents the time for the air traffic control tower ground controller to clear a departure to enter the movement area. This service rate is also applied to arrivals.
- The service rate for the departures of 2.0 minutes approximates to typical operations rate of 30 aircraft per hour observed for individual runways at CLT through analysis of 2009 ASDE-X surveillance data.
- The service rate for the departure fixes corresponds to a typical in-trail spacing of 7 miles used by terminal airspace controllers, and a crossing speed of 250 knots typical of terminal airspace operations [TI2016].

The current model of CLT uses a queue length limit of 1 aircraft for each gate. Length limits were not modeled for the other categories of nodes.

- For the gate, this models the physical occupancy limit of a single aircraft.
- For the runway and spot, queue length limits could be implemented to represent the physical space of the taxiways and ramp area available to accommodate queued flights.

The current model of CLT uses inter-queue transit times of 4.0 minutes for transit between the gate and the spot, 2.0 minutes for transit between the spot and the runway, 14.0 minutes for transit between the runway and the departure or arrival fix, and 30.0 minutes for transit between the arrival or departure fix and the origin or destination airport of the flight.

- The gate-spot transit time of 4.0 minutes was determined from SOSS simulation data for CLT from a previous project [SS2012]. It is the average of the nominal gate-spot transit times of all the departures simulated in that study.
- The spot-runway transit time of 2.0 minutes was determined from SOSS simulation data for CLT from a previous project [SS2012]. It is the average of the nominal spot-runway transit times of all the departures simulated in that study. We have ASDE-X surface surveillance data from 2009 and associated analysis scripts from which to estimate transit time; a nominal time corresponding to the 5th percentile of the taxi times might be a reasonable value.
- The runway-fix transit time of 14.0 minutes was determined from high fidelity flight simulations of departures along the CLT MERIL departure procedure conducted in the base year of this study [AT2015]. The transit times of the other SIDs were estimated by distance scaling of the transit time mean and standard deviation obtained for CLT MERIL. In turn, a mean transit time for all the CLT departure procedures was estimated.

- The fix-destination/origin airport transit time of 30.0 minutes is a placeholder value for more detailed modeling. Transit to destination/origin airport nodes is currently not simulated in the What-if Analysis Tool, although easily could be by including the origin and destination airports for flights as nodes in the airport model.

Once the nodes and links modeling the airport surface and terminal airspace have been identified and configured, then the What-if Analysis Tool is ready for traffic flow simulation.

2.1.3 Traffic Flow Simulation

Traffic flow simulation is the propagation of each departure and arrival flight through the sequence of gate, spot, runway and fix nodes comprising its route. Departure flights initiate upon entry to their assigned gates and terminate upon exit of their assigned departure fixes. Arrival flights initiate upon entry to their assigned fixes and terminate upon exit of their assigned gates (at the end of the arrival process, the first half of the total turnaround process). Movement of each flight initiates at its simulation entry time specified in the traffic input file. Simulation continues until each flight has an exit time from the last node in its route. In the simulation, the node service rate and queue length limit parameters and link transit time parameters, and specialized logic for managing the flow of aircraft through each node and link, determine the time-based movement of aircraft. The simulation steps are described below.

2.1.3.1 Initialization

Each flight's route is the sequence of gate, spot, runway and fix nodes specified for it in the input traffic file. Associated with each node in the route are entry and exit times when the flight enters and exits the node. For each flight, the entry time to the first node in its route (gates for departures, arrival fixes for arrivals) is assigned as its entry time specified in the traffic input file.

For departures, the gate exit times are also initialized. The gate exit time depends on whether or not departures are being metered as per a DMP. Without departure metering, the gate exit time of each departure is its gate entry time plus the gate service rate (occupancy time). This represents its airline scheduled gate pushback time. With departure metering, the gate exit time of each departure is the gate pushback time scheduled by the departure metering program. The departure metering program scheduling ensures the exit time complies with the departure's gate entry time, the gate service rate and gate queue size limit of 1 aircraft.

2.1.3.2 Process

The traffic flow simulation is a discrete time simulation. At each time step, each node and link in the airport model is scanned for occupants and entrants. Flights enter the node as per their node entry times and the queue size limit of the node. Flights exit the node as per the queue service time of the node and the time at which the node processes the flight. The node processes each occupant to assign an exit time from the node. The steps are described below.

Each node in the model is scanned for occupants of and entrants to its queue. Each node processes its queue occupants to determine which may exit at this simulation time step. Entrants to the node's queue have requested node queue entry times which are earlier than the current time. Entrants are admitted to the node's queue if the node's queue size limit is not exceeded. If the flight may enter the node's queue, it is assigned an actual node entry time.

Occupants of the node's queue are the sequence of flights currently queued and awaiting exit. Occupants have actual node entry times which are earlier than the current time, but do not yet have node exit times assigned. The node queuing model processes the current queue occupants in the order of queue entry (i.e., first in, first out). Each occupant is evaluated for node queue exit. An occupant is assigned a node queue exit time if it satisfies the queue service rate and other external constraints (e.g., departure fix spacing), and is equal to or earlier than the current simulation time.

Each link in the model scans for new entrants. A link entrant has an exit time from the node at one end of the link, but no entry time to the node at the other end of the link. For each entrant, it assigns a requested entry time to the queue of the next node in the flight's route.

As the simulation time progresses, aircraft propagate through the nodes and links of their route by exiting one queue, entering the next link, exiting the next link, and entering the next queue. Given this overall process, details of operation of each category of node queueing model are in the following subsections.

2.1.3.2.1 Gate Nodes

The gate node model coordinates the entry and exit of arrivals and departures to each gate of the airport model to ensure compliance with the queue size limit of 1 aircraft or each gate node and the queue service rate (gate occupancy time) of 30 minutes.

The current gate node model gives preference to departures for gate use. Departures enter their assigned gate node at their scheduled gate entry times defined in the traffic schedule input file. Departures occupy the gate as per the specified service rate for the gate node and their scheduled push back time as per the departure metering program. Arrivals enter their assigned gate node at the first available time window. An available time window occurs when the previous gate occupant has exited the gate node, and, the next gate occupant (a departure) enters the gate node sufficiently later to permit this arrival to enter the gate and occupy it for the queue service time of the gate node (e.g., 30 minutes). This permits explicitly controlling departures to their departure metering times and explicitly comparing the departure metering program to baseline times. One consequence is that arrivals may absorb significant taxi-in delay waiting for their gate to become available, and tail tracking of incoming arrivals which turn around to become departures implicit in the input traffic file may not be satisfied.

2.1.3.2.2 Runway Nodes

The current runway node model coordinates the entry and exit of departures and arrivals to each runway of the airport model. Runway node exit times ensure compliance with the service time of the runway node and any applicable departure fix restrictions. The runway node service time and departure restrictions are discussed in more detail below.

Regarding the service time, for each departure or arrival, the runway node model determines the earliest takeoff time for the aircraft to comply with the service time, based on the previous flight to exit the runway node and the entry time of this flight. The runway node model selects the later of the two times as the flight's candidate processing time. The processing time plus the service time yield the earliest feasible takeoff or landing time for the flight.

Regarding departure restrictions, for each departure, the runway node model determines if any departure restrictions apply based on the departure fix of the flight and the time window the departure restrictions are active. For each applicable restriction for a departure, the runway queueing model identifies the previous flight to that fix, and determines the earliest takeoff time for the departure to comply with the restriction. The runway queueing model compares the earliest takeoff time as per the departure restrictions to the earliest takeoff times as per the queue service rate (e.g., runway separation requirements), and selects the latest time as the flights runway node exit time (takeoff time).

2.1.3.2.3 Other Nodes

The current spot and arrival and departure fix node models coordinates the entry and exit of departures and arrivals to each of these points in the airport model. Node exit times ensure compliance with the modeled service rate.

The departure fix node model does not currently enforce the departure fix restrictions on departures as they request exit from the fix node. This is because the effect of departure fix restrictions on airport traffic is modeled through enforcement at the runway. The runway node model for handling departure restrictions could be applied to the departure fix node model if modeling of aircraft delay in the terminal airspace to satisfy the restrictions, was desired.

2.1.3.2.4 Links

The link model propagates aircraft from one queue to the next according to user-specified link transit times. Once an aircraft has been assigned an exit time by one queue, the link model determines the appropriate transit time from a lookup table of user-specified link transit time values, and determines the queue entry time of the aircraft to the next queue in its route. The link transit time assigned to a flight in its route may be modified when the flight encounters queue size limit constraints at the next node. In this case, the actual entry time of the flight to the node will be delayed until the node queue size decreases sufficiently to admit the flight to the queue of the node. This associates the delay with transit along the link.

2.1.3.3 Post-processing

Post-processing of the simulation data includes verifying that flights adhere to the physical parameters and logic. Post-processing includes verifying the following:

- The sequence of node entry and exit times in the flight's trajectory monotonically increase and comply with the fundamental link transit times and queue service rates of the airport model.
- The exit times of flights comply with the node service rate, the queue lengths comply with the queue size limit of the node, and the queuing delays incurred by flights are greater than or equal to zero.

- The runway node exit times of flights to the constrained fix within the applicable time period comply with the departure restriction.
- Flights are not overlapping in their occupancy of the gate node and that occupancy times comply with the service rate.

Once verification is complete, per-runway and aggregate airport performance metrics are evaluated for departures and arrivals to assess traffic flow and transit performance.

2.2 Departure Metering Program Emulation

The FAA Surface CDM Concept of Operations calls for DMPs to assign TMATs to individual departures to alleviate traffic congestion in the movement area of the airport. The concept implies the use of gate holding as the primary means for aircraft operators to comply with the TMATs assigned to the departures. However, in prescribing TMATs, the concept affords aircraft operators flexibility in departure push back times, permitting delay to be absorbed elsewhere in the non-movement area of the airport other than the gate, to comply with the TMATs.

The DMP emulation of the What-if Analysis Tool prescribes gate pushback times for departures, assuming that aircraft operators will exclusively use gate holding to meet TMAT times. The TMAT for each flight may be computed from its DMP-scheduled pushback time and an assumed transit time in the non-movement area. For what-if analysis and DMP planning, exclusive use of gate holding may be a reasonable assumption; it provides aircraft operators and other stakeholders with insight into the impact of the proposed metering program on their departure schedules and gate utilization plans, and to what extent surface delay reservoirs may have to be used to comply with the DMP. Aircraft operators may shift the actual pushback times of individual departures to earlier than the DMP-scheduled gate pushback time to allocate some portion of the required departure delay from the gate to the non-movement area.

The DMP emulation is designed to prescribe a certain level of delay to individual flights such that taxiway congestion is alleviated. The gate exit time is the primary control available to the DMP. The emulator considers allowable runway departure rates, MIT departure restrictions at departure fixes, and required gate occupancy times. Figure 2-7 illustrates the reference points[1] considered by the DMP Emulator. The first reference point is the gate. The DMP Emulator schedules both the gate entry time and the gate exit time for each departure. It assumes that flights must first arrive at a particular gate, utilize the gate for a prescribed amount of time and then exit the gate prior to taxi and takeoff. The gate entry and exit times are scheduled such that no two flights may occupy a gate at the same time. However, the gate exit time must also satisfy all of the scheduling constraints downstream of the gate.

[1] A term coined by Wong et al. [WO2000] to describe points of interest along a trajectory where flights may need to be monitored or scheduled

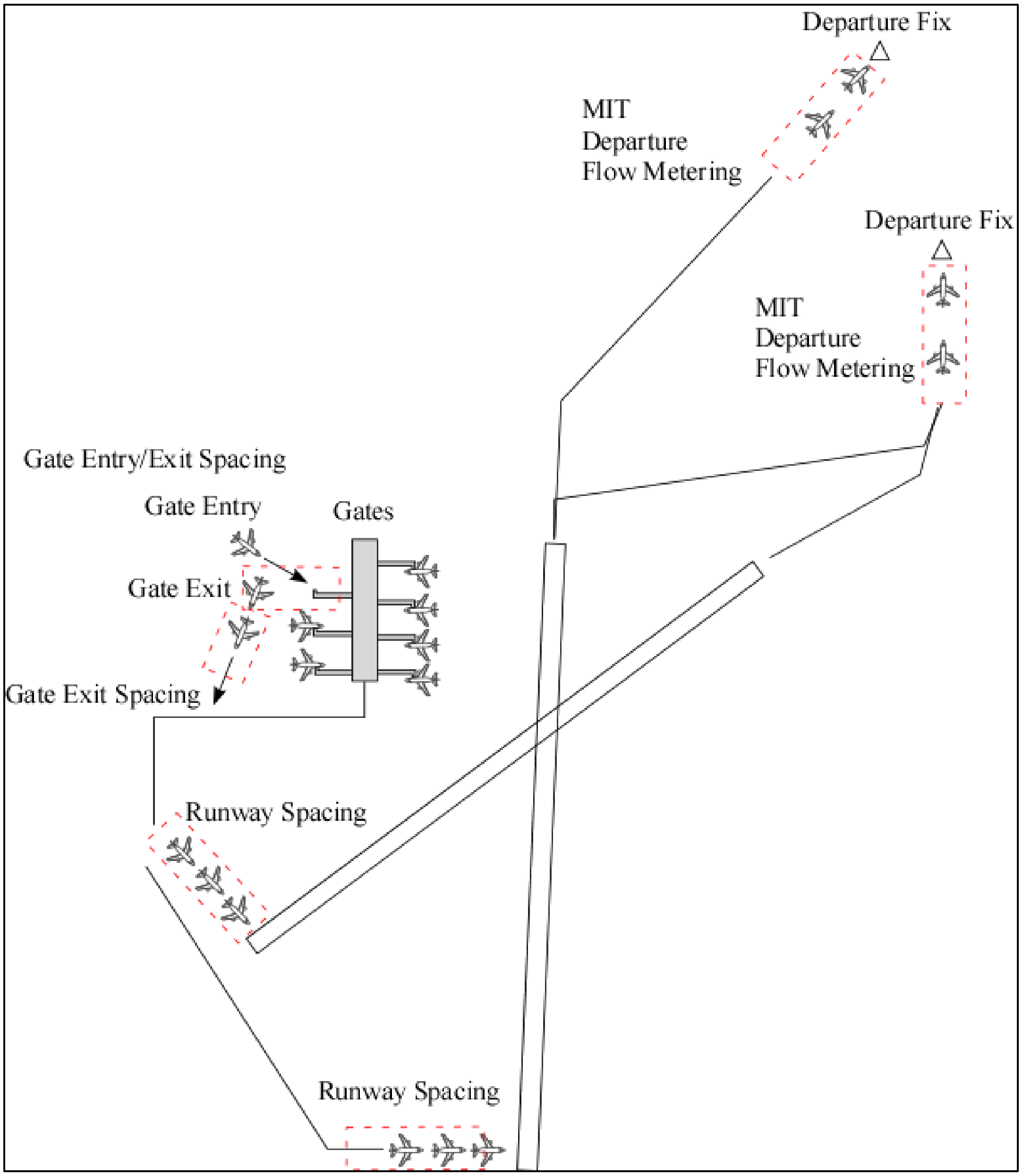


Figure 2-7. Reference Points for Time-Based Scheduling Considered by the DMP Emulator.

The next reference points after the gates are the runway thresholds. The departures must be adequately spaced for runway occupancy at the runway thresholds. The final reference points are the departure fixes. MIT flow restrictions are occasionally applied to departure fixes, which require flights crossing those fixes to have spacing in addition to the gate and runway spacing already applied. The flow restrictions require that a subset of the aircraft crossing the fix in question to be spaced with respect to each other independent of the other flights in the system. The DMP Emulator must generate a schedule that simultaneously satisfies the gate spacing, the runway spacing and all flow restrictions that may exist.

In addition to spacing, the DMP Emulator will try to manage queue lengths at the runway for aircraft waiting to takeoff to insure that no additional delay is incurred due to lost due to gaps in runway usage. The point is to always make sure that there is an aircraft ready to takeoff, and no gap in runway usage due to the schedule spacing. To do this the DMP Emulator will schedule aircraft at a rate slightly higher than the expected runway departure rate until a particular queue length is achieved at the runways. After the queue has been established, the DMP Emulator adjusts the runway scheduling to maintain the queue.

2.2.1 High Level Functionality

The high-level functionality of the DMP Emulator consists of three main components as shown in Figure 2-8. The first component sorts all the flights in the scenario by their respective reference points. Flights destined to use a particular gate or runway are assigned to that reference point. A departure fix with a flow restriction is also considered a reference point and is treated identically to a gate or a runway. A list of flights associated with each reference point is created.

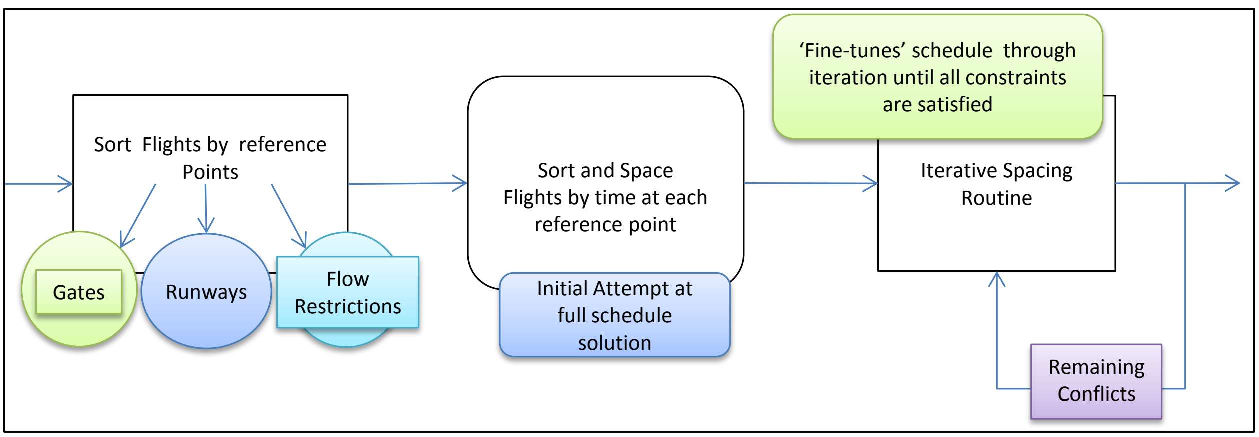


Figure 2-8. The Three High-level Functions of the DMP Emulator.

The second component of the DMP Emulator is the initial sorting and spacing of the flights within each of the reference point arrays. Here, flights are first sorted with respect to their time of arrival (or departure if warranted) at a particular reference point. This process maintains the first-come first-serve order for the reference point. The second component then makes the first estimate at a spacing solution. When the second component of the DMP Emulator completes, the order of the flights and an estimate of the flight spacing/delay solution to the scheduling problem is established.

The third component of the DMP Emulator is designed to take the first estimate of the spacing solution, which is not conflict free, and iterate until it achieves a solution that satisfies all scheduling constraints simultaneously. The function loops through the spacing algorithms for the various reference points until all the spacing algorithms simultaneously generate a conflict free schedule.

2.2.2 Component 1: Initial Sorting and Assignment

The initial sorting and assignment component starts with a characterization of the airport environment in terms of the reference points involved (i.e. the number of gates, runways, departure fixes) and the estimated transit times between reference points. Next, the flights that are to be scheduled by the DMP Emulator are evaluated. Each flight comes to the DMP Emulator with a scheduled gate entry and exit time, and the appropriate reference points already enumerated (i.e. an assigned gate, runway, and departure fix). For each flight, the times at the relevant reference points are calculated using the scheduled gate exit time and the estimated transit times from the airport environment. The transit times come from a fixed database and represent fixed nominal transit times between gate-runway pairs and then fixed times for runway-departure fix pairs. For each flight, an unimpeded transit estimate is calculated so that the unimpeded times at the gate, runway, and departure fix are known. In software, each flight is represented as its own object, and the appropriate reference points and their unimpeded transit times are stored within. These flight objects are stored in a master flight array. Figure 2-9 shows the basic process. Several time terms are presented in the figure, such as t^{i}_{runway} , where the superscript represents the sequence in the array, and the subscript reflects the type of reference point.

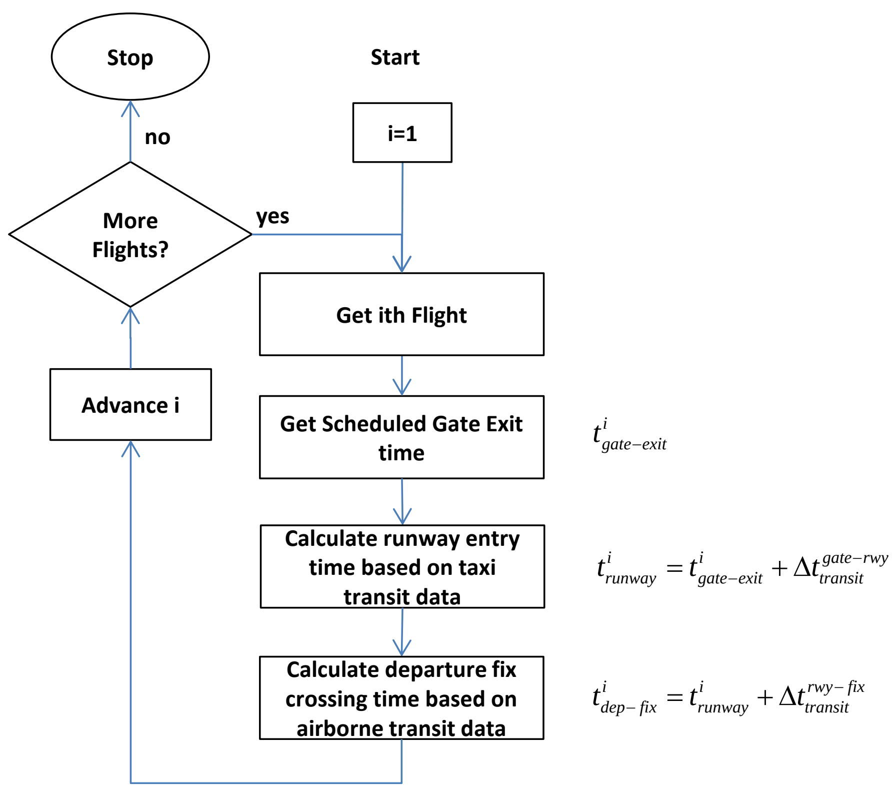


Figure 2-9. Logic Flow Diagram to Calculate the Unimpeded Transit Times of Flights.

The next task is to sort the flights by reference point. Each reference point maintains a list of all the flights that will be using it. For instance, for a particular gate or runway, a list of all the flights that will be using it is maintained. In a software representation (see Figure 2-10), each reference point is represented by an object containing an array of flights. Since a particular flight object is represented in multiple reference point arrays, it must be allocated by *reference*; that is, one instance of each flight is created, but multiple arrays have a *reference* to it. In the DMP Emulator there are four types of reference points. These are: gate entry, gate exit, runway, and flow restriction (departure fix). While the gate is physically only one reference point in reality, for the purposes of the algorithm, it is useful to consider it as two distinct points and model the flights as transitioning between them. The term flow restriction is preferred for departure fix reference point, since only departure fixes that have flow restrictions are considered in the spacing problem.

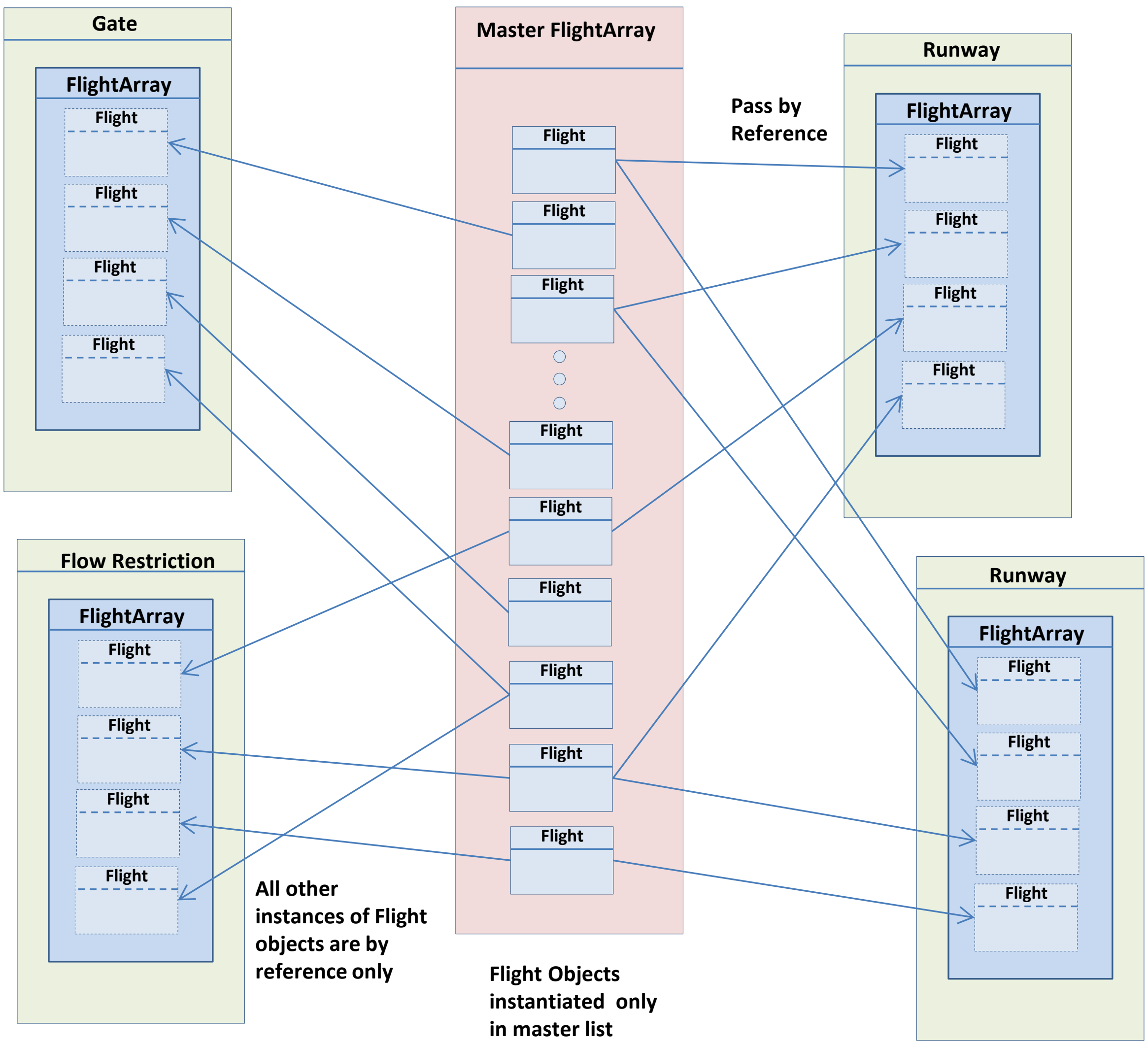


Figure 2-10. Representation of the "Pass-by-reference" Relationship between Flights and the Reference Point Arrays.

Figure 2-11 contains flow diagrams that represent the basic functionality. In most cases, assignment of a flight to a particular array is as simple as evaluating its assigned reference point. For instance, the flight data specifies the gate and runway, so here a basic assignment is made. For the flow restrictions, the flight data doesn't explicitly define which flight is subject to a particular restriction, so this must be determined from the available data. To be subject to a restriction, a flight must be using the departure fix subject to the restriction, and the flight must be estimated to cross the fix within the time window for when the flow restriction is in effect. Figure 2-11 shows the restriction conditionals next to the departure flow restriction decision-box. The flight's estimated departure crossing time is used to determine if the flight falls within the active time for the restriction, and if it does, it is added to the appropriate flow restriction array.

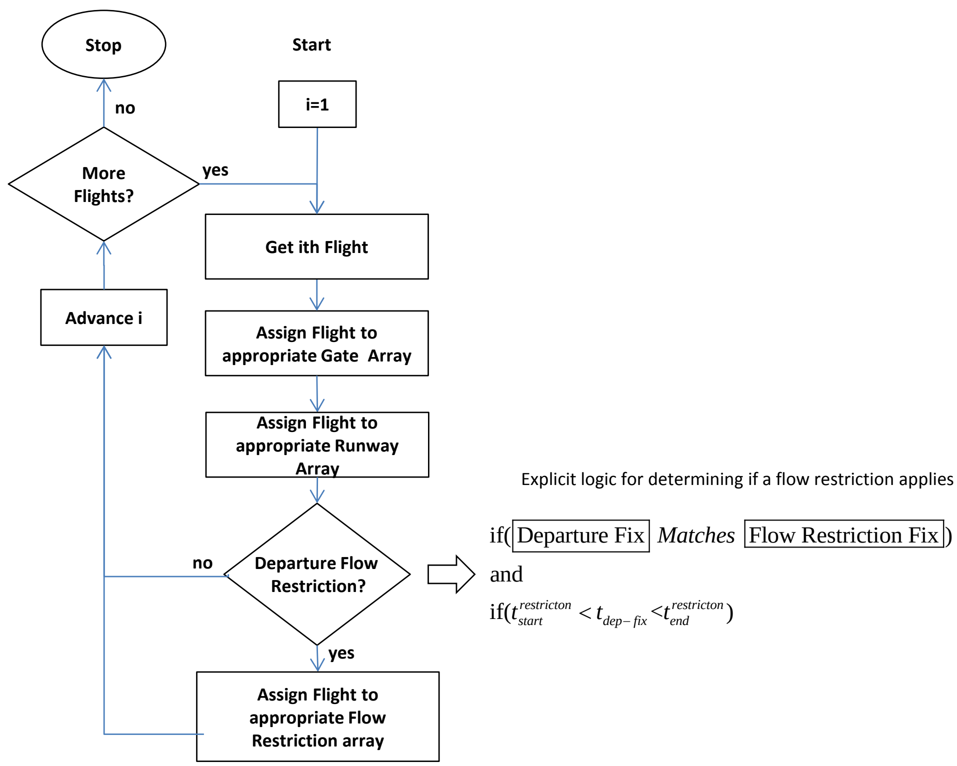


Figure 2-11. High Level Logic Flow for the Population of Reference Point Arrays with Flights.

2.2.3 Component 2: Sorting and Initial Spacing

The second component focuses on sorting and spacing flights within each individual reference point array. In this task, the flights are sorted by their respective reference point times so that they are all in ascending order. For instance, at a runway reference point, all the flights using that runway are sorted based on their unimpeded runway arrival time. A similar sort is applied at the gates (using gate exit time) and at the departure fixes (using fix crossing time). Spacing is also applied during this process. Here, aircraft are spaced according to an externally specified spacing criterion (e.g., 120 seconds runway spacing). The order of the operation is important because the spacing of aircraft in one array may influence the sorted order of the aircraft in another array. This is particularly true of the flow restrictions. With flow restrictions, flights are likely to be given large spacing constraints (e.g., 5 minutes or more) and this will impact their order with the other flights at the runway. Once delay is added to a flight, those updated times are used for all subsequent sorting and spacing operations. Figure 2-12 shows the order of operation. Each box in Figure 2-12 represents a series of sorting (or spacing) operations for all arrays of a particular type as shown in Figure 2-13, where the "Space At Runways" operation is used as an example.

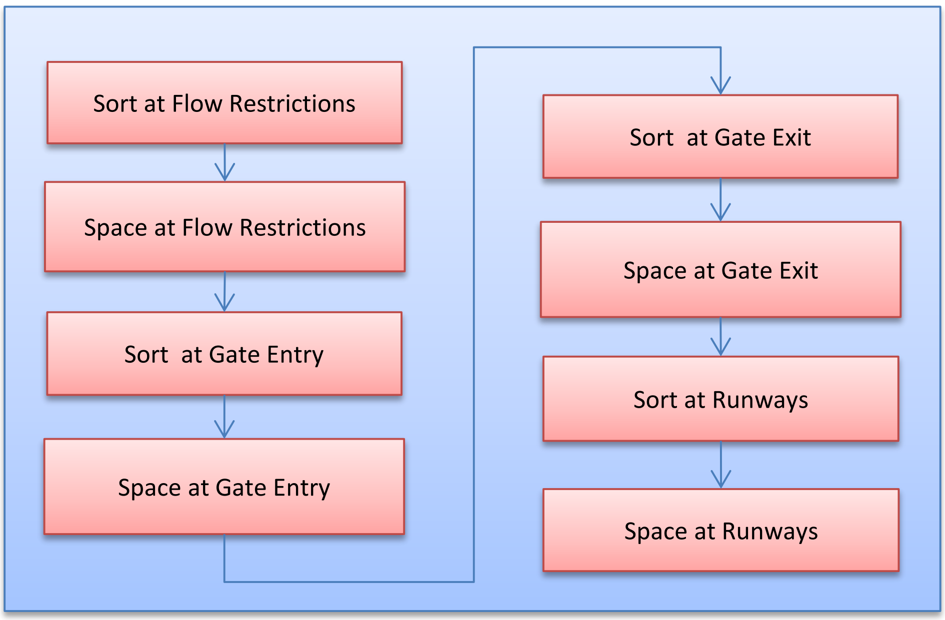


Figure 2-12. Order of Operation for Component 2 Functionality.

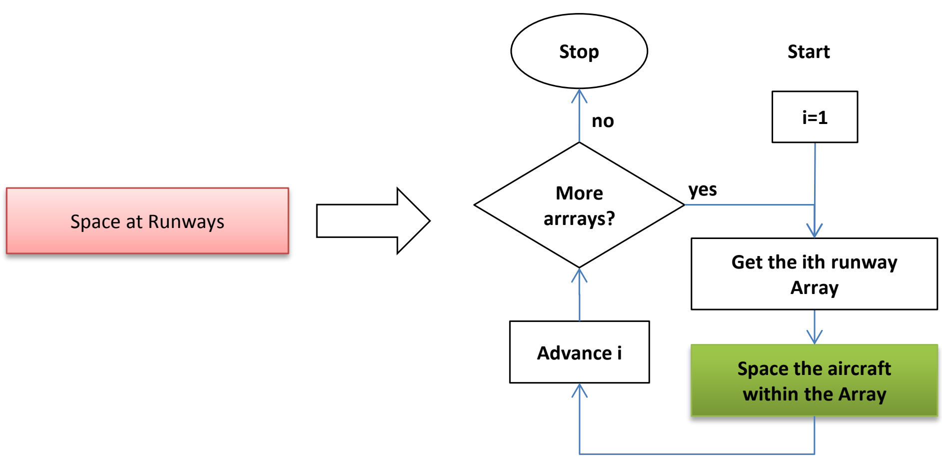


Figure 2-13. Representative Expansion of the Internal Functionality of Component 2 (Using Space at Runways as an Example).

The sort and space routines represented in the block diagrams in Figure 2-12 show that all the flights of a particular type of reference point are sorted (or spaced) at the same time. The algorithms are constructed in software such that a single sorting and spacing algorithm performs the operation on all the reference point arrays regardless of their type, with the one exception being runway spacing. With runway spacing, a modified spacing algorithm is used to enable queue management. For instance, all gate exit reference point arrays are looped through and low level sort and spacing routines are then applied directly to the flights in the particular array. The one detail missing from Figure 2-13 is that the routine must know what type of reference point array it is working with to know what times to use. For instance, the algorithm must know that it is working with runway reference points so that it can sort and space based on runway arrival time rather than gate or departure fix time. One other anomaly peculiar to the gate entry time spacing is that the times used for spacing between aircraft are not the same. In this particular case, the entry time of the aircraft entering the gate must be spaced against the exit time of the aircraft leaving the gate, to insure no two aircraft occupy the gate at the same time. However, in all other cases like-times are compared (e.g. runway arrival time versus runway arrival time for both leading and trailing aircraft). The low level spacing algorithms are covered in depth in Section 2.2.5.

When the Component 2 function completes execution, the flights are properly sorted in time, and an initial spacing has been accomplished. However, spacing at the runway will have invariably created conflicts in the prior reference points, in particular the flow restrictions. For this reason Component 3 of the algorithm is needed to eliminate these residual spacing conflicts.

2.2.4 Component 3: Iterative Spacing

To eliminate all residual spacing conflicts, an iterative approach is applied as shown in Figure 2-14. The iterative spacing algorithm runs the same spacing algorithms in the same order as component 2, but runs them in an iterative fashion. In addition it keeps track of whether additional delay was added at any point throughout the process. If delay was added, then there is a chance that a new residual conflict may have been created, and the algorithm must run another cycle. The algorithm cycles until no spacing changes have been added in any of the components, and then it returns. As a matter of practicality, the number of iterations is limited to prevent an infinite loop, however the solution usually converges with 5-10 iterations.

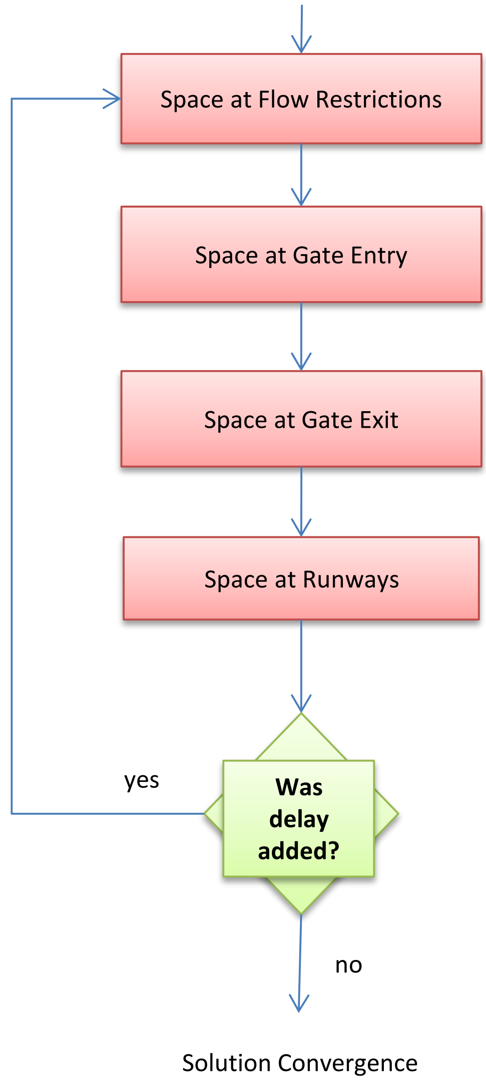


Figure 2-14. Iterative Spacing Algorithm Flow Diagram.

The basic premise of this convergence algorithm is that conflicts created by a spacing/delay addition in a particular reference point array (in another reference point array) are always downstream of the flight in question. Therefore, successive iterations of the algorithms continually move conflicts further down-stream until they are eliminated entirely.

2.2.5 Spacing Operation

The low level spacing operation (the green highlighted box of Figure 2-13) is illustrated graphically in Figure 2-15 and represents how spacing is done internally within each reference-point array. The sorted flights associated with a particular reference point are assessed to insure the minimum acceptable time spacing, Δt_{sp}, is provided, and delayed as needed to ensure they comply with this spacing. A flow diagram shows how this operation is explicitly performed in Figure 2-16.

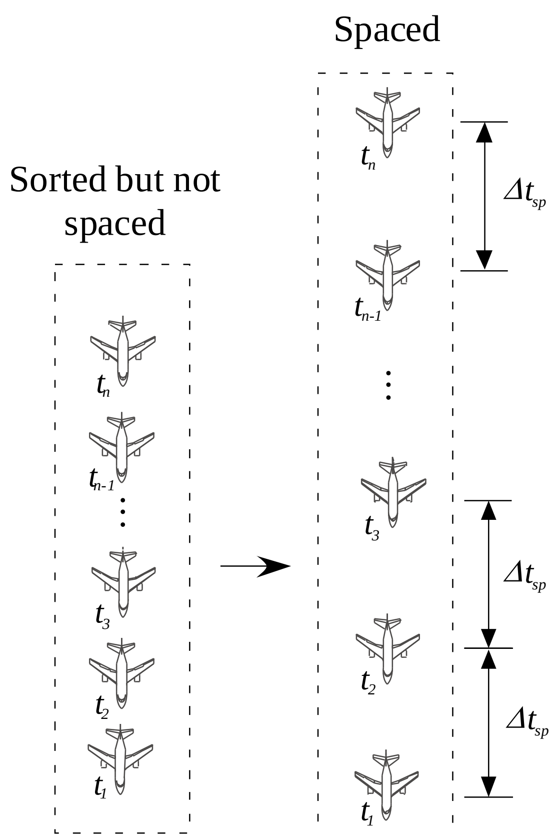


Figure 2-15. Basic Spacing Illustration Where Δt_{sp} is the Minimum Required Spacing.

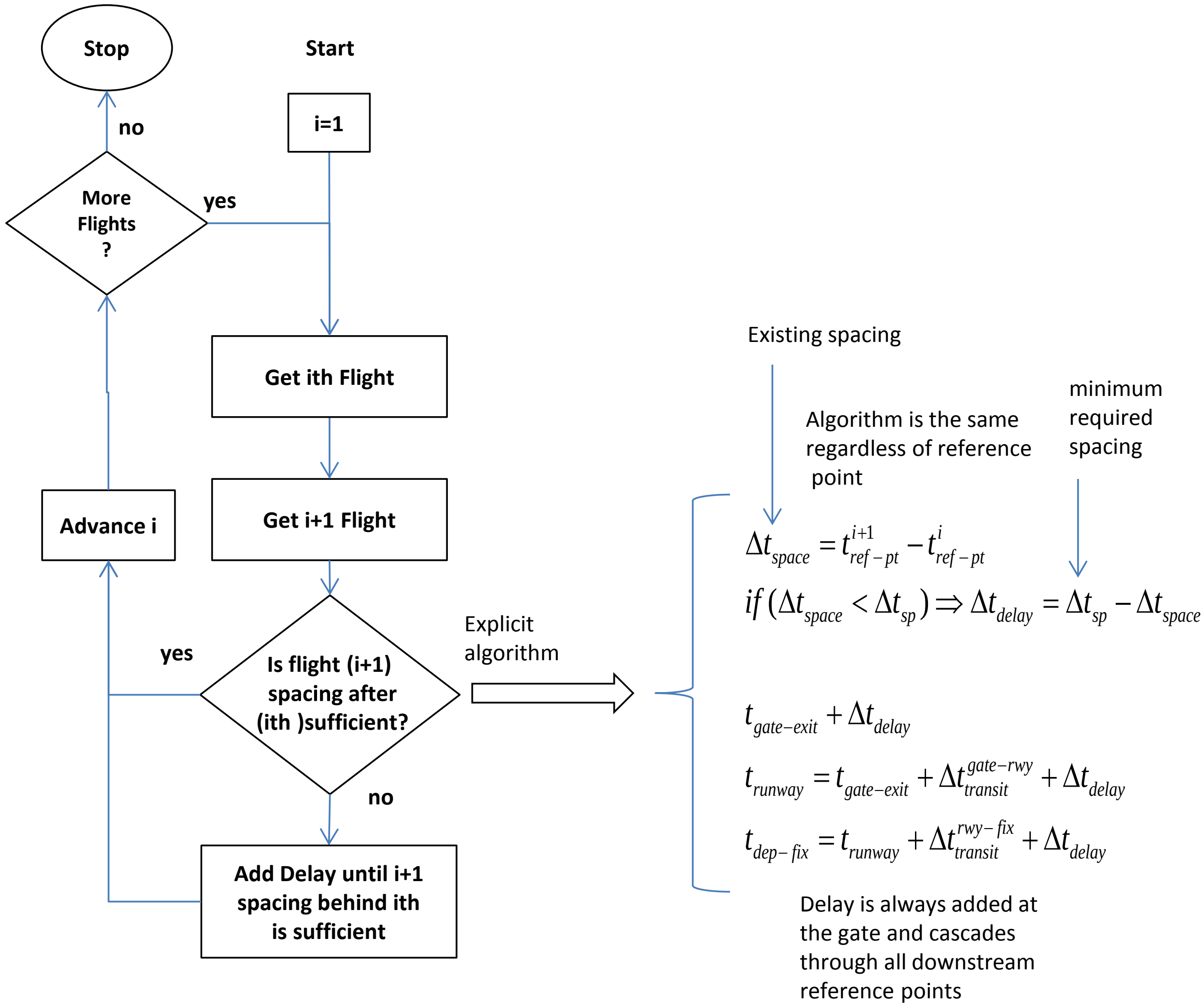


Figure 2-16. Basic Spacing Flow Diagram.

2.2.6 Spacing to Maintain a Queue Length

The spacing algorithm used to maintain runway spacing differs from the general spacing algorithm because the spacing between flights is not maintained constant. Rather the spacing may be reduced below the nominal spacing parameter, Δt_{sp}, (see Figure 2-15) to build up a queue at the runway. This section discusses how the spacing parameter is calculated.

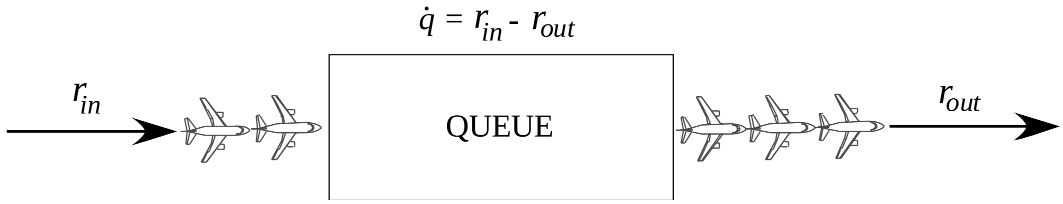


Figure 2-17. Basic Queue Rates.

The basic queue model is shown in Figure 2-17 and is comprised of the rate of aircraft flowing in, $r_{in,}$, and the rate of the aircraft flowing out, r_{out} . The total queue rate, $\dot{q}$, is the difference between the flow in and the flow out as shown in Equation (1). For the queue model, aircraft are not considered as discrete entities, but rather as a continuous flow, so fractional aircraft quantities are considered. The total size of the queue is represented as the integral of the queue rate as shown in Equation (2). However, the integral form of the equation is not particularly useful, therefore a discretized version of the relation is used as shown in Equation (3). The term, i , in this context refers to the iteration of the spacing algorithm. It refers to the ith flight in the spacing sequence within a particular runway reference-point array. In other words, the estimated runway queue size when the ith flight arrives at the runway is q_i . The term, Δt_{sp_i} , is the spacing parameter, but is no longer the minimum or nominal spacing parameter. In this case it is a parameter unique to the spacing between i and $i+1$ aircraft in the sequence.

$$\dot{q} = r_{in} - r_{out} \tag{1}$$

$$q = \int \left(r_{in} - r_{out} \right) dt \tag{2}$$

$$q_{i+1} = q_i + \left(r_{in_i} - r_{out_i} \right) \Delta t_i \tag{3}$$

It is not obvious how the rates are defined with respect to the aircraft sequence. First, a new term, Δt_{rwy} , is defined representing the required runway spacing, since the term Δt_{sp_i} can no longer be assumed to equal to runway spacing. The rate out of the queue is the reciprocal of Δt_{rwy} (see Equation (4)) since one aircraft can leave the queue every Δt_{rwy} time increment. The rate out is a constant. Similarly, the rate into the queue is the reciprocal of the spacing parameter, Δt_{sp_i} , since one aircraft enters the queue every Δt_{sp_i} time increment.

$$r_{out} = \frac{1}{\Delta t_{rwy}} \tag{4}$$

$$r_{in} = \frac{1}{\Delta t_{sp_i}} \tag{5}$$

Therefore, the queue size at the $i+1$ spacing sequence is related by Equation (6).

$$q_{i+1} = q_i + \left(1 - \frac{1}{\Delta t_{rwy}}\right)\Delta t_{sp_i} \tag{6}$$

Using Equation (6), the queue size can be directly controlled by the spacing parameter, Δt_{sp_i} .

2.2.6.1 Feedback Control of Queue Size

The queue size can be controlled by a simple feedback control strategy. First a queue length error value e_q is defined (see Equation (7)) as the difference between the target queue length, q_t , and the estimated queue size at the ith spacing sequence , q_i .

$$e_q = q_t - q_i \tag{7}$$

The error value is used to calculate a spacing parameter using Equation (8), where K_q is a feedback gain that can be tailored to suit. For the DMP Emulator, a value of $K_q = 0.5$ is used.

$$\Delta t_{sp_i} = \Delta t_{rwy} - K_q \Delta t_{rwy} \frac{e_q}{q_t} \tag{8}$$

Hence, the total delay added to a the aircraft in the $i+1$ spacing sequence is a function of Δt_{sp_i} as shown in Equation (9). Of course, if the nominal spacing, $\Delta t_{spacing}$, is greater than Δt_{sp_i} , no delay is required.

$$\begin{aligned} &\Delta t_{spacing} = t^{i+1}_{runway} - t^{i}_{runway} \\ &if\,(\Delta t_{spacing} < \Delta t_{sp_i}) \Rightarrow \Delta t_{delay} = \Delta t_{sp_i} - \Delta t_{spacing} \end{aligned} \tag{9}$$

2.2.6.2 Preventing Negative Queue Estimates

It is not always possible to specify the spacing between flights, since the nominal spacing of flights may not require the addition of delay. Figure 2-16 shows that delay is only added if the spacing between the aircraft is needed. If the spacing is already greater than the calculated Δt_{sp_i} , no delay is warranted. Delay can be added, but the schedule can't be advanced, so the queue will naturally diminish under these circumstances. Therefore, only when the nominal spacing between aircraft falls below Δt_{sp_i} does the feedback control element even come into play. If the nominal spacing is sufficiently large due to the natural spacing the queue estimate (Equation (6)) is driven negative values, which are not physically representative of the real system. Therefore the queue estimate must be bounded to always be positive. This is a similar problem to an integrator wind-up problem, and so the queue estimate must be bounded to not ever be less than zero.

2.2.7 Start and Stop Time

DMPs are tailored to operate during a selected interval of time, so start and stop times may be input to the DMP Emulator. If start and stop times are specified, the DMP emulator only considers flights whose gate pushback time fall within the specified start and stop times. In cases where considerable delay is needed, a certain number of flights that fall near the DMP stop time will likely be delayed to a time later than the stop time. This can be problematic because the gate pushback times of departures subject to the DMP may overlap with flights whose airline-scheduled gate pushback times are later than the DMP stop time.

From a traffic scheduling point of view, there isn't any benefit to turning the DMP gate pushback/TMAT scheduling on and off. The DMP scheduling could be in effect all the time, since it only delays flights that need it, and in theory should not do anything but transfer delay from the ramp area to the gate area. For times when airport demand is low, the DMP scheduling won't add delay even if it is active.

2.3 Traffic Performance Metrics

Metrics for evaluating airport traffic performance for what-if analysis were selected for their utility to the DRC in detecting demand/capacity imbalances, measuring their impact on airport operations, and assessing the impact of a DMP proposed to mitigate those impacts.

The primary focus of DMPs is to maintain airport departure throughput while minimizing, to the extent possible, traffic congestion in the airport movement area and its primary and secondary negative effects. Primary effects of airport traffic congestion include runway queues which are unreasonably long, taxi-out times which are longer and exhibit greater variability, and reduced airport throughput. Secondary effects include increased noise and exhaust emissions to the airport; increased costs to aircraft operators through increased fuel burn and crew time, and lack of schedule integrity; and increased workload for the airport traffic control tower.

The What-if Analysis Tool presents airport traffic performance metrics on a per-runway basis for each 15- or 60-minute time bin throughout the entire period of what-if assessment, and as aggregate metrics over the entire period of what-if assessment. The per-runway metrics enable the DRC to understand airport operations in greater detail, and to identify if a DMP for a single runway or airport-wide departures is required. The time bin metrics show the trends in traffic performance throughout the time period of assessment to provide the DRC with a more detailed understanding of traffic behavior, and to help to specify DMP start and stop times. The aggregate metrics show the overall traffic performance over the time period of evaluation.

2.3.1 Departures

Performance evaluation metrics for departure traffic selected for presentation to the DRC in what-if analysis include the departure pushback rate, the departure takeoff rate, the runway departure queue length, taxi-out time and gate pushback delay on a per-runway basis.

Departure pushback rate indicates to the DRC the level of anticipated demand for particular airport runway and ancillary resources that is expected. This helps understand the nature of the traffic demand and the need for a DMP. This may influence the specification and implementation of a DMP, or traffic management strategies to accommodate the DMP.

Departure takeoff rate is a fundamental airport performance metric. The takeoff rate indicates to the DRC the airport throughput that is being achieved, and whether the DMP is starving the runway of departures or helping to sequence and schedule departures to maximize throughput.

Runway queue length is the primary metric for departure metering programs [FA2012]. Queue length is managed to maximize airport throughput as per the operating conditions [AN2000][WE2001][NA2011]. Excessively long queues indicate the need for a DMP. Excessively short or lack of queues indicates the need to stop or redesign the DMP.

Taxi-out time is an important metric. If gate holding is employed by airlines to conform to the TMATs specified under the DMP, taxi-out times are reduced. Otherwise, taxi-out times indicate the impact on non-movement area resources for holding departures to comply with the TMATs.

Gate holding is an important metric for DMPs. If gate holding is employed by aircraft operators to satisfy the TMATs under the DMP, gate delay is increased. Otherwise, non-movement area resources must be used for holding departures to comply with the metering, and the possible fuel burn, noise and exhaust emissions, and crew time benefits of departure metering may not be realized.

Figure 2-18 shows the per-runway number of gate pushbacks for departures from what-if simulations with the *hitl6-training-advisory.list_data* traffic file.

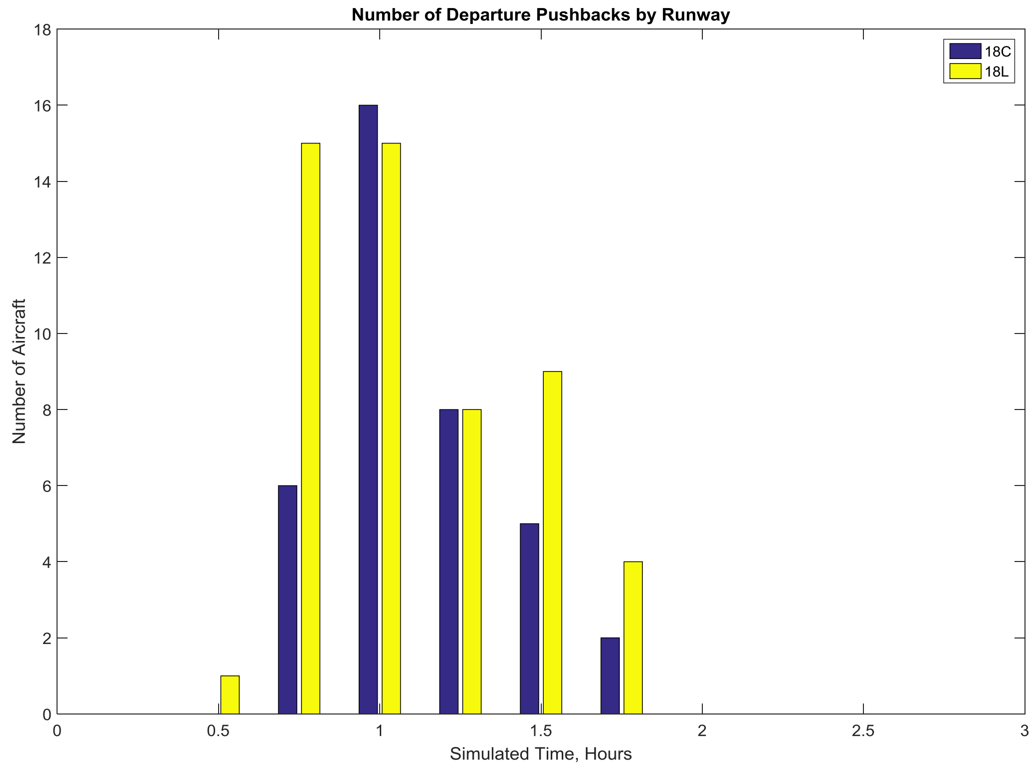


Figure 2-18. Per-runway Airline-Scheduled Departure Pushbacks Obtained for Simulated Departures in the *hitl6-training-advisory.list_data* File.

The departure pushback rate is the number of departures scheduled to push back within a particular time period. Time bin metrics and aggregate metrics present the DRC with the actual count of scheduled departure pushbacks in a specified time period. This metric is intended to provide the DRC with a detailed understanding of the departure demand for airport runway resources.

Figure 2-19 shows the per-runway time bin takeoff, queue length, taxi-out, and gate delay metrics computed for departures from what-if simulations with the *hitl6-training-advisory.list_data* traffic file. A dashed red line shows the target departure queue length of 3 aircraft for departure runways 18C and 18L.

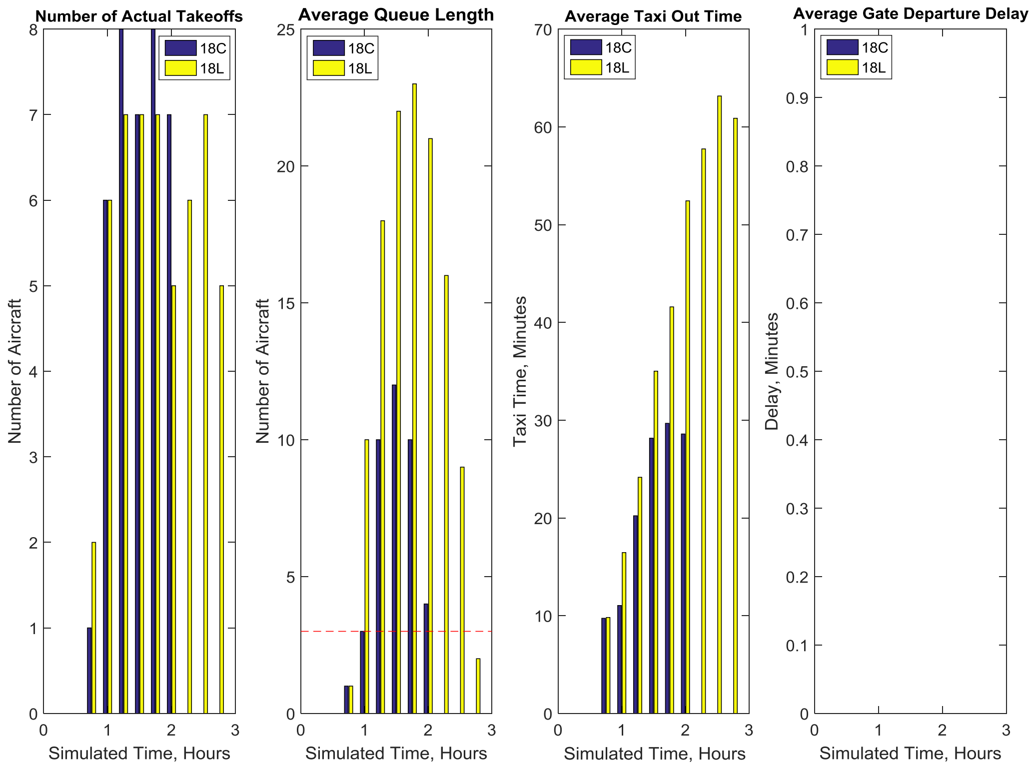


Figure 2-19. Quarter-hour Per-runway Takeoffs, Queue Length, Taxi-out, and Gate Departure Delay Metrics For Simulated Departures in the *hitl6-training-advisory.list_data* File.

The departure takeoff rate is the number of departure takeoffs from a runway in the particular time period. Time bin metrics present the DRC with the actual count of departure takeoffs. Aggregate metrics present the DRC with the number of departure takeoffs divided by the total time in which they took off.

The runway departure queue length is the number of departures waiting to take off at a runway at each simulation time step. Time bin metrics present the DRC with the average of the queue length values among the simulation time steps falling within the time bin. Aggregate metrics present the average, maximum and minimum of the queue length values among all the simulation steps.

The taxi-out time is the time difference between takeoff and gate pushback for a departure. Time bin metrics present the DRC with the average of the taxi-out times of the departures that have taken off from a runway within the time bin. Aggregate metrics present the average of the taxi-out times of all the simulated departures. Airport traffic controllers, airline ramp controls and other airport operations personnel have intuitions for the taxi-out times of aircraft, rather than delay values above a nominal time, thus raw taxi-out times were selected for presentation to the DRC.

Gate pushback delay is the time difference between the actual pushback time and the airline-scheduled gate pushback time of a departure. Time bin metrics present the DRC with the average of the gate pushback delay of the departures that have taken off from a runway within the time bin. Aggregate metrics present the average of the gate pushback delays of all the simulated departures.

In addition to presenting the metrics on a quarter-hour or hourly basis for the DRC to observe variation and trends in airport traffic performance, the What-if Analysis Tool includes a table of summary metrics to assess the aggregate performance of traffic within the forecast time window. Table 2.1 presents the aggregate takeoff, queue length, taxi-out, and gate delay metrics computed for departures for each runway from what-if simulations of the *hitl6-training-advisory.list_data* traffic file.

Table 2.1. Aggregate Per-runway Takeoffs, Queue Length, Taxi-out Time, and Gate Departure Delay Metrics for Simulated Departures in the hitl6-training-advisory.list_data File.

Departure Runway	Average Throughput, Departures Per Hour	Average Queue Length, Departures	Maximum Queue Length, Departures	Minimum Queue Length, Departures	Average Taxi-out Time, Minutes	Average Gate Delay, Minutes
18C	29	3	12	0	23.6	0
18L	26	9	25	0	41.9	0

2.3.2 Arrivals

Performance evaluation metrics for arrival traffic selected for presentation to the DRC in what-if analysis include the arrival entry rate to the terminal airspace and the taxi-in time on a per-runway basis.

Arrival entry rate indicates to the DRC the level of anticipated contention of departures with arrivals for airport gate, taxiway and runway resources that might be expected. Such contention may influence the specification and implementation of a DMP, or particular traffic management strategies to employ in conjunction with the DMP.

Arrival landing rate is a fundamental airport performance metric. Arrival entry rate indicates to the DRC the airport throughput that is being achieved, and indicates the level of contention of departures with arrivals for airport gate, taxiway and runway resources that might be occurring.

Taxi-in time is another fundamental airport performance metric which can be impacted by departure metering programs. Gate holding of departures undertaken to conform to the departure metering program can result in contention between arrivals and departures for gate resources, resulting in increased taxi-in delay for arrivals. This may influence the specification and implementation of a DMP, or traffic management strategies employed as part of the DMP.

Figure 2-20 shows the per-runway number of fix crossings computed for arrivals from what-if simulations with the *hitl6-training-advisory.list_data* traffic file.

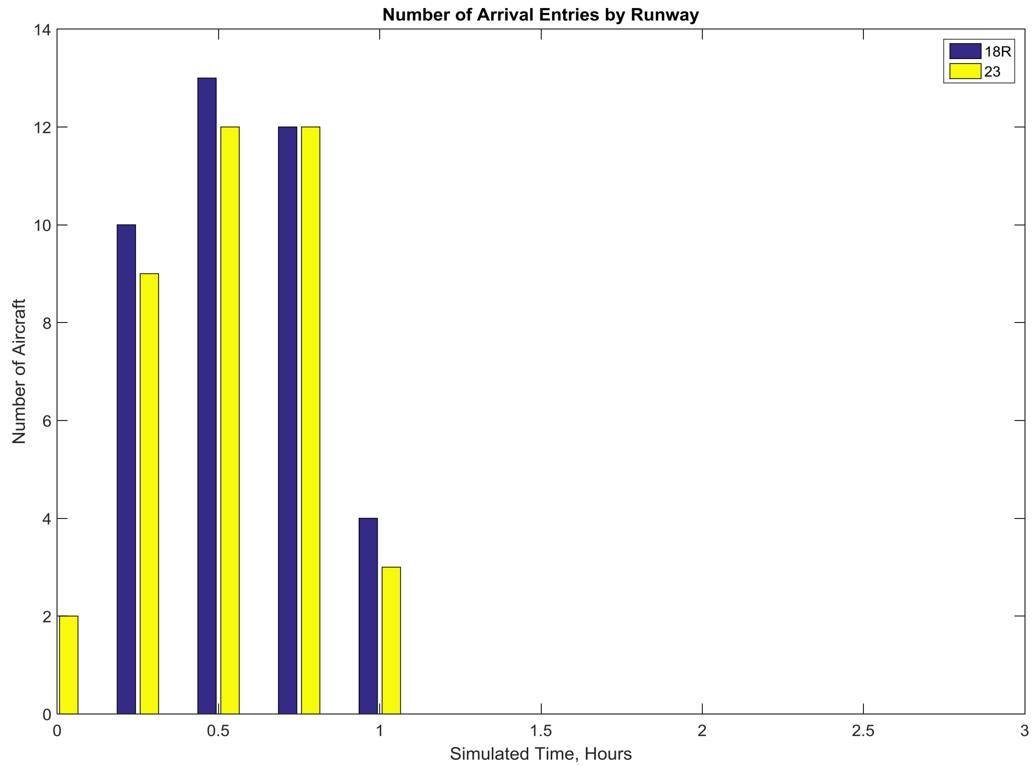


Figure 2-20. Quarter-hour Per-runway Arrival Fix Crossings for Simulated Arrivals in the *hitl6-training-advisory.list_data* File.

The arrival entry rate is the number of arrivals scheduled to cross their assigned arrival fixes within a particular time period. Time bin metrics and aggregate metrics present the DRC with the actual count of arrival fix crossings in a specified time period. This metric is intended to provide the DRC with a detailed understanding of the arrival demand for airport resources.

Figure 2-21 shows the per-runway time bin landing and taxi-in metrics computed for arrivals from what-if simulations with the *hitl6-training-advisory.list_data* traffic file.

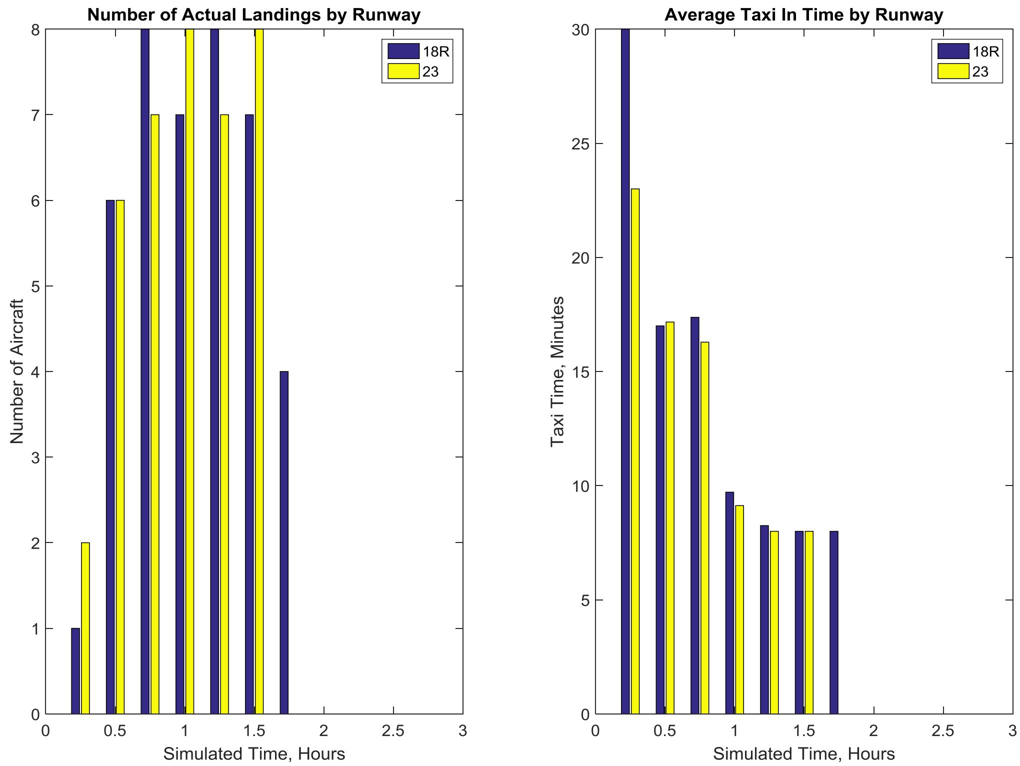


Figure 2-21. Per-runway Arrival Landings and Taxi-in Times for Simulated Arrivals in the *hitl6-training-advisory.list_data* File.

The arrival landing rate is the number of arrival landings to a runway in the particular time period. Time bin metrics present the DRC with the actual count of arrival landings. Aggregate metrics present the DRC with the number of arrival landings divided by the total time in which they all occurred.

The taxi-in time is the time difference between landing and gate entry for an arrival. DMPs may increase taxi-in times due to gate holding of departures to comply with the TMATs. Time bin metrics present the DRC with the average of the taxi-in times of the arrivals that have landed to a runway within the time bin. Aggregate metrics present the average of the taxi-in times of all the simulated arrivals. Airport traffic controllers, airline ramp controls and other airport operations personnel have intuitions for the taxi-in times of aircraft, rather than delay values above a nominal time, thus raw taxi-out times were selected for presentation to the DRC.

In addition to presenting the metrics on a quarter-hour or hourly basis for the DRC to observe variation and trends in airport traffic performance, the What-if Analysis Tool includes a table of summary metrics to assess the aggregate performance of traffic within the forecast time window. Table 2.2 presents the aggregate landing and taxi-in metrics computed for arrivals for each runway from what-if simulations of the *hitl6-training-advisory.list_data* traffic file.

Table 2.2. Aggregate Per-runway Landing and Taxi-in Time Metrics for Simulated Arrivals in the hitl6-training-advisory.list_data File.

Arrival Runway	Average Throughput, Arrivals Per Hour	Average Taxi In Time, Minutes
18C	29	23.6
18L	26	41.9

2.4 Verification

Verification of the What-if Analysis Tool includes verification of the airport traffic simulation and of the DMP emulation.

The airport traffic simulation of the What-if Analysis Tool was verified to ensure reasonable results in conjunction with the modeling fidelity and assumptions. Verification included ensuring simulation compliance with the modeling parameters and behavior, and comparison of simulation results to actual airport operations data. Verifying compliance with the physical parameters of the node-link modeling included verifying that each node and link model complied with its respective node service rate and link transit time specified by the user and that departures were adhering to their applicable restrictions. Verifying the performance of simulated traffic entailed comparison of simulation results to FAA ASPM data for various performance criteria.

The DMP emulation was verified to meet the overall requirements of delaying departure pushback times to meet a target queue length and reduce taxi-out delay.

The following subsections present verification methods and results obtained for simulated departures. Arrival flight behavior was also verified.

2.4.1 Link Transit Times

To verify simulation of the link transit times, the entry times of the 89 departures in the *hitl6-training-advisory.list_data* traffic file are rescheduled such that one departure pushes back every two minutes. This realizes an effective departure demand rate of 30 departures per hour; this is half of 60 departures per hour implied by the node service rates of 2 minutes for departure runway nodes 18L and 18C. Therefore, each departure should transit at the nominal link transit times since it should not incur delay due to traffic congestion. Figure 2-22 shows the resulting 15-minute period counts of scheduled departure pushbacks.

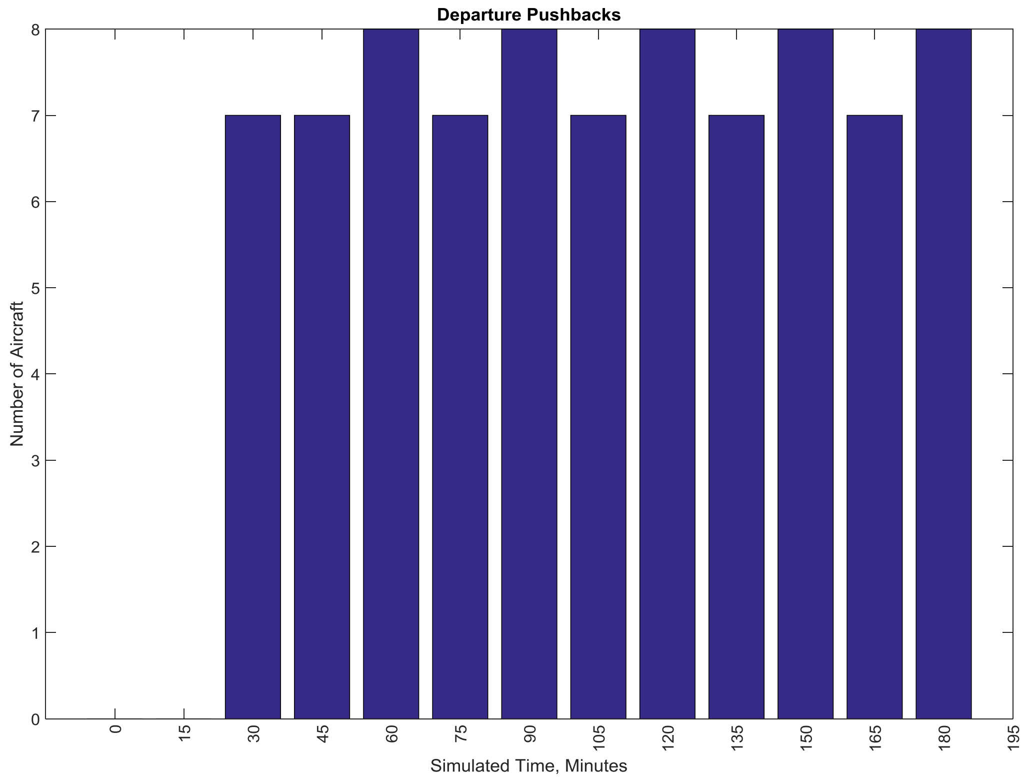


Figure 2-22. Sparse Departure Pushback Schedule for Verifying Link Transit Times.

The figure indicates the 15-minute period counts of departure pushbacks remain within 7-8 departures, corresponding to an hourly departure demand of 28-32 departures.

Figure 2-23 depicts the distribution of gate-spot (non-movement), spot-runway (movement area), and runway-fix (airspace) transit times among the simulated departures.

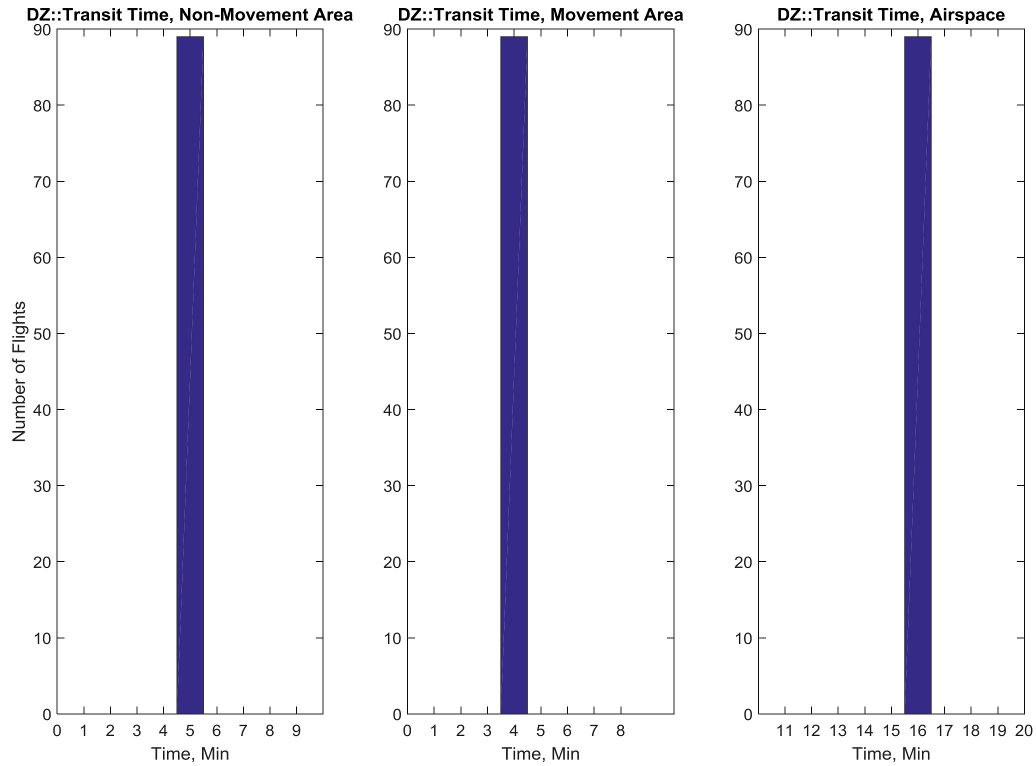


Figure 2-23. Distribution of Transit Times of Departures with Sparse Pushback Schedule.

The results indicate each departure transits at the nominal transit time of 5.0 minutes for gate-spot links, 4.0 minutes for spot-runway links, and 16.0 minutes for runway-fix links. No departure incurs any excess transit time.

Figure 2-24 depicts the distribution of gate-spot (non-movement), spot-runway (movement area), and runway-fix (airspace) delays among the simulated departures.

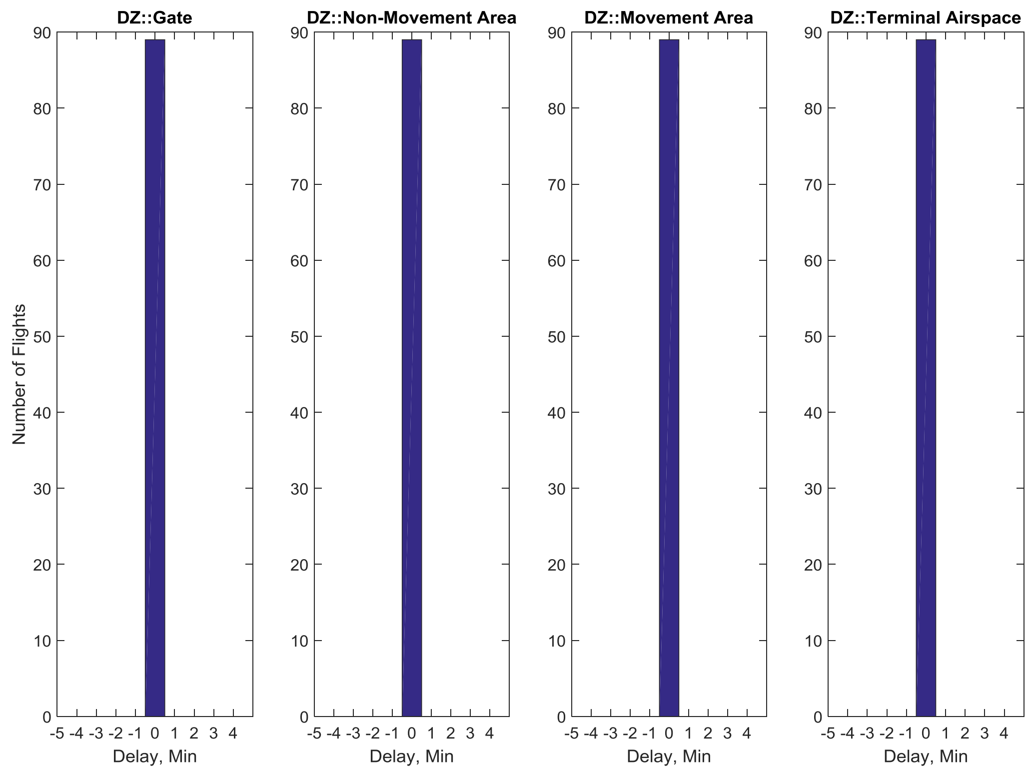


Figure 2-24. Distribution of Transit Delays of Departures with Sparse Pushback Schedule.

The results indicate each departure incurs zero delay at the gate, spot, runway and fix nodes bounding its gate, non-movement area, movement area and terminal airspace transit phases.

2.4.2 Node Service Rates

To verify simulation of the node service rates, the entry times of the 89 departures in the *hitl6-training-advisory.list_data* traffic file are retained. The result is that departure demand to departure runways 18L and 18C exceeds airport departure capacity. Under saturated traffic demand conditions, departure takeoffs should comply with the minimum queue service rate of 2 minutes for the departure runways. Figure 2-25 shows the resulting 15-minute period counts of scheduled departure pushbacks.

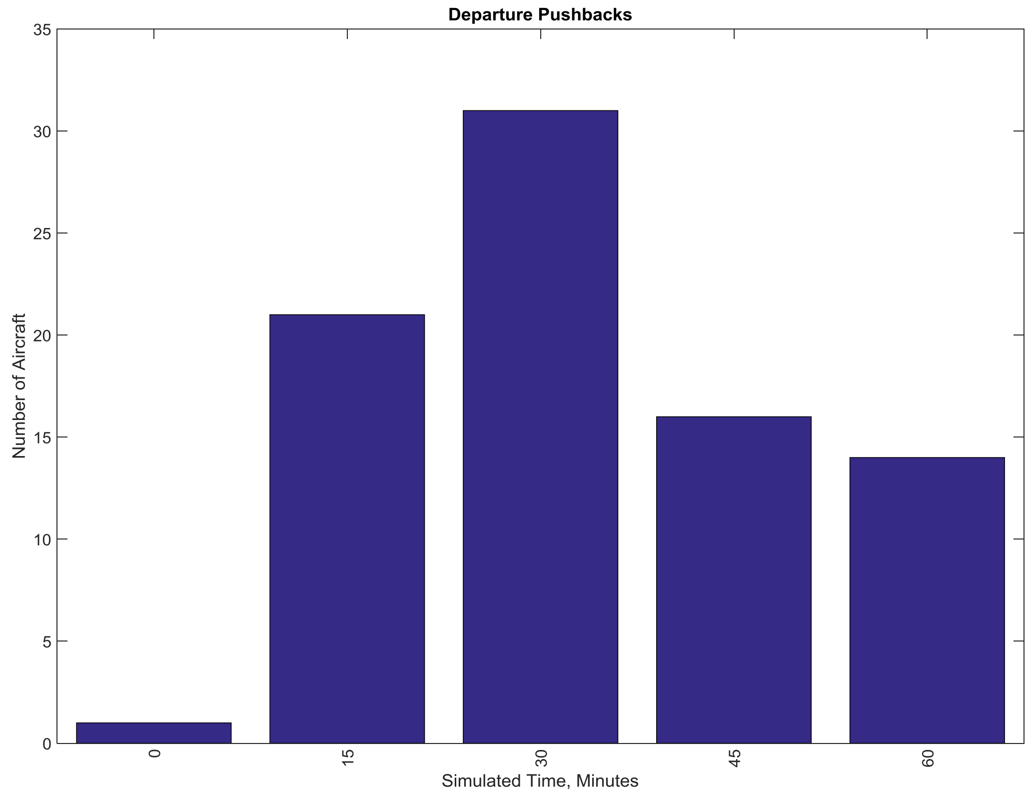


Figure 2-25. Dense Departure Pushback Schedule for Verifying Queue Service Times.

The figure indicates the departure demand rate is 21 departures in the second 15-minute period and 31 departures in the third 15-minute period of the traffic input file; these exceed the airport departure rate 15 departures per 15-minute period implied by the service rates of 2 minutes for departure runway nodes 18L and 18C.

Figure 2-26 depicts the distribution of queue occupancy times, time intervals between the sequence of departures exiting the runway, and the queue length for departure runway 18L.

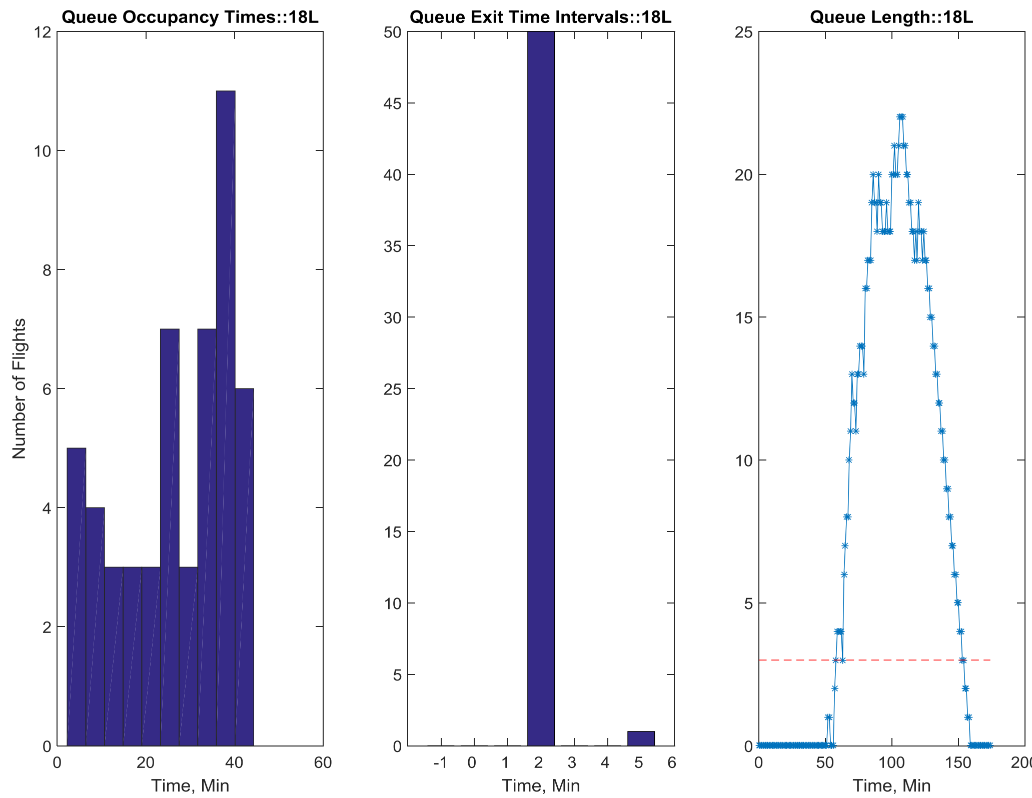


Figure 2-26. Queue Occupancy Times, Time Spacing of Node Exits, and Queue Length of Runway Node 18L.

The results of node exit time intervals between successive departures indicate that, under the saturated traffic demand, the departure takeoff times comply with the runway 18L node service rate of 2 minutes, corresponding to a maximum departure rate of 30 departures per hour for runway 18L. Similar results were obtained for departure runway 18C.

2.4.3 Node Queue Size Limit

To verify simulation of the node queue size limits, the entry times of the 89 departures in the *hitl6-training-advisory.list_data* traffic file are retained. The result is that there are multiple occurrences of contention for utilization of individual gates at the airport. Under saturated traffic demand conditions, occupancy of gate nodes should comply with the queue size limit of 1 aircraft, and the queue service rate of 30 minutes should be satisfied.

Figure 2-27 depicts the gate occupancy durations, gate entry time delays, and gate entry-exit time differences among the flights using each of the gates of the airport in the simulation. Results of the individual gates are aggregated.

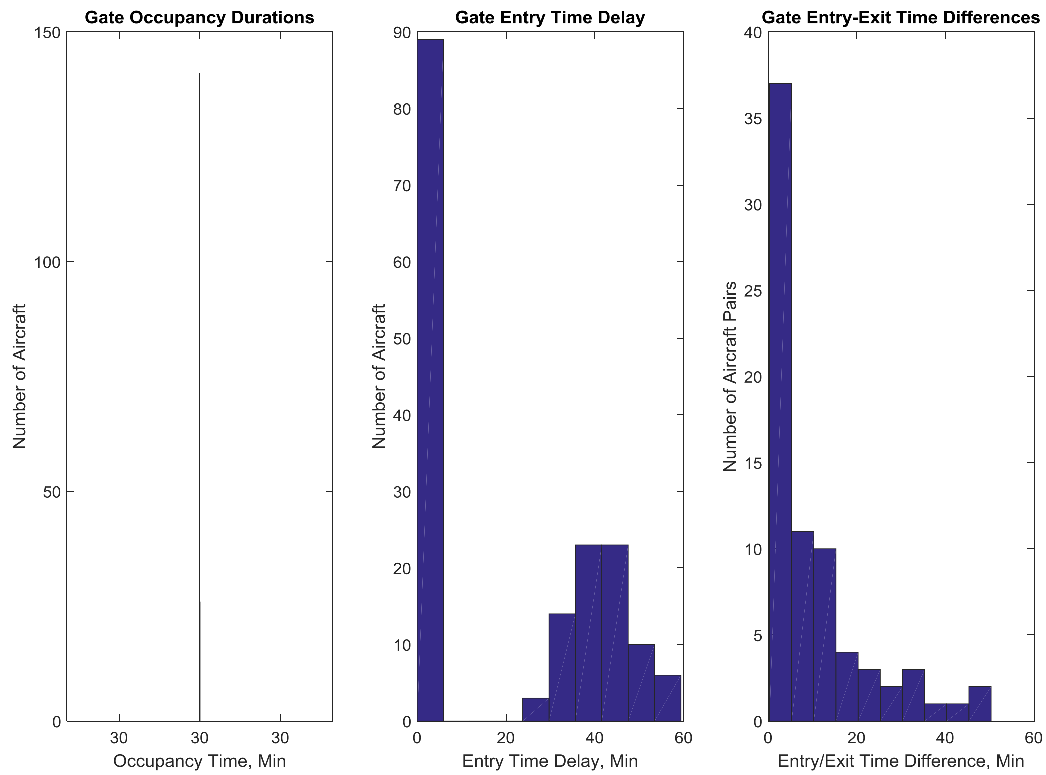


Figure 2-27. Queue Occupancy Times, Entry Time Delays, and Entry-Exit Time Differences among Flights Sharing Gates.

The gate occupancy time duration results indicate that all flights satisfy the gate node service rate/occupancy time of 30 minutes. The results also indicate that the difference between the exit time of the previous occupant and the entry time of the next occupant, for the sequence of occupants at each gate, is non-negative, such that there is no overlapping gate occupancy in the simulation.

2.4.4 Departure Restrictions

To verify simulation of the node queue size limits, the entry times of the 89 departures in the *hitl6-training-advisory.list_data* traffic file are retained. This ensures a dense traffic schedule under which departure restrictions may influence the traffic flow. In addition, departure restrictions to two departure fixes are included in the scenario, listed in Table 2.3.

Table 2.3. Modeled Departure Fix Miles-In-Trail (MIT) Restrictions for Verification.

Operation Type	Category	Category Name	MIT	Time Start, Minutes	Time End, Minutes
Departure	First Fix	MERIL6	20	50	150
Departure	First Fix	BUCKL7	15	75	200

The data in the table indicate in-trail spacing restrictions for departures to the MERIL6 and BUCKL7 departure fixes. Departures to MERIL6 must meet or exceed 20 MIT when crossing the fix between the times of 50 to 150 minutes in the simulation. Departures to BUCKL7 must meet or exceed 15 MIT when crossing the fix between the times of 75 to 200 minutes in the simulation.

Figure 2-28 depicts the results of analyzing the in-trail separations of departures taking off to the MERIL6 departure fix during its restriction time period.

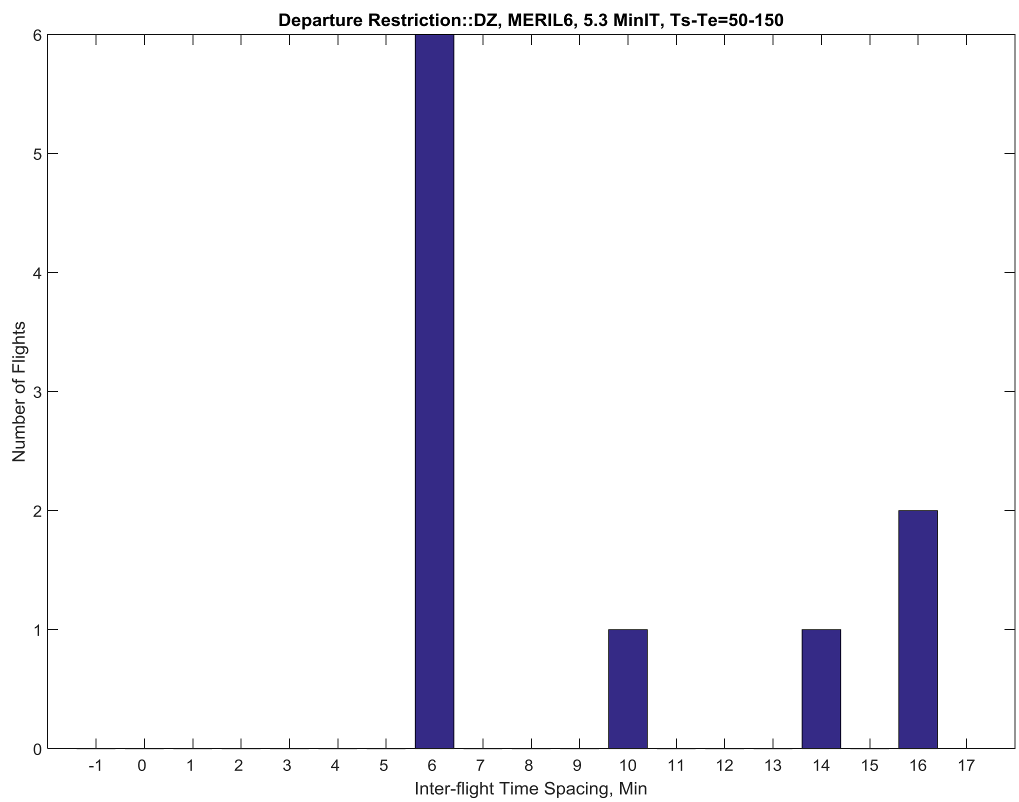


Figure 2-28. Distribution of Time Differences between Successive Departures to the MERIL6 Departure Fix Node during the 50-150 Minutes in the Simulation.

The results indicate the departures to the MERIL6 fix node during 50 to 150 minutes of simulated time meet or exceed the equivalent time spacing of 5.3 minutes at the runway (as per the modeled runway spacing-to-fix spacing ratio and takeoff speed). Time spacing is rounded to the simulation time step size of 1 minute.

Figure 2-29 depicts the results of analyzing the in-trail separations of departures taking off to the BUCKL7 departure fix during its restriction time period:

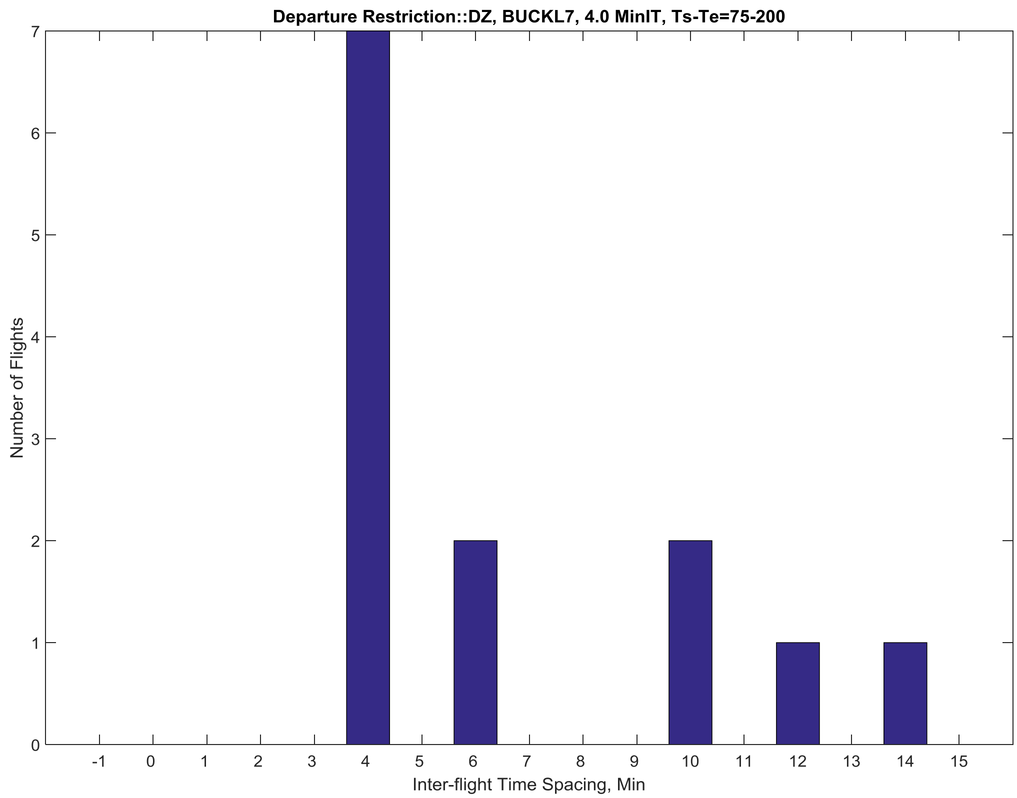


Figure 2-29. Distribution of Time Differences between Successive Departures to the MERIL6 Departure Fix Node during the 50-150 Minutes in the Simulation.

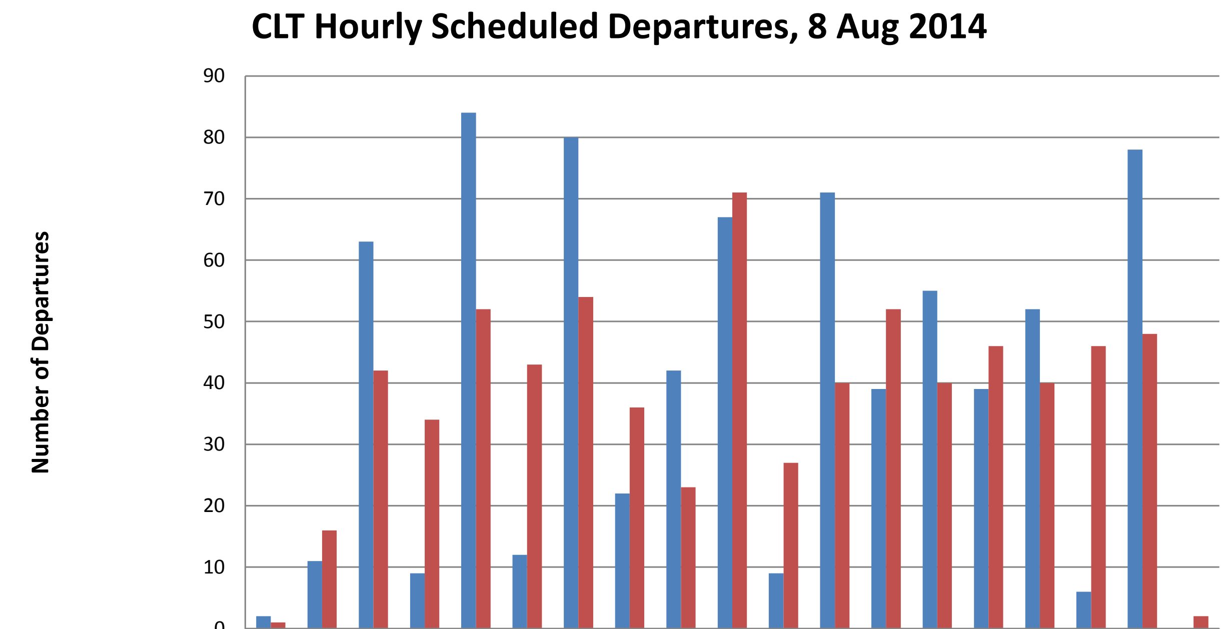
The results indicate the departures to the BUCKL7 departure fix node during the time period of 75 to 200 minutes of simulated time meet or exceed the equivalent time spacing of 4.0 minutes at the runway.

2.4.5 FAA ASPM Comparison

We compare What-if Analysis Tool simulation results of the entire 18-hour traffic scenario to FAA ASPM data on hourly basis to assess the representation of airport operations. To do this, the What-if Analysis Tool is used to simulate the entire 19-hours of arrival and departure traffic captured in the baseline traffic scenario. The baseline traffic scenario is to represent scheduled arrivals and departures for CLT on August 8, 2014, a day of consistent south flow runway configuration and minimal departure restrictions. The What-if Analysis Tool demand analysis throughput and taxi time results are compared to FAA ASPM data on an hourly and aggregate basis. Differences in the hourly scheduled traffic counts contribute to differences in the hourly taxi time and throughput results. However, hourly and aggregate taxi-out times and aggregate throughput results compare reasonably well.

2.4.5.1 Traffic Input

We compare the hourly and aggregate results from our simulation to those of FAA ASPM data for August 8, 2014. Figure 2-30 depicts the number of hourly scheduled departures between what was recorded in the FAA ASPM data (the OAG_DEP field) to the scheduled pushback times of departures in the traffic input file.

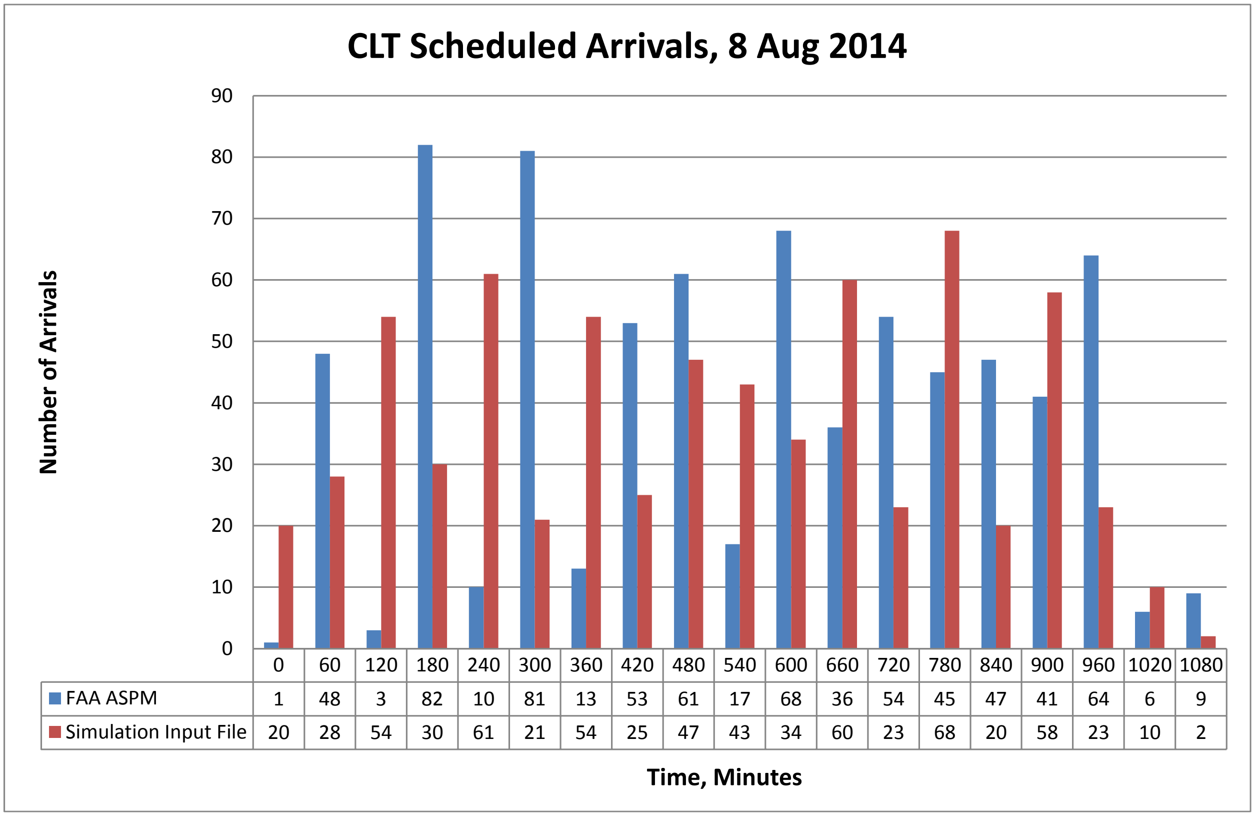


	0	60	120	180	240	300	360	420	480	540	600	660	720	780	840	900	960	1020	1080
FAA ASPM	2	11	63	9	84	12	80	22	42	67	9	71	39	55	39	52	6	78	0
Simulation Input File	1	16	42	34	52	43	54	36	23	71	27	40	52	40	46	40	46	48	2

Figure 2-30. Comparison of CLT Hourly Scheduled Departures for August 8, 2014 from FAA ASPM Data and Baseline Traffic File for What-if Analysis.

The results indicate significant differences between the hourly counts of scheduled departures of the FAA ASPM data and the traffic input file. This is because the scheduled pushback times in the traffic input file are derived from actual operations, thus reflecting actual gate pushback times, and reflect the actions of controllers in delaying aircraft to reduce hourly demand peaks. The total number of departures in FAA ASPM is 741, and in the traffic file is 713.

Figure 2-31 depicts the number of hourly scheduled arrivals between what was recorded in the FAA ASPM data (the OAG_ARR field) to the scheduled arrival fix crossing times of arrivals in the traffic file.



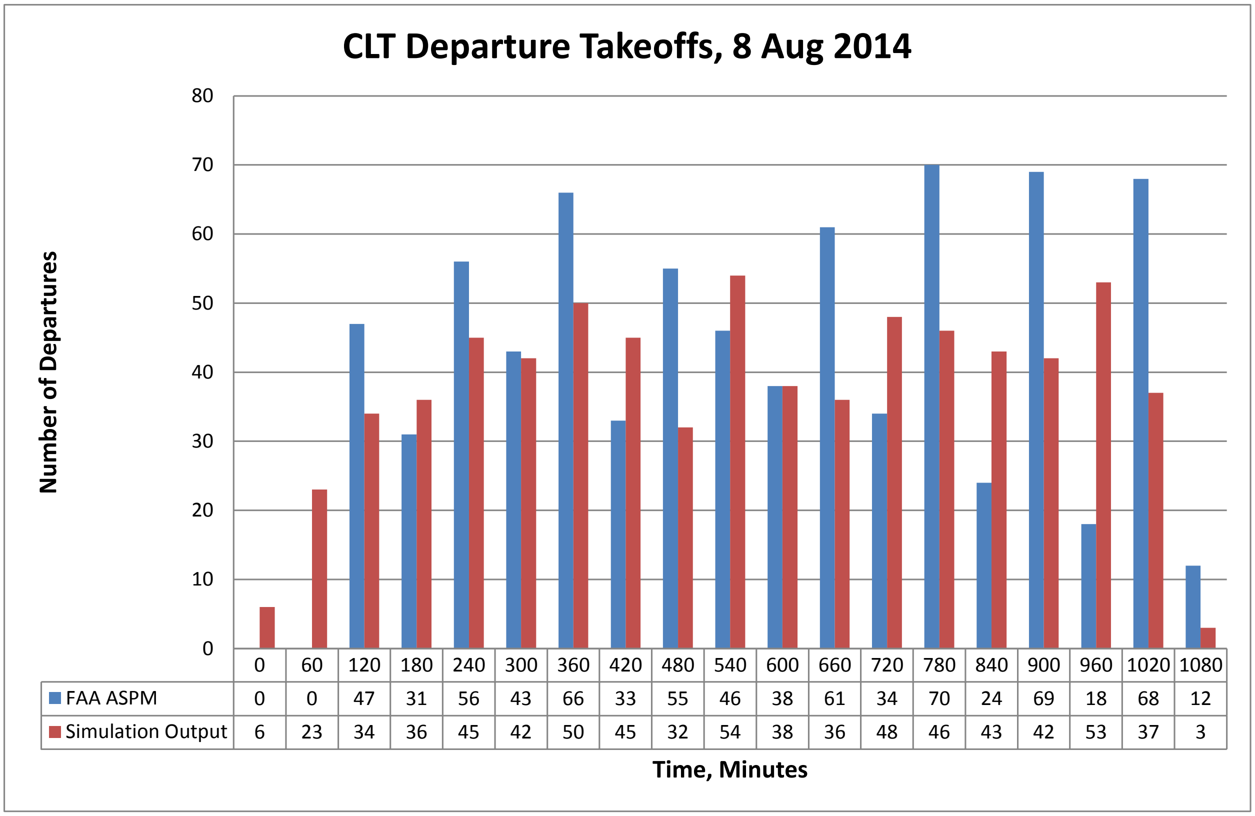
	0	60	120	180	240	300	360	420	480	540	600	660	720	780	840	900	960	1020	1080
FAA ASPM	1	48	3	82	10	81	13	53	61	17	68	36	54	45	47	41	64	6	9
Simulation Input File	20	28	54	30	61	21	54	25	47	43	34	60	23	68	20	58	23	10	2

Figure 2-31. Comparison of CLT Hourly Scheduled Arrivals for August 8, 2014 from FAA ASPM Data and Baseline Traffic File for What-if Analysis.

The figure indicates differences between the number of scheduled arrivals of the FAA ASPM data and the traffic input file. This is also because the scheduled arrival times in the traffic input file are derived from actual operations. The total number of arrivals in the FAA ASPM is 712, and in the traffic file is 679.

2.4.5.2 Traffic Output

Figure 2-32 depicts the number of hourly departure takeoffs recorded in the FAA ASPM data (the FRO_DEP field reporting facility reported departures) and simulated in the What-if Analysis Tool. Total count of departure takeoffs recorded in the ASPM data is 771, and in the simulation is 713.



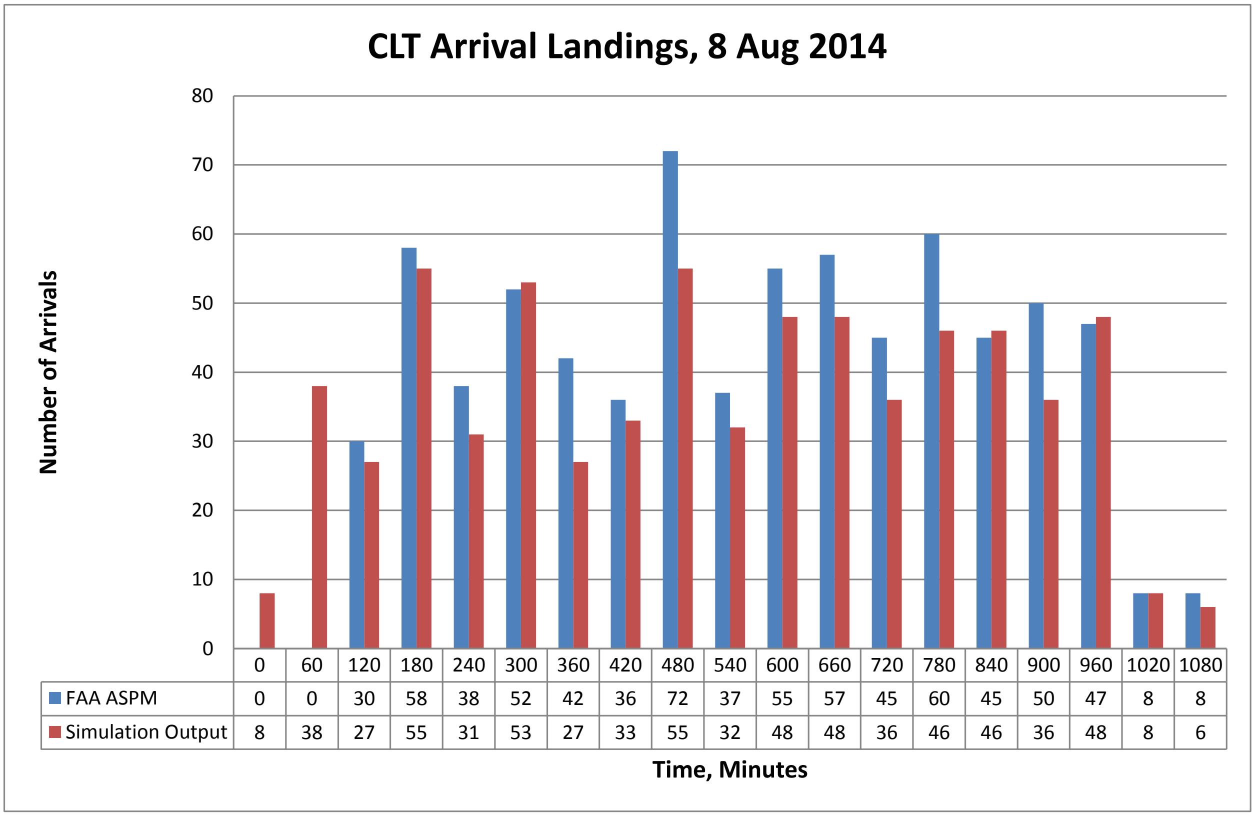
	0	60	120	180	240	300	360	420	480	540	600	660	720	780	840	900	960	1020	1080
FAA ASPM	0	0	47	31	56	43	66	33	55	46	38	61	34	70	24	69	18	68	12
Simulation Output	6	23	34	36	45	42	50	45	32	54	38	36	48	46	43	42	53	37	3

Figure 2-32. Comparison of CLT Hourly Departure Takeoffs for August 8, 2014 from FAA ASPM Data and What-if Analysis Tool Traffic Simulation.

The data in the figure indicate differences between the hourly takeoff counts of FAA ASPM and the what-if analysis tool traffic simulation. The hours of 180, 300, 540 and 600 minutes show the closest agreement. The hours of 120, 240, 360, 660, 780, 900 and 1020 minutes show the FAA ASPM recording a greater number of takeoffs than the simulation. The hours of 420, 720, 840 and 960 minutes show the What-if Analysis Tool simulating a greater number of takeoffs than those recorded in FAA ASPM.

Given the input traffic file is derived from operational data, closer agreement in the hourly takeoff counts might be expected. However, What-if Analysis Tool gate occupancy modeling delays departures by 30-minutes, transit time modeling introduces differences in the demand to the runways, runway modeling simplifies the variability in the instantaneous runway departure rate achieved by airport local controllers, and other factors introduce differences between simulated and actual traffic flow.

Figure 2-33 depicts the number of hourly arrival landings recorded in the FAA ASPM data (the FRO_ARR field reporting facility reported departures) and simulated in the What-if Analysis Tool. Total count of arrival landings recorded in the ASPM data is 713, and in the simulation is 681.

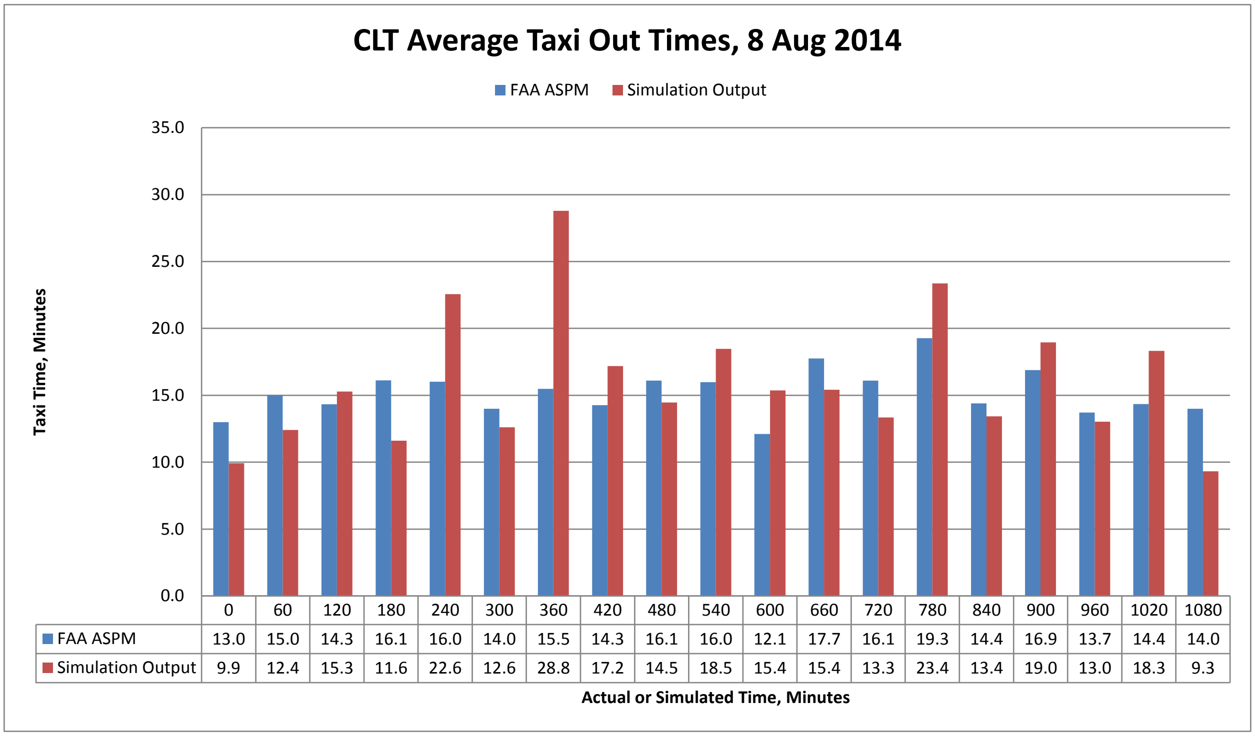


	0	60	120	180	240	300	360	420	480	540	600	660	720	780	840	900	960	1020	1080
FAA ASPM	0	0	30	58	38	52	42	36	72	37	55	57	45	60	45	50	47	8	8
Simulation Output	8	38	27	55	31	53	27	33	55	32	48	48	36	46	46	36	48	8	6

Figure 2-33. Comparison of CLT Hourly Arrival Landings for August 8, 2014 from FAA ASPM Data and What-if Analysis Tool Traffic Simulation.

The results indicate closer agreement in the hourly counts of arrival landings in the FAA ASPM and the What-if Analysis Tool traffic simulation. This indicates the service rates specified for the arrival fixes and arrival runways are reasonable.

Figure 2-34 compares the average hourly taxi-out times recorded in the FAA ASPM data to those computed from the What-if Analysis Tool traffic simulation output data. Hourly average taxi-out times are computed from the FAA ASPM using the T_TAXI_OUT and DEP_CNT fields; for each hour, the sum of the taxi-out times recorded in T_TAXI_OUT are divided by the number of departures recorded in DEP_CNT. Hourly average taxi-out times are computed from the What-if Analysis Tool as follows. Taxi-out time is the difference between the takeoff time and gate pushback time of the flight. The taxi-out times of the departures with takeoff times in each hour are averaged to compute the hourly average takeoff time.



	0	60	120	180	240	300	360	420	480	540	600	660	720	780	840	900	960	1020	1080
FAA ASPM	13.0	15.0	14.3	16.1	16.0	14.0	15.5	14.3	16.1	16.0	12.1	17.7	16.1	19.3	14.4	16.9	13.7	14.4	14.0
Simulation Output	9.9	12.4	15.3	11.6	22.6	12.6	28.8	17.2	14.5	18.5	15.4	15.4	13.3	23.4	13.4	19.0	13.0	18.3	9.3

Figure 2-34. Comparison of CLT Hourly Departure Average Taxi-out Times for August 8, 2014 from FAA ASPM Data and What-if Analysis Tool Traffic Simulation.

The results indicate reasonable agreement between the average hourly taxi out times computed from the FAA ASPM data and from the What-if Analysis Tool. Analysis of the differences between the average hourly taxi times of the traffic simulation data and the FAA ASPM data, ignoring the significant outlier at the hour of 360 minutes, yields an error mean of 0.1 minutes and standard deviation of 3.2 minutes. This indicates the nominal taxi time parameter and the coupling of departure capacity with the demand yield a reasonable taxi model.

Figure 2-35 compares the average hourly taxi-in times recorded in the FAA ASPM data to those computed from the What-if Analysis Tool. Average hourly taxi-in times are computed from the FAA ASPM data using the T_TAXI_IN and ARR_CNT fields, and for the arrival landings in the traffic simulation, the same way as for departures.

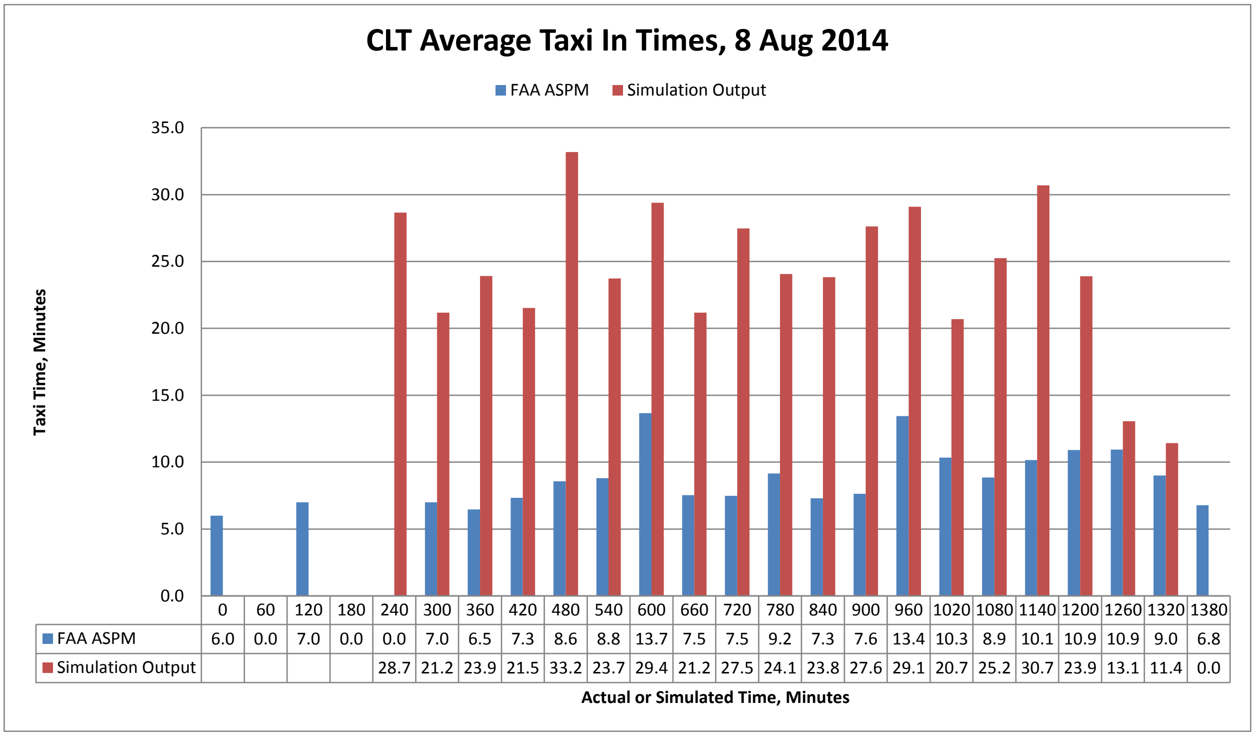


Figure 2-35. Comparison of CLT Hourly Arrival Average Taxi-in Times for August 8, 2014 from FAA ASPM Data and What-if Analysis Tool Traffic Simulation.

The results indicate a significant bias in the average hourly taxi-in times computed from the What-if Analysis Tool compared to the FAA ASPM data. Analysis of the differences between the average hourly taxi times of the traffic simulation data and the FAA ASPM data yields an error mean of 14.4 minutes and standard deviation of 7.7 minutes.

The greatest contributor to this error is likely the gate management model of the What-if Analysis Tool. The gate management model maintains fixed gate assignments for arrivals. If an arrival's gate is occupied, the arrival is delayed until the occupant leaves the gate. The gate nodes were modeled with service rates/occupancy times of 30 minutes. Depending on the relative timing of flights this can introduce significant delay to the taxi-in times. One solution to this is to model groups of gates as a single node, with a queue size limit corresponding to the number of gates in the group. This would model the dynamic assignment of gates to flights as conducted by airlines to avoid excessive taxi in delay due to gate occupancy. Another solution is to model a delay buffer to account for the hard stands in the non-movement area. The hard stands provide the flexibility to the ramp controller to move aircraft off of the gates to make them available for incoming arrivals.

Aggregate throughput and taxi statistics are computed from the FAA ASPM data performance statistics and presented in Table 2.4.

Table 2.4. Comparison of Aggregate Departure Performance Statistics from FAA ASPM Data and the What-if Analysis Tool Traffic Simulation.

Source	Average Departure Throughput, Departures Per Hour	Average Taxi Out Time, Minutes
FAA ASPM, 8 August 2014	45	16.0
What-if Analysis Tool Traffic Simulation	36	15.9

Aggregate throughput and taxi statistics are computed from the FAA ASPM data performance statistics and presented in Table 2.5.

Table 2.5. Comparison of Aggregate Arrival Performance Statistics from FAA ASPM Data and the What-if Analysis Tool Traffic Simulation.

Source	Average Arrival Throughput, Arrivals Per Hour	Average Taxi In Time, Minutes
FAA ASPM, 8 August 2014	44	9.6
What-if Analysis Tool Traffic Simulation	36	23.0

The results indicate the average arrival and departure throughput simulated with the What-if Analysis Tool is less than the average arrival and departure throughput computed from the FAA ASPM data. This is attributable to the traffic file input to the simulation capturing fewer flights than the FAA ASPM data recorded in the same time span. The results also indicate close agreement in the average taxi-out time of departures in the FAA ASPM and the what-if traffic simulation. The average taxi-in time of arrivals simulated in the What-if Analysis Tool is far higher, likely due to the gate occupancy model of the traffic simulation.

2.4.6 DMP Implementation

The departure metering program emulation was verified to meet the overall requirements of delaying departure pushback times to meet a target queue length and reduce taxi-out delay.

Under the traffic and departure fix conditions specified in Section 2.4.4 for verifying the implementation of the departure restrictions, the What-if Analysis Tool DMP emulation was used to schedule the departure traffic, and the What-if Analysis Tool traffic simulation was used to evaluate traffic performance. Figure 2-36 depicts the distribution of departure fix use among the departures in the 4-hour traffic schedule under evaluation.

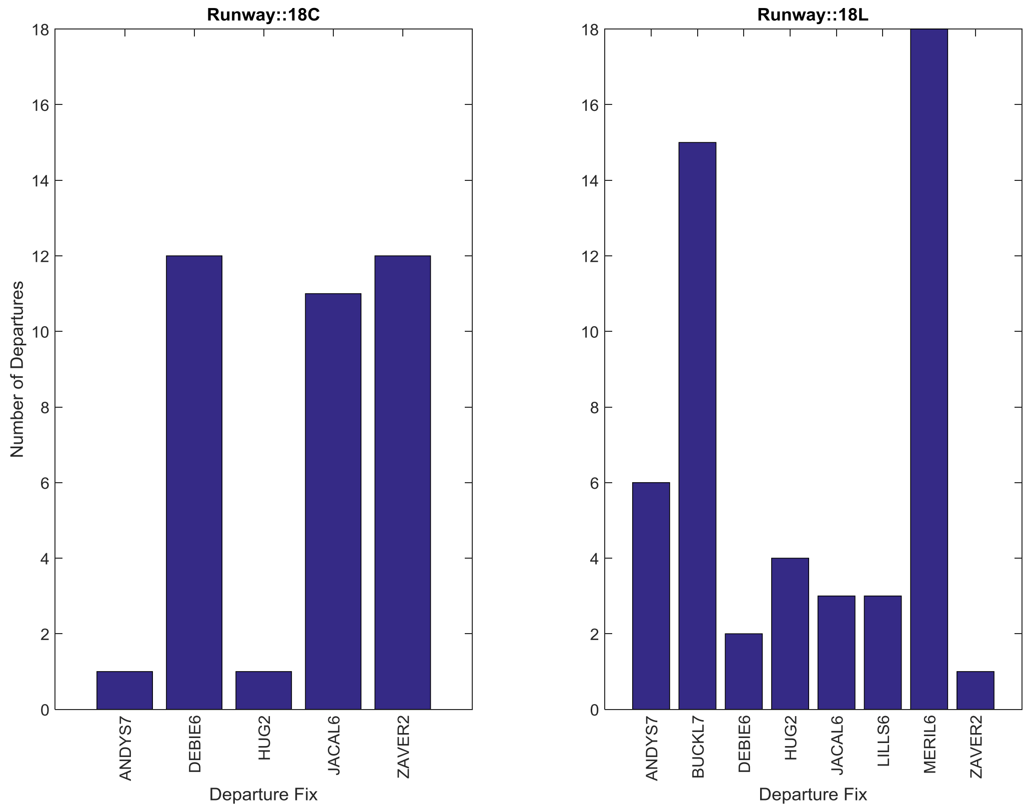


Figure 2-36. Number of Departures from Each Airport Departure Runway to Each Departure Fix Inherent in the Traffic Scenario.

The results indicate that, among the 89 departures in the scenario, 18 transit the MERIL departure fix and 15 transit the BUCKL departure fix. All 33 of the departures to these fixes depart from runway 18L.

Figure 2-36 shows the per-runway time bin takeoff, queue length, taxi-out, and gate delay metrics computed for departures from what-if simulations with the traffic and fix conditions without departure metering.

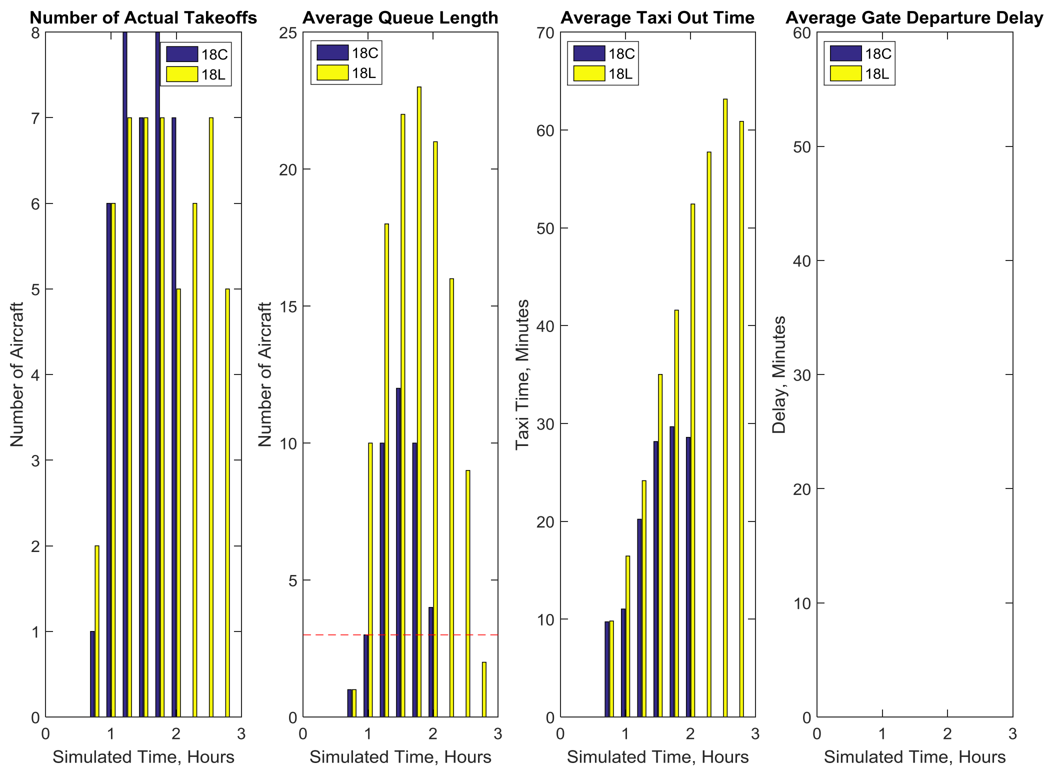


Figure 2-37. Quarter-hour Performance Metrics for Simulated Departures in the *hitl6-training-advisory.list_data* File and Departure Fix Restrictions, without Metering.

The results show the departure queue lengths on runways 18C and 18L exceed the target length of 3 aircraft and that the average quarter-hour taxi-out times of runway 18C departures climb to 30 minutes, while those of 18L departures climb to 65 minutes. The effect of the departure restrictions impacting runway 18L departures is evident in the greater queue lengths and taxi out times of runway 18L departures.

In this scenario, a DMP is implemented for the entire time duration of traffic, metering the departures as needed to satisfy the target queue length of 3 aircraft, runway departure rate of 30 departures per hour, and the specified departure restrictions.

Analysis of the runway takeoff times scheduled by the DMP emulation show that the inter-departure time spacing of same-runway departures meets or exceeds the runway node service time of 2-minutes, and the inter-departure time spacing of same-fix departures meets or exceeds the departure fix in-trail spacing during the time periods of restriction application.

Figure 2-38 shows the per-runway time bin takeoff, queue length, taxi-out, and gate delay metrics computed for departures from what-if analysis with the traffic and fix conditions with the metering of departure gate pushbacks implemented.

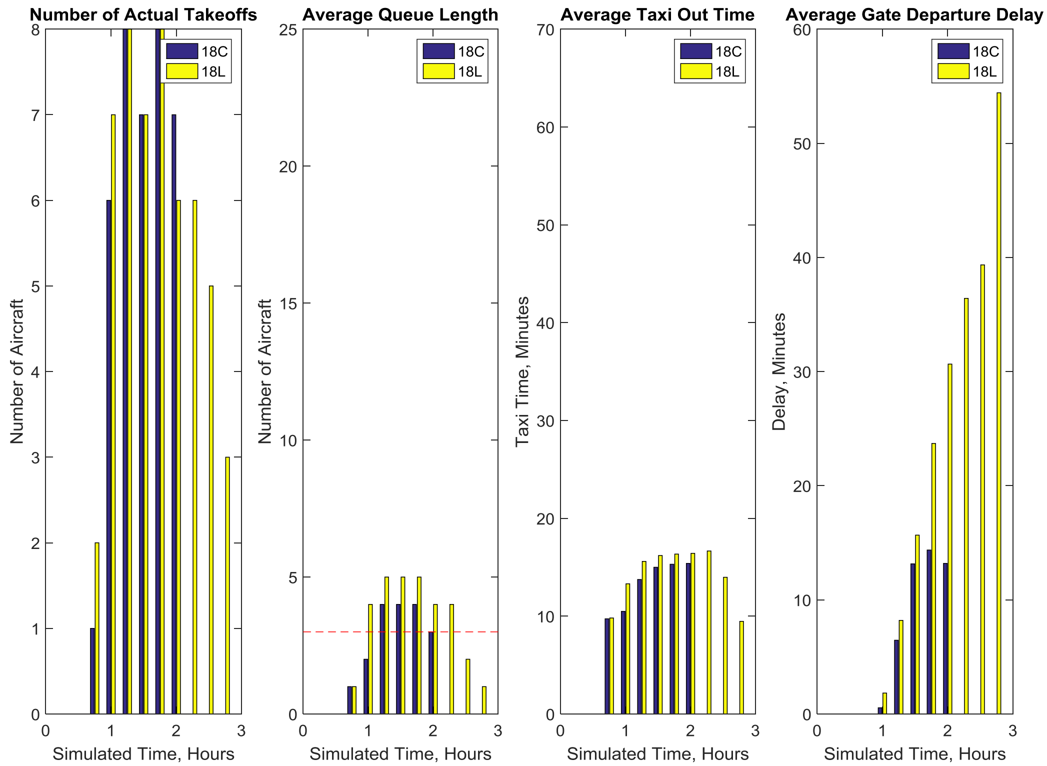


Figure 2-38. Quarter-hour Performance Metrics for Simulated Departures in the *hitl6-training-advisory.list_data* File and Departure Fix Restrictions, with Metering.

The results show the DMP emulation was effective in scheduling the gate pushback times of the departures to meet the queue length and taxi-out requirements. The departure queue lengths on runways 18C and 18L comply with the target length of 3 aircraft within a tolerance of +1 to +2 aircraft, and that the average quarter-hour taxi-out times of runway 18C and 18L departures are sharply reduced to under 20 minutes. The resulting departure gate delays are significantly increased (assuming all the delay is absorbed at the gate).

3 Traffic and Weather Scenarios

This section presents the methodology for selecting and modeling historical traffic and weather scenarios for what-if analysis. This section also presents the methodology for and an example of modeling notional weather scenarios based on subject matter expert consultation, and parametric uncertainty in what-if analysis.

3.1 Historical

The approach to creating traffic and weather scenarios for what-if analysis of CLT from historical data was to identify a day for which there were few traffic flow restrictions on CLT departures, then to identify other days where there were extensive traffic flow restrictions at CLT. The day of few traffic flow restrictions was the basis for modeling airport arrival and departure traffic, on the premise that the operations on that day represented as closely as possible the schedule intention of the aircraft operators at CLT. The days of extensive traffic flow restrictions were the basis for modeling "disturbances" to operations at CLT, thus requiring deviations from the ideal traffic schedule. Airline operations at airports are based on a regular timetable that is usually constant for 6 months, so traffic and weather scenario definitions focused on such an airline schedule for the summer of 2014.

The scenarios were developed from the following sources of information:

- Out/Off/On/In (OOOI) data from a major operator at Charlotte during August 2014 that included other airlines.
- Command Center Traffic Management Initiatives (TMI) from May to December 2014 including:
    - Expected Departure Clearance Time (EDCT)
    - Call for Release (CFR)
    - (MIT with fix location, MIT separation for a destination or ARTCC
- Ramp controller procedures were obtained and used to infer the gate to spot to runway allocation
- ASDI data consisting of lat, long pairs and altitude and speed; could provide the inbound fix or TRACON entry fix position and time (actual time over)
- Weather information was obtained from Weather Underground as a historical source in order to identify scenario days

The CLT traffic was examined for several years of recordings to gather days that would provide real scenarios for the baseline and some disturbed non-nominal days for scenarios that would be more challenging for departure metering. Days with consistent South flow were selected.

The traffic for scenario days was captured for the period 05:00 AM to 23:59 PM local time. This provided sufficient flights for the What-if Analysis Tool to produce stable metrics on aircraft and gate allocations.

The gating plan and the IN and OUT times (plus turnaround time) input data were used to link actual aircraft (i.e., tail number) so that there was an association between an arrival flight and the corresponding departure flight. This meant that the earliest departure for an aircraft tail could not be before it had arrived and turned around at a gate.

The ramp taxi patterns from the gates to the ramp exit 'spots' were inferred from Ramp Operator Standard Operating Procedures that provide rules based on the gate and the allocated departure runway.

3.1.1 Baseline Traffic

The baseline scenario for CLT was selected to be based on a day with a minimal number of TMIs and a normal traffic load. The selected day also had good weather and a consistent south flow runway configuration throughout the day. After searching through various records August 8th 2014 was selected as the baseline traffic day.

The histogram in Figure 3-1 depicts the number of aircraft pushing back from the gate in any 15-minute period throughout the day. This histogram is based on scheduled out time (scheduled pushback time), which is part of the scenario data.

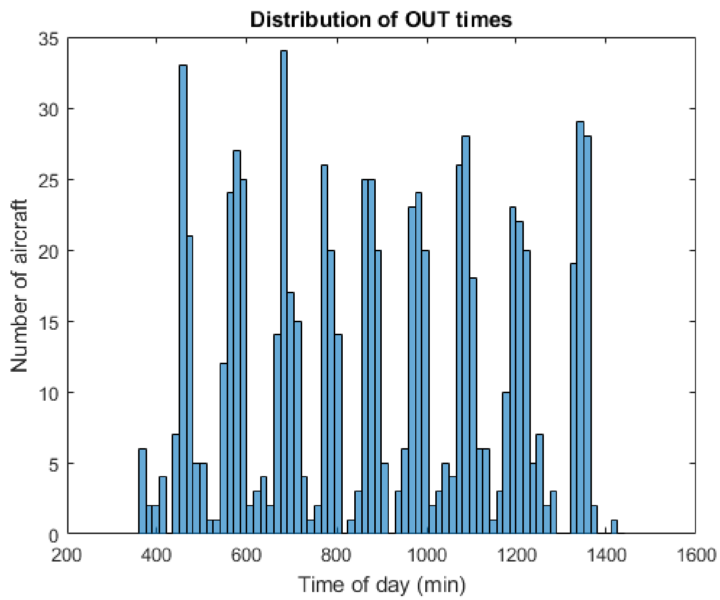


Figure 3-1. Distribution of Push-back Times in 15 minute Intervals, August 8, 2014.

The traffic profile depicted in the figure indicates that departures are scheduled into 9 departure banks, which occur at roughly 100 minute intervals early in the day, and less often as the day goes on.

3.1.2 Disturbed Scenario Days

South flow days with comparable traffic and weather characteristics to the baseline day were then assessed for restrictions. The reason for selecting similar days to the baseline day was to insure that the movement schedule and gating plan for the airport would be the same as the baseline day. Days were selected that had restrictions mainly MIT through the exit fixes of the TRACON. The days that were chosen were August 11th, 15th and 18th. These restricted days all had TMIs with MIT on the TRACON exit fixes and were also consistently corresponding to CLT in the south flow runway configuration so could use the baseline day as a comparator.

Table 3.1 summarizes the days selected and compares the characteristics weather and traffic features.

Table 3.1. Historical Days Selected for Traffic and Weather Scenarios.

Condition	2014 Date	Weather at Charlotte-Douglas Airport (CLT)	# of EDCT	# of CFR	# of MIT	Comment
Baseline (Good Weather)	August 8th (Friday)	Clear, visibility 8 nautical miles	4	25	42	Usual restrictions for CLT
Disruptive Events (Bad Weather)	August 11 (Monday)	Rainfall at CLT; reduced visibility to 1 nautical mile	1	25	45	Storm moving through CLT
	August 15 (Friday)	Visual conditions and operations, no flow reversals	7	42	76	Weather near Atlanta with restrictions imposed by Atlanta Air Route Traffic Control Center (ARTCC)
	August 18 (Monday)	Consistent south flowing traffic	2	41	180	Heavy volume restrictions due to extreme rainfall event in Tennessee and northeast Alabama

More detailed information on the selected days was provided in the “Traffic and Weather Scenarios” report deliverable for this project [AT2016-3].

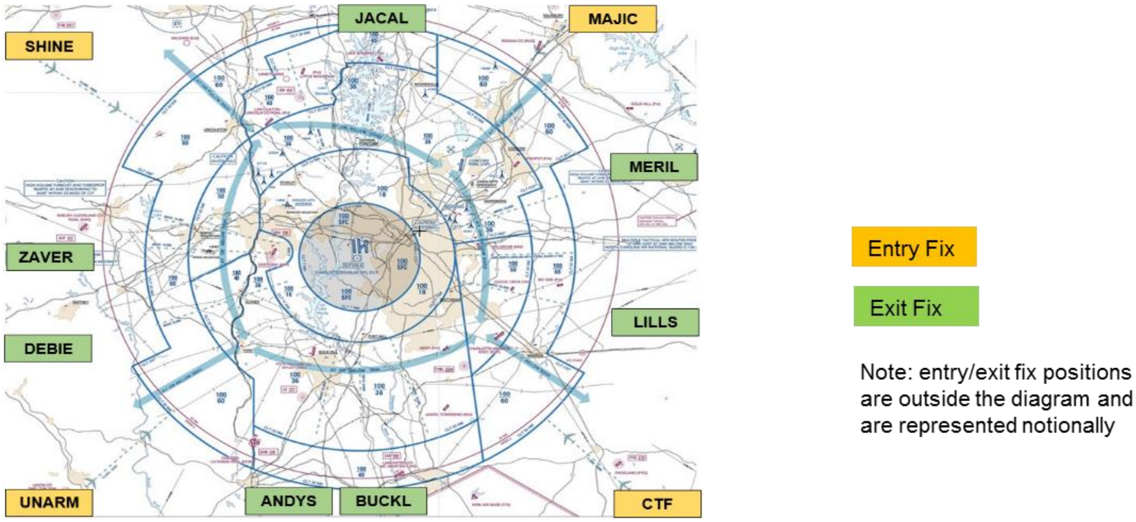


Figure 3-2. CLT Operational Constraints: Arrival Flows and TRACON Fixes.

Disturbance scenarios emphasized the MIT restrictions on CLT departures. The ZDC, ZTL, and ZNY ARTCCs routinely impose MIT restrictions on CLT departures. A fairly typical day might have 40 – 45 flights with MIT restrictions, typically starting at noon local time.

We processed data for the 3 days shown in Table 2.1. August 11 had about 45 MIT through the MERIL departure fix, August 15 had 76 MIT restrictions through the ANDYS (3 flights) and BUCKL (73 flights) departure fixes, and August 18 had a very high number of restricted flights through the MERIL and ZAVER departure fixes.

Airlines commonly plan flights using a few different routes. For August 11 (45 restricted flights), we found by processing the OOOI data that none of the scheduled restricted flights to the affected destinations actually passed through the restricted fix. The restricted flights probably exited the CLT airspace via another fix, most likely to the west.

Likewise on August 15th, 2014, with 76 restricted flights scheduled through the BUCKL and ANDYS fixes, none of the 3 restricted flights actually passed through ANDYS, and 59 of the 73 restricted flights scheduled for BUCKL actually flew through BUCKL with a 15 or 20 MIT restriction.

August 18 was a day with an extreme rainfall event in Tennessee and Alabama. The rainfall caused an increase in the volume of traffic to the north of those states, and that traffic volume increase resulted in restrictions on departures to the north of CLT. MERIL was the most restricted departure fix: about 156 restricted flights actually flew through the MERIL waypoint. Of the 33 restricted flights scheduled through ZAVER, only 2 actually flew the departure.

Table 3.2 summarizes the Charlotte departure traffic restrictions for August 18th 2014. It is an example for one of the scenario days of the restrictions applied in the What-if Analysis Tool; the other bad weather scenario days were modeled similarly.

Table 3.2. Model of Miles-In-Trail Departure Restrictions For August 18, 2014 Weather Scenario.

Operation Type	Category	Category Name	MIT	Time Start, Minutes	Time End, Minutes
Departure	Fix	MERIL	10	554	559
Departure	Fix	MERIL	15	570	732
Departure	Fix	MERIL	15	780	970
Departure	Fix	MERIL	20	970	1005
Departure	Fix	MERIL	25	1005	1090
Departure	Fix	MERIL	25	1139	1261
Departure	Fix	ZAVER	10	475	505
Departure	Fix	ZAVER	15	1100	1185

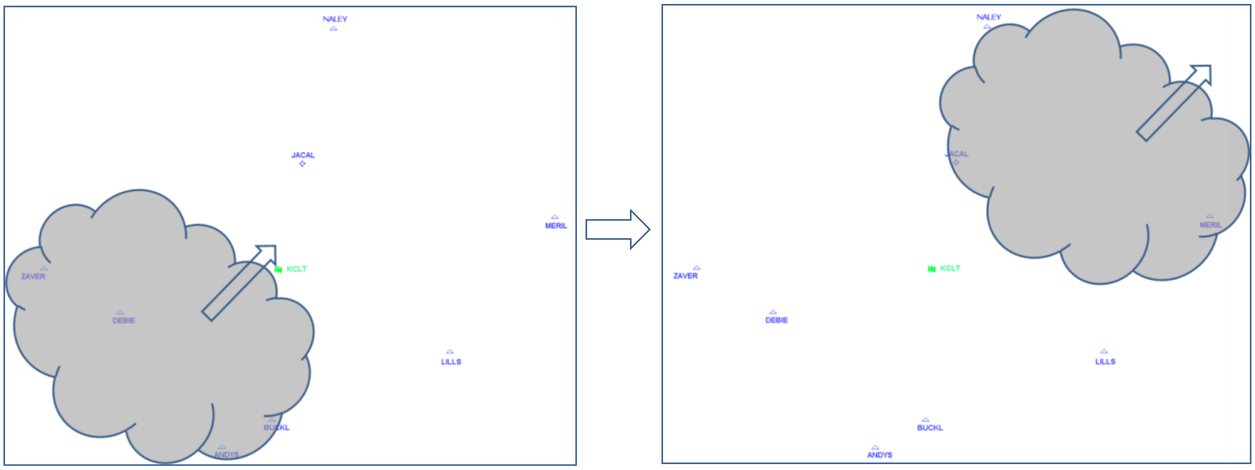
For departures flights and the August 18th day scenario, it lists the restriction times allocated to flights crossing either the MERIL or the ZAVER fix. The table indicates how the MIT value increased throughout the day as controllers contended with congestion from re-routed flights.

3.2 Notional Local Weather Scenario

As an alternative to deriving scenario parameters from historical data, scenarios for what-if analysis may also be modeled based on subject matter consultation and engineering estimation.

One example models the scenario of a weather front local to CLT moving from west to east across the airport, as presented in Section 6.1.1. The weather front first impacts the westerly departure fixes, then impacts the easterly departure fixes. Based on consultation with subject matter experts, this was determined to be a realistic and frequently occurring condition at CLT in summer afternoons. Figure 3-3 depicts this notional scenario.

Air traffic control might respond to such an event by imposing restrictions on the affected fixes (as increased in-trail spacing or closure), or by imposing a ground stop on departures for runways supplying flights to the affected fixes. In lieu of historical data as the basis for modeling the departure restrictions under this scenario, consultation with subject matter experts could support estimating the departure restrictions possible under this scenario. Modeling approaches to each scenario are presented below.



60 – 120 minutes 120 – 180 minutes

Figure 3-3. Notional Scenario of Local Weather Front Moving from West to East across CLT.

A notional approach to modeling of the departure restrictions which might by synthesized by ARTCC controllers to address this weather event and its impact on local operations is presented in Table 3.3.

Table 3.3. Candidate Model of Departure Fix Restrictions to Address Weather Impacting CLT.

Operation Type	Category	Category Name	MIT	Time Start, Minutes	Time End, Minutes
Departure	Fix	ZAVER	20	60	120
Departure	Fix	DEBIE	20	60	120
Departure	Fix	ANDYS	20	60	120
Departure	Fix	BUCKL	20	60	120
Departure	Fix	JACAL	20	120	180
Departure	Fix	LILLS	20	120	180
Departure	Fix	MERIL	20	120	180
Departure	Fix	NALEY	20	120	180

The data in the table present the following modeled restrictions:

- 20 MIT for the westerly fixes ZAVER, DEBIE, ANDYS and BUCKL, starting at 60 minutes and ending at 120 minutes into the forecast time period;
- 20 MIT for the easterly fixes JACAL, LILLS, MERIL and NALEY, starting at 120 minutes and ending at 180 minutes into the forecast time period.

Applying these departure fix restrictions to the baseline traffic scenario would be a way to evaluate the impact of a weather front moving across the airport.

Table 3.4 presents an initial approach to modeling of the runway rates which might by synthesized by ARTCC controllers to address this weather event and its impact on local operations.

Table 3.4. Candidate Model of Runway Rates to Address Weather Impacting CLT.

Operation Type	Category	Category Name	Departures Per Hour	Time Start, Minutes	Time End, Minutes
Departure	Runway	18L	6	60	120
Departure	Runway	18L	6	120	180

Applying these runway rates to the baseline traffic scenario would be a way to evaluate the impact of a weather front moving across the airport.

These restrictions models are a first step towards modeling such an event. The models may be elaborated on to make the scenario increasingly realistic, such as modeling overlap in the time periods under which the east and west departure fixes are affected, extending the time periods during which the fixes are affected, closing the fixes for some time period, or other actions the air traffic control might take. Further consultation with ARTCC, TRACON and airport tower controllers would help refine the modeling of this scenario, as well as help identify additional scenarios of importance.

3.3 Parametric Uncertainty

A consideration in what-if analysis is the uncertainty in forecast conditions that can determine the need to implement a departure metering program or the timing and duration of a departure metering program. Such uncertainties are mentioned in Section 6.1. Sources of uncertainty include:

- The start time, duration and in-trail spacing of miles-in-trail restrictions;
- The timing and implied departure rates of Traffic Flow Management Ground Delay Programs (GDPs) or Airspace Flow Programs (AFPs); and,
- Schedule response of aircraft operators to forecast flow restrictions, including flight rerouting and flight cancellations.

Examples of uncertainty values that could be used in what-if analysis include:

- For the departure restrictions, the in-trail spacing may vary +/- 5 nautical miles from forecast conditions and the duration may be extended to + 60 minutes from forecast conditions.
- For traffic demand, the hourly traffic levels may be reduced by 10 percent from forecast conditions due to aircraft operator cancellation of flights, or traffic demand to a particular fix may be shifted by 25 percent to a different fix.
- For the departure management program, the start time could be extended by +60 minutes from initial time to allow aircraft operators to depart certain flights before the DMP is implemented.

What-if analysis can be conducted for the range of uncertainties to determine their impact on the need and design of the departure metering program. For given forecast traffic and weather conditions, studies may be performed to assess demand/capacity imbalance sensitivity to the uncertainty in traffic demand and airport and airspace capacity parameters, and to assess the sensitivity of the effectiveness of the departure management program to its parameters. Uncertainties in the forecast conditions may be estimated from subject matter expertise and analysis of operations.

4 What-if Analysis Demonstration

The approach to the what-if analysis demonstrations based on historical operations is to model an idealized traffic schedule, then to introduce modeled disturbances which require deviation from that idealized schedule. The idealized traffic schedule represents, as closely as possible, the schedule intent of the aircraft operators for arrivals to and departures from the subject airport. The disturbances represent traffic flow restrictions which require aircraft to be delayed from their idealized schedules in order to accommodate the flow restrictions. This approach of using the What-if Analysis Tool to evaluate the idealized traffic schedule in conjunction with the severe weather restrictions approximates the conditions the Departure Reservoir Coordinator (DRC) would be evaluating when deciding to implement a DMP.

For the demonstration, the baseline traffic schedule represents CLT traffic for 8 August 2014, when CLT operated continuously in a South Flow runway configuration and experienced minimal disturbance to the intended traffic flow of the airlines due to local or distant weather or other events. The disturbance scenario represents the occurrence of extreme rainfall in Tennessee and northeast Alabama on August 18, 2014 resulting in 180 miles-in-trail restrictions being applied to flights transiting via particular departure fixes at the boundary of the CLT TRACON with the en route airspace.

The following subsections demonstrate use of the What-if Analysis Tool to evaluate CLT airport traffic without and with departure metering for the first weather scenario.

4.1 Traffic Schedule

The traffic scenario models CLT traffic occurring throughout the entire 24-hours of August 8, 2014. The 24-hour traffic demand set captures 19-hours of continuous CLT traffic which starts at approximately 4:58 a.m. and ends at approximately 23:47 p.m. local Charlotte time.

For the What-if Analysis Tool demonstration, a 4-hour time period was extracted from the longer-duration traffic and weather scenarios. This is consistent with the 2- to 4-hour forecast time period for traffic prediction that the What-if Analysis Tool is expected to be used for. Figure 4-1 depicts the entire schedule of departure pushbacks captured in the baseline traffic demand set; the time period isolated for the evaluations is outlined in a red box.

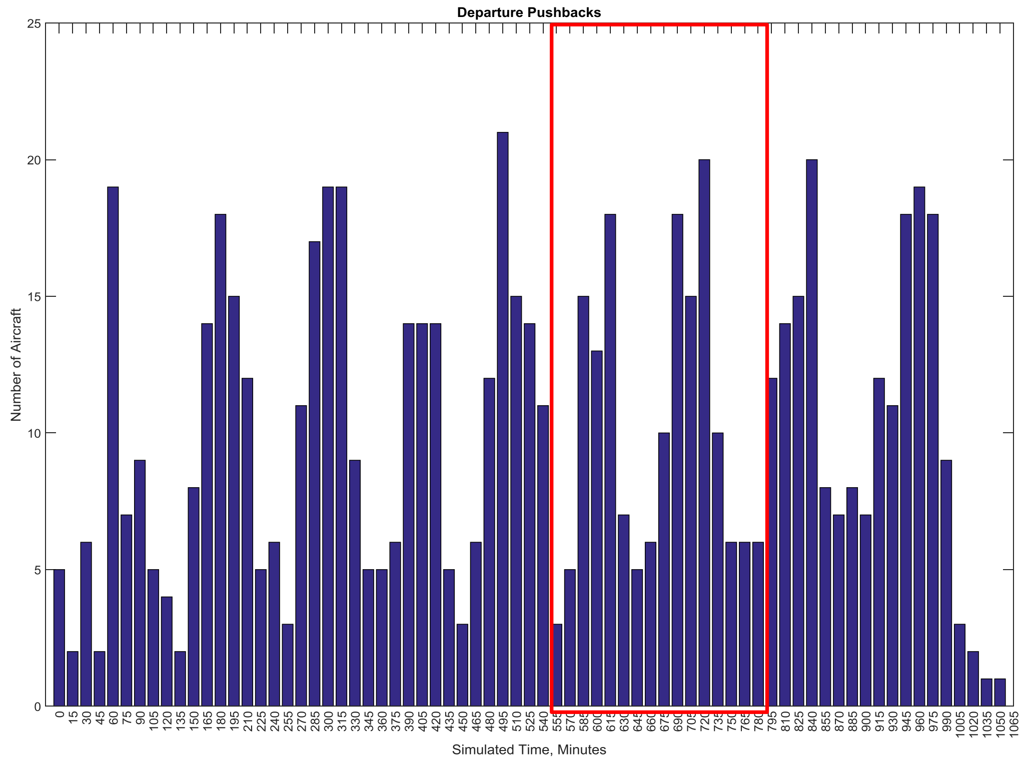


Figure 4-1. Quarter-hour Period Counts of Scheduled Departure Pushbacks in the Entire Baseline Traffic Schedule and the 4-hour Subset of Departures Captured for Demonstration.

The time period captured for the demonstration occurs during the afternoon hours of 2:08 p.m. to 5:58 p.m. local CLT time. The figure indicates the selected traffic period initiates during a lull period (although is preceded by a significant peak), and captures two banks in the departure demand. Capturing the two banks permits assessing the impact of DMPs under varying traffic demand conditions.

4.2 Weather Model

The weather scenario models traffic flow restrictions impacting CLT departures occurring throughout the entire 24-hours of August 18, 2014. The weather scenario models the MIT restrictions on departures on that day. Modeling parameters include the particular departure fixes, the miles-in-trail spacing for departures to that fix, and the start and end times for the restriction to be applied. The models were developed through analysis of historical departure restrictions data furnished by NASA.

For the demonstration, the restrictions occurring during the selected 4-hour time period of traffic were captured from the departure restrictions file. Table 4.1 presents the subset of traffic flow restrictions modeled for this demonstration.

Table 4.1. Departure Restrictions Modeled for Disturbance Scenario 1 Demonstration.

Operation Type	Fix	Miles In Trail	Start Time, Minutes	End Time, Minutes
Departures	MERIL	10	4	9
Departures	MERIL	15	20	182

Figure 4-2 depicts the distribution of departure fix use among the departures in the 4-hour traffic schedule under evaluation.

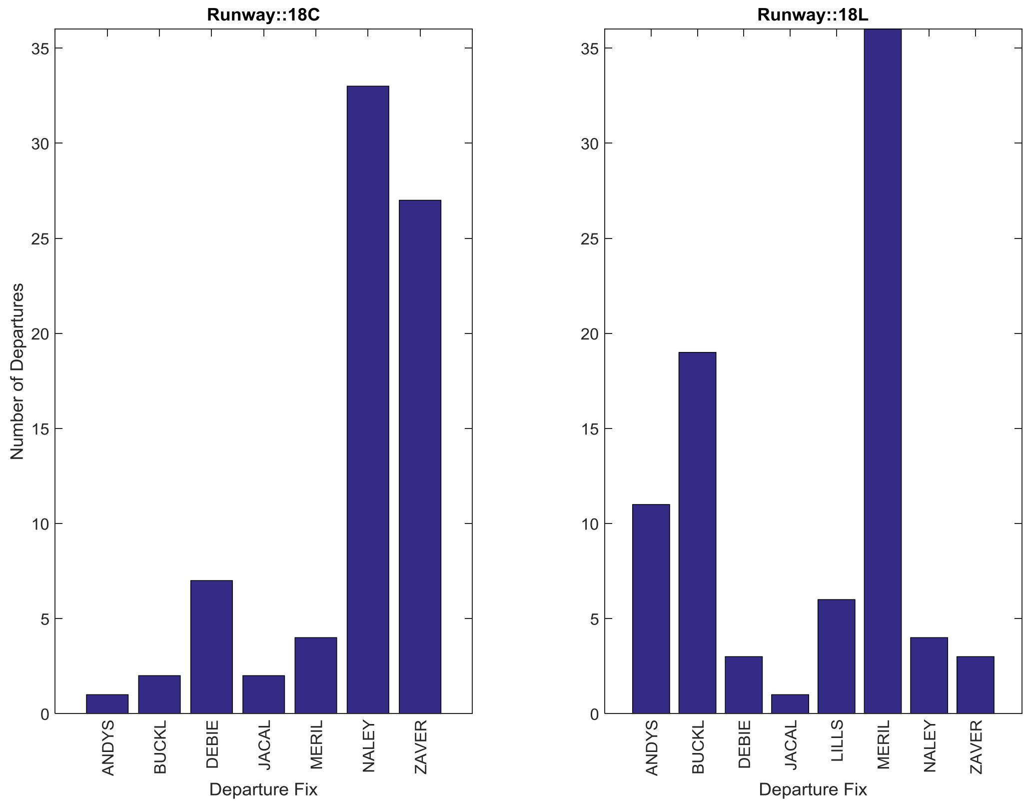


Figure 4-2. Number of Departures from Each Airport Departure Runway to Each Departure Fix Inherent in the Traffic Scenario.

The results indicate that, among the 159 departures in the scenario, 40 of them transit the MERIL departure fix. Thus, the MERIL departure restrictions could have a significant impact on airport departure performance. Of the departures transiting the MERIL departure fix, 36 depart from runway 18L and the other 4 depart from runway 18C. The MERIL departure restrictions would likely have a greater impact on the performance of runway 18L departures

4.3 Airport Demand Analysis

As per the what-if analysis process, airport demand analysis simulates airport traffic under the planned operating conditions (traffic and, in this case, weather), and identifies occurrences of excessive demand/capacity imbalance.

Figure 4-3 depicts the quarter-hour time period counts of airline scheduled departure pushbacks for each departure runway, 18C and 18L, inherent in the traffic schedule under analysis. In addition, the quarter-hour departure rate of 7.5 aircraft per quarter hour, corresponding to the capacity of 30 aircraft per hour per runway modeled for each runway node, is superimposed on the plot.

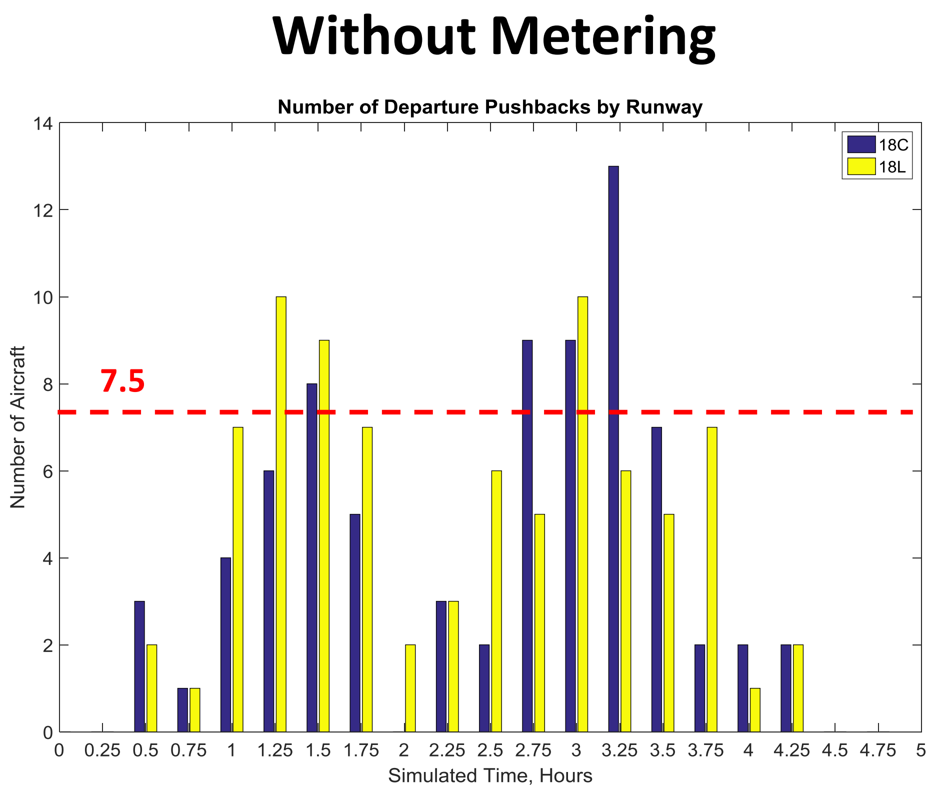


Figure 4-3. Quarter-hour Counts of Airline-Scheduled Departure Pushbacks for Each Departure Runway for CLT Traffic Scenario with No Metering.

The figure indicates that the number of scheduled pushbacks for each departure runway exceeds the capacity of the runway in hours 1.25, 1.50, 2.75, 3.00 and 3.25. This signals that a demand-capacity imbalance is inherent in the operating conditions under evaluation.

Figure 4-4 depicts the quarter-hour time period counts of airline scheduled arrival landings to each arrival runway, 18C, 18R and 23, inherent in the traffic schedule under analysis.

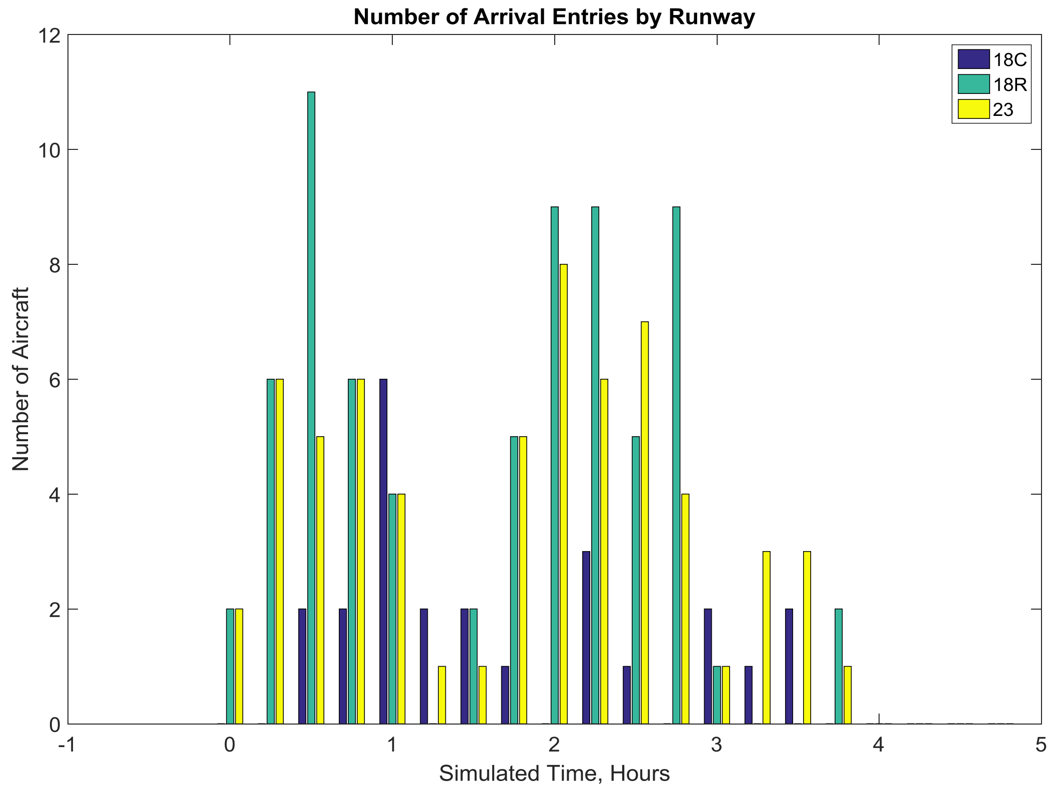


Figure 4-4. Quarter-hour Counts of Airline-scheduled Landings for Each Arrival Runway for CLT Traffic Scenario.

The figure indicates that runway 18C is shared between arrivals and departures during the time period under evaluation. Sharing of departure runways with arrivals can complicate departure metering unless accounted for via capacity allocation or explicit scheduling.

Figure 4-5 depicts the performance of airport departures with no metering (thus pushing back at their airline-scheduled gate pushback times) obtained from the what-if airport demand analysis.

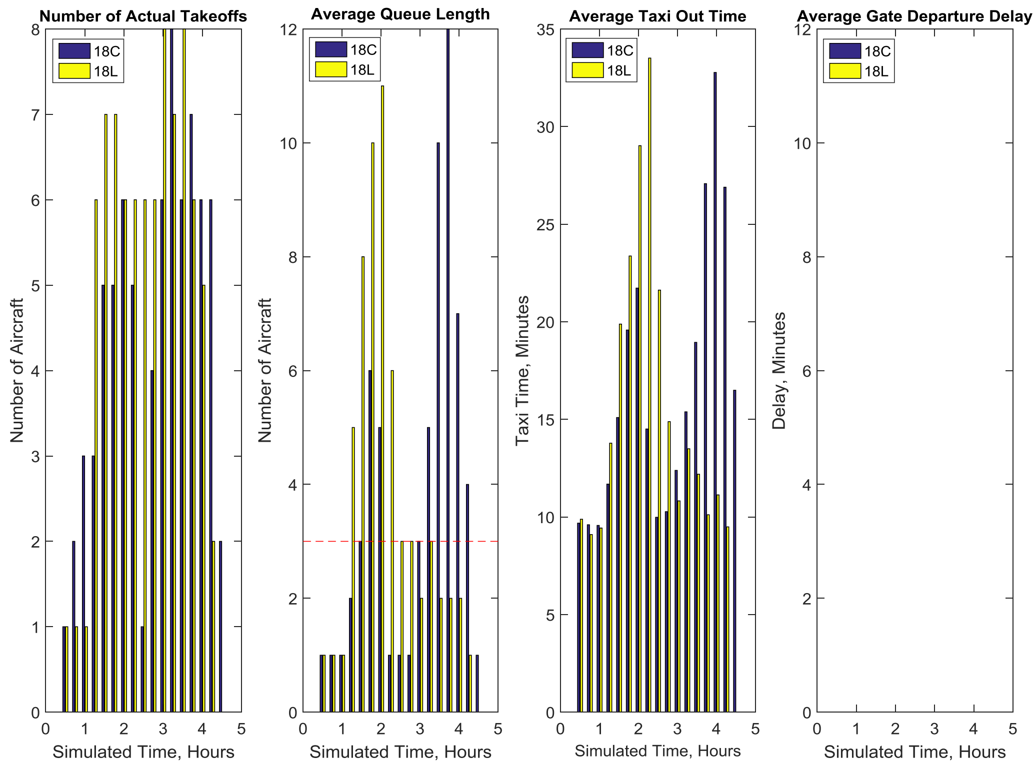


Figure 4-5. Departure Performance Results for CLT Weather Scenario with No Metering.

The results indicate that the two departure banks each correspond to demand-capacity imbalances within the operating conditions under evaluation. During the simulated time period, the throughput of the departure runways reaches their peaks at 7-8 aircraft per quarter-hour during the banks. The average quarter-hour queue length of each runway exceeds its target queue length of 3 departures; the runway 18L queue reaches 11 aircraft in the first bank, then the runway 18C queue reaches 12 aircraft in the second bank. The quarter-hour average taxi-out times of departures from each runway peaks at approximately 34 minutes during each bank. Because aircraft push back at their airline-scheduled gate pushback times, there is zero gate departure delay.

Figure 4-6 depicts the performance of airport arrivals with no departure metering as obtained from the what-if airport demand analysis.

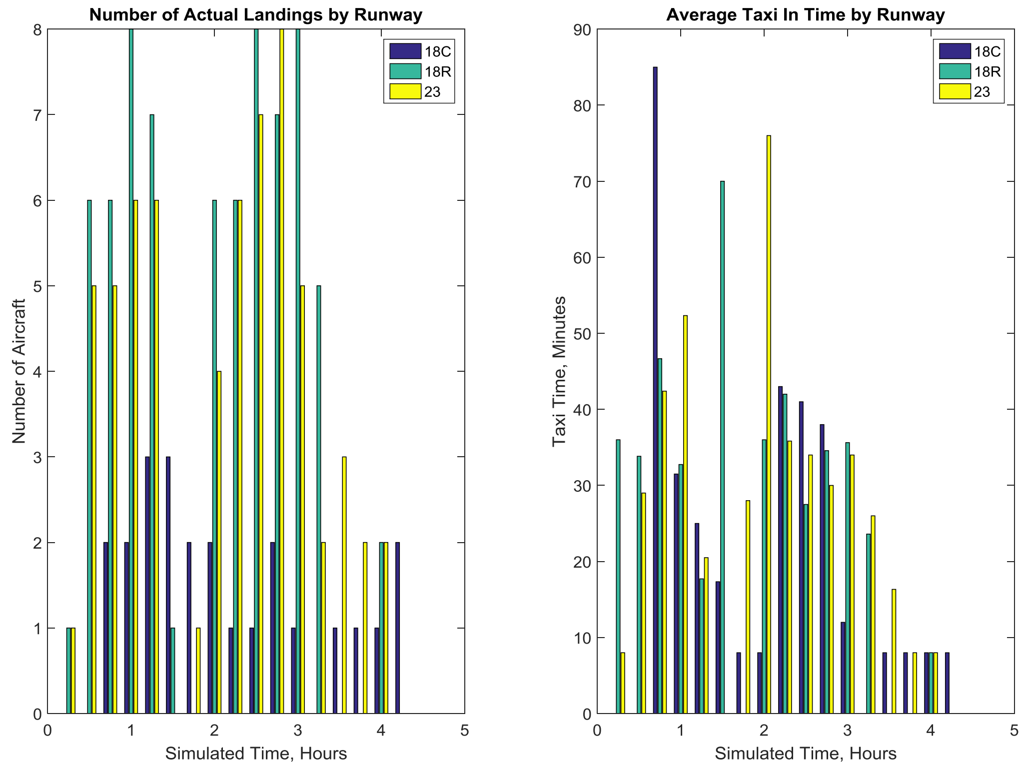


Figure 4-6. Arrival Performance Results for CLT Weather Scenario with No Metering.

The results indicate that, during the operating conditions under evaluation, the throughput of the arrival runways 18R and 23 reach their peaks at 7-8 aircraft per quarter-hour, and 1-3 aircraft per quarter-hour are landing to mixed-use runway 18C. The quarter-hour average taxi-in times vary from fewer than 10 minutes, where arrivals are not delayed entry into their assigned gates, to up to 30-40 minutes—even approximately 80 minutes—where arrivals are delayed to an available time period at their gate.

The taxi-in times are clearly unrealistic. However, they are a result of two key simulation components: the traffic schedule input to the simulation, and the gate utilization modeling of the What-if Analysis Tool. The gate assignment and flight timing inherent in the input traffic schedule can promote conditions for gate contention causing such excessive taxi-in delay. The current what-if analysis gate utilization modeling rigidly adheres to the gate assignments of flights, gives precedence of gate use to departures at their scheduled times, and models 30-minutes for each phase of the turnaround process; these also contribute to excessive taxi-in delay. Modeling refinements for both traffic schedule creation and gate utilization would produce more realistic taxi-in times.

Notwithstanding the magnitude of the simulated taxi-in times, comparing the differences between the simulated taxi-in times without metering of departures and with metering of departures is useful for assessing the impact of proposed departure metering programs on arrivals.

4.4 Departure Management Program Emulation

To address the departure demand-capacity imbalance occurring under the operating conditions under evaluation, a departure management program is explored. Candidate start and stop times for the DMP are identified by the What-if Analysis Tool from the queue length data obtained in the airport demand analysis. As per this data, the departure metering program is prescribed to begin at 79 minutes into the future, when the queue of runway 18L exceeds its target queue length of 3 departures, and stop at 289 minutes into the future, when the queue of runway 18L drops below its target queue length. The DMP emulation schedules gate pushback times of departures to comply as closely as possible with the runway departure rates, departure restrictions and gate occupancy times over the period of evaluation.

Figure 4-7 depicts the quarter-hour counts of departure pushbacks for each departure runway, 18C and 18L, with departures pushing back at the gate pushback times scheduled by the DMP emulation, assuming gate holding to meet their TMATs. Superimposed on the plot is the quarter-hour departure rate of 7.5 aircraft per quarter hour, corresponding to the capacity of 30 aircraft per hour per runway modeled for each runway node.

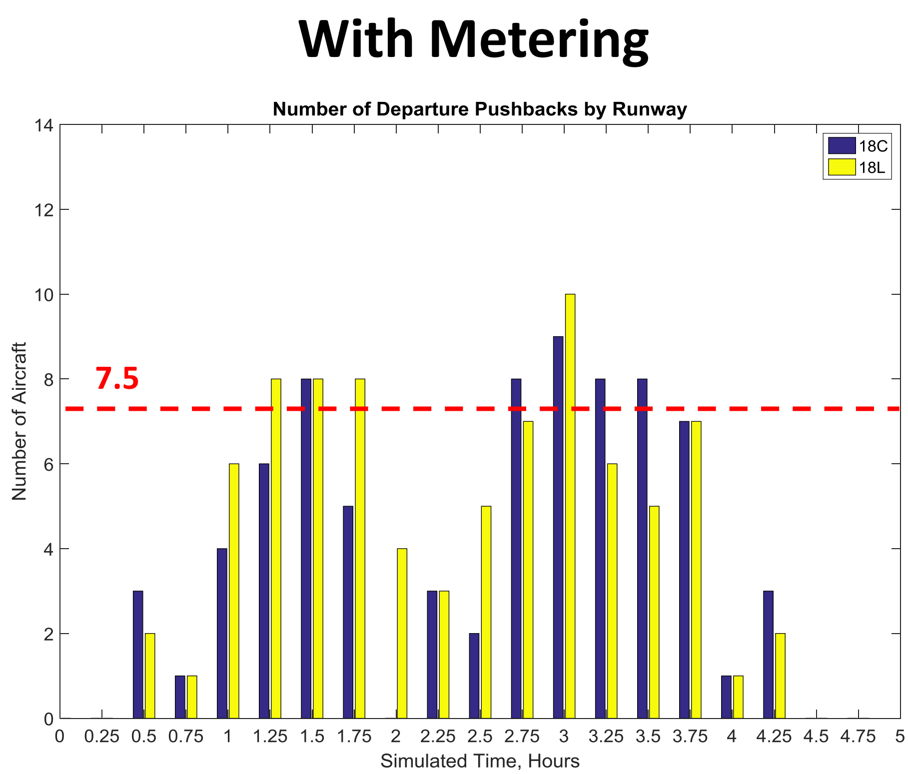


Figure 4-7. Departure Metering Program-Scheduled Departure Pushbacks for Each Departure Runway at CLT.

The figure indicates that the number of scheduled pushbacks for each departure runway is in closer compliance with its capacity.

Figure 4-8 depicts the performance of airport departures under the proposed DMP as obtained from the What-if Analysis Tool.

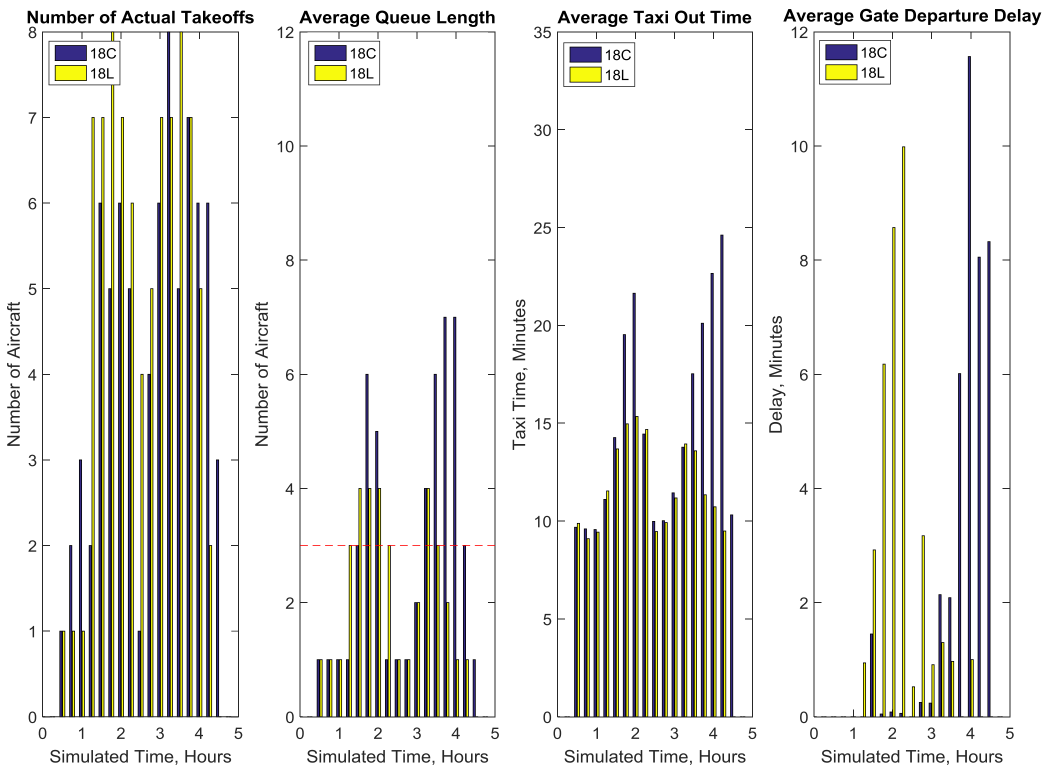


Figure 4-8. Departure Performance Results for CLT Weather Scenario with Departure Metering.

The results indicate that, during the simulated time period, the throughput of the departure runways reaches their peaks at 7-8 aircraft per quarter-hour. The average quarter-hour queue length of each runway is greatly reduced; the runway 18L queue is limited to 4 aircraft, and the runway 18C queue reaches 7 aircraft. The quarter-hour average taxi out times for departures from runway 18C peaks at peak at approximately 25 minutes, and for runway 18L departures peaks at 15 minutes. Because aircraft push back at their DMP-scheduled gate pushback times to meet their TMATs, thereby shifting taxi-out delay to gate holding, quarter-hour gate departure delay now peaks at 10 minutes for 18L departures and almost 12 minutes for 18C departures.

Figure 4-9 depicts the performance of airport arrivals under the DMP as obtained from the What-if Analysis Tool.

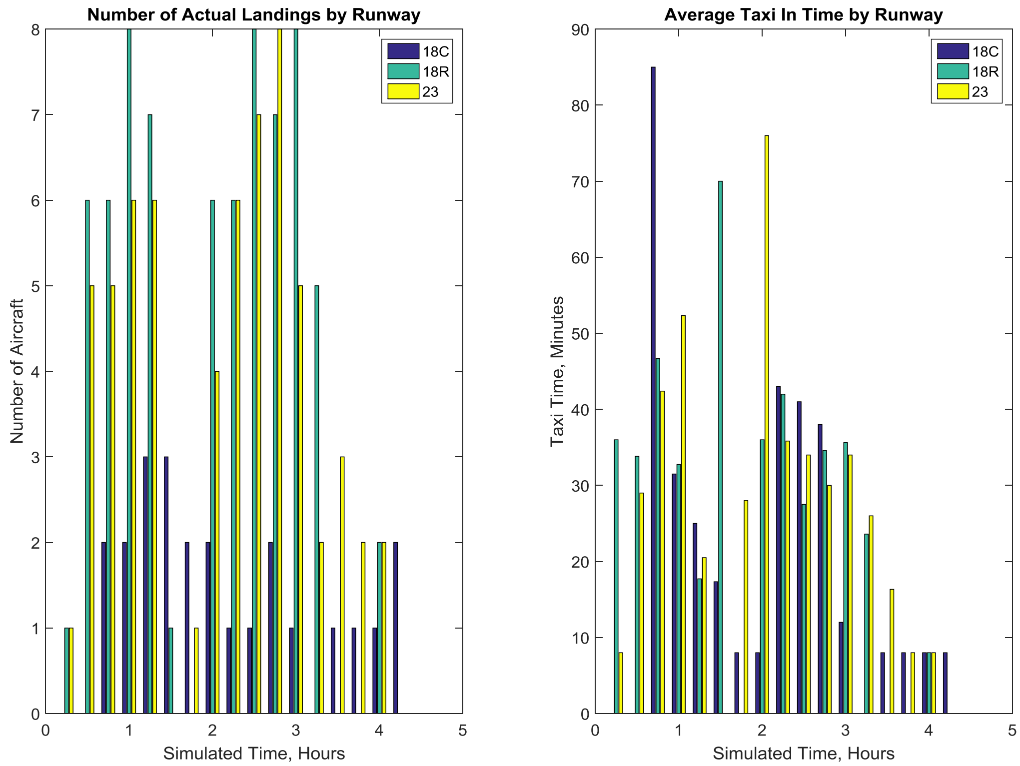
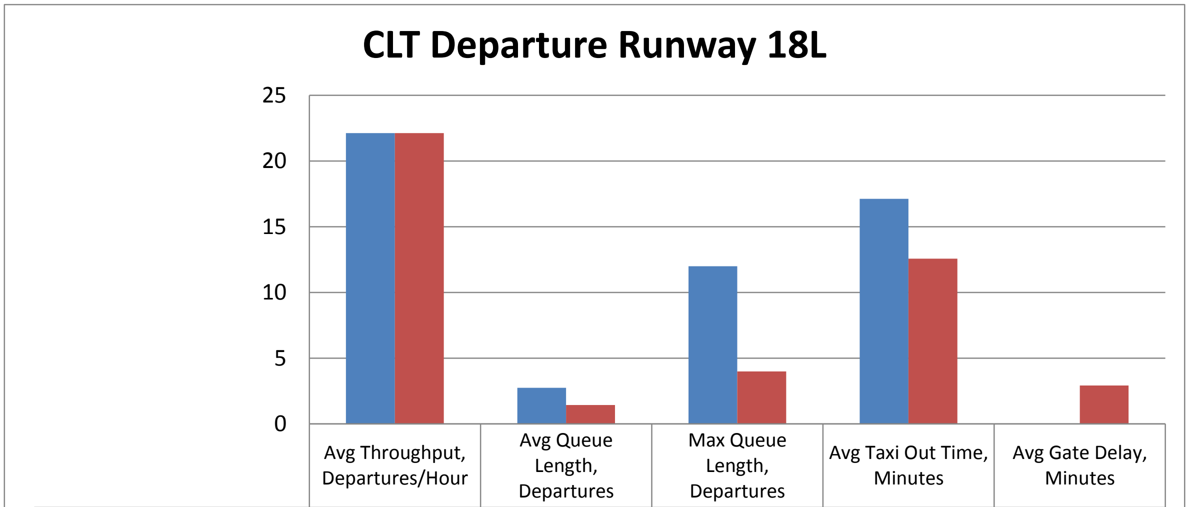


Figure 4-9. Arrival Performance Results for CLT Weather Scenario without Departure Metering.

The results indicate that, during the simulated time period, the throughput of the arrival runways 18R and 23 reach their peaks at 7-8 aircraft per quarter-hour, and 1-3 aircraft per quarter-hour are landing to mixed-use runway 18C. The average taxi-in times have increased in many quarter-hour periods due to the increased occupancy times of departures at their gates under the DMP using gate holding to meet the TMATs.

4.5 Performance Impact Assessment

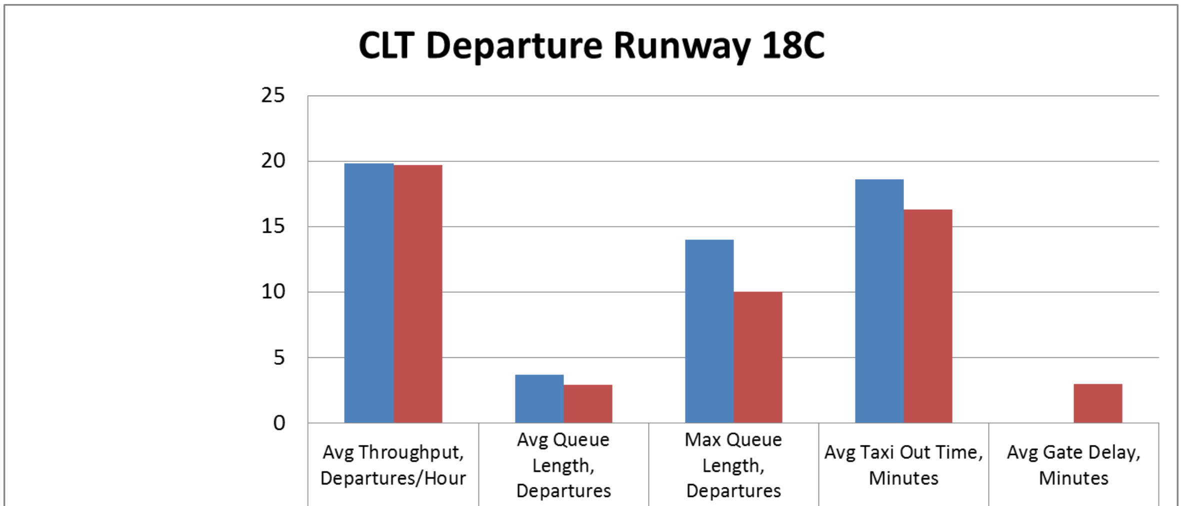
Figure 4-10 compares the aggregate performance metrics for simulated departures from runway 18L without and with departure metering.



	Avg Throughput, Departures/Hour	Avg Queue Length, Departures	Max Queue Length, Departures	Avg Taxi Out Time, Minutes	Avg Gate Delay, Minutes
Without Departure Metering	22	3	12	17.1	0
With Departure Metering	22	1	4	12.6	2.9

Figure 4-10. Aggregate Performance of Simulated Departures from CLT Runway 18L without and with Departure Metering.

Figure 4-11 compares the aggregate performance metrics for simulated departures from runway 18C without and with departure metering.



	Avg Throughput, Departures/Hour	Avg Queue Length, Departures	Max Queue Length, Departures	Avg Taxi Out Time, Minutes	Avg Gate Delay, Minutes
Without Departure Metering	20	4	14	18.6	0
With Departure Metering	20	3	10	16.3	3.0

Figure 4-11. Aggregate Performance of Simulated Departures from CLT Runway 18L without and with Departure Metering.

The results indicate that the DMP may be effective in reducing the runway queue lengths and departure taxi-out times, while maintaining departure throughput, for each runway.

- For runway 18L, throughput is maintained at 22 departures per hour, while average queue length is reduced from 3 to 1 aircraft, maximum queue length is reduced from 12 to 4 aircraft, and average taxi-out time is reduced from 17.1 to 12.6 minutes.
- For runway 18C, throughput is maintained at 20 departures per hour, while average queue length is reduced from 4 to 3 aircraft, maximum queue length is reduced from 14 to 10 aircraft, and average taxi-out time is reduced from 18.6 to 16.3 minutes.
- The cost of average departure pushback delay increase from 0 to 2.9 minutes for runway 18L departures and 0 to 3.0 minutes for runway 18C departures to achieve the queue length and taxi-out benefits is relatively minor.

The results also indicate the DMP has greater impact on runway 18L departures than runway 18C departures. The maximum queue length and average taxi-out times for runway 18L departures reduce by 8 departures and by 4.5 minutes, respectively, whereas for runway 18C departures they reduce by 4 departures and 2.3 minutes, respectively. This more dramatic impact on 18L departures may be attributed to the sharing of departure runway 18C with arrivals, which was not accounted for in the scheduling of the DMP emulation. The more dramatic impact on 18L departures is also quite noteworthy, because 40 of the 159 departures in the scenario were transiting the MERIL departure fix which was subject to departure restrictions; the DMP was effective in addressing those restrictions when planning departure pushbacks.

Departure metering could account for shared use of a departure runway with arrivals either by:

- Reducing the runway departure rate the departure metering program emulation uses from 30 to, say 26 or 22 departures per hour to account for the 1 to 2 arrivals landing to runway 18C in each quarter-hour period, or,
- Explicitly scheduling departures around arrivals to the shared use runway, similar to our current model for the gate node utilization.

Figure 4-12 compares the aggregate performance metrics for simulated arrivals to dedicated arrival runways 18R and 23, and shared-use runway 18C, without and with departure metering.

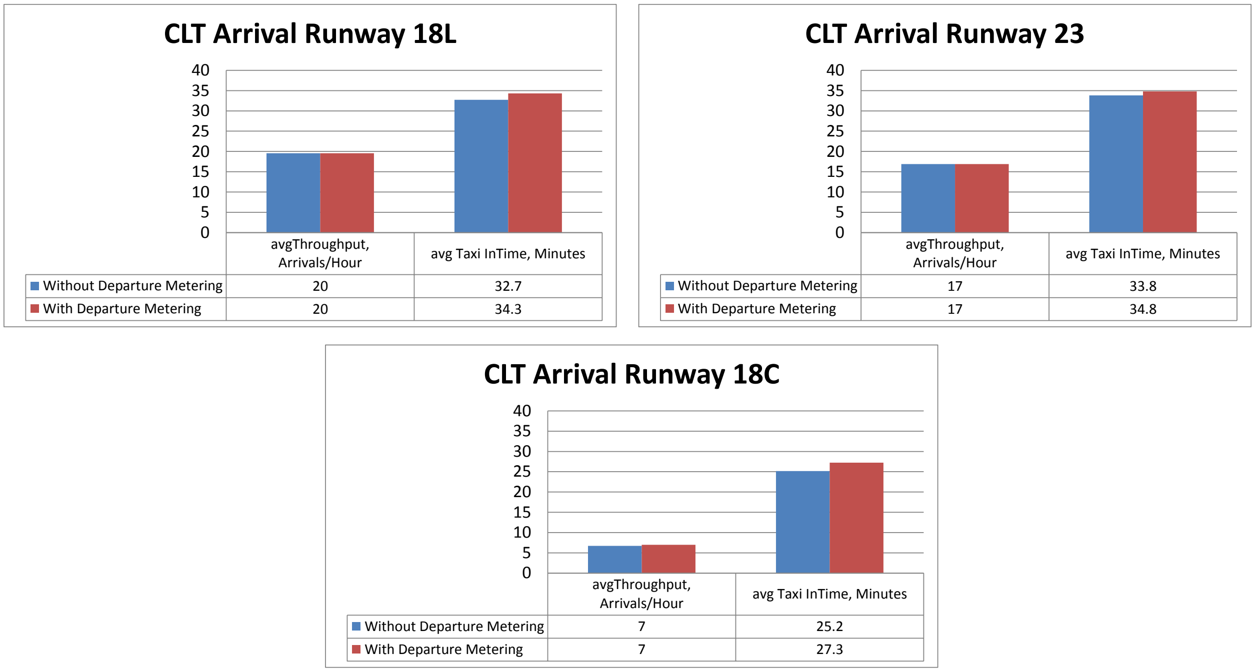


Figure 4-12. Aggregate Performance of Simulated Arrivals to CLT without and with Departure Metering.

The results indicate that arrival throughput is maintained throughout the DMP, and that the average taxi-in time of arrivals does increase due to the use of gate holding to meet DMP-specified TMATs, as modeled in the What-if Analysis Tool. In this scenario, however, the average arrival delay costs of 1.6 minutes for arrivals to runway 18L, 1.0 minutes for arrivals to runway 23, and 2.1 minutes for arrivals to runway 18C are not outstanding.

5 User Interface Guide

A graphical user interface was developed to support the what-if airport demand and DMP emulation analyses. The User Interface (UI) was developed as part of the Option Year 1 enhancements. The main purpose of this UI is to provide the user with a flexible mechanism for selecting scenarios, changing parameters, and iteratively conducting what-if evaluations. A mock-up UI design for a more capable What-if Analysis Tool is illustrated in Section 6.1.

The UI was developed with MATLAB® R2015a in order to be compatible with the enhanced What-if Analysis Tool, which is also implemented in MATLAB. MATLAB provides a good environment for rapid UI prototyping. This section presents the current UI and serves as a guide for running the What-if Analysis Tool.

5.1 Start the What-if Analysis Tool

In MATLAB change navigate to the directory where the What-if Analysis Tool's code is located. From the MATLAB Command Window type the command:

```
>> WhatIf
```

The Airport Demand What-if Analysis window, Figure 5-1, appears.

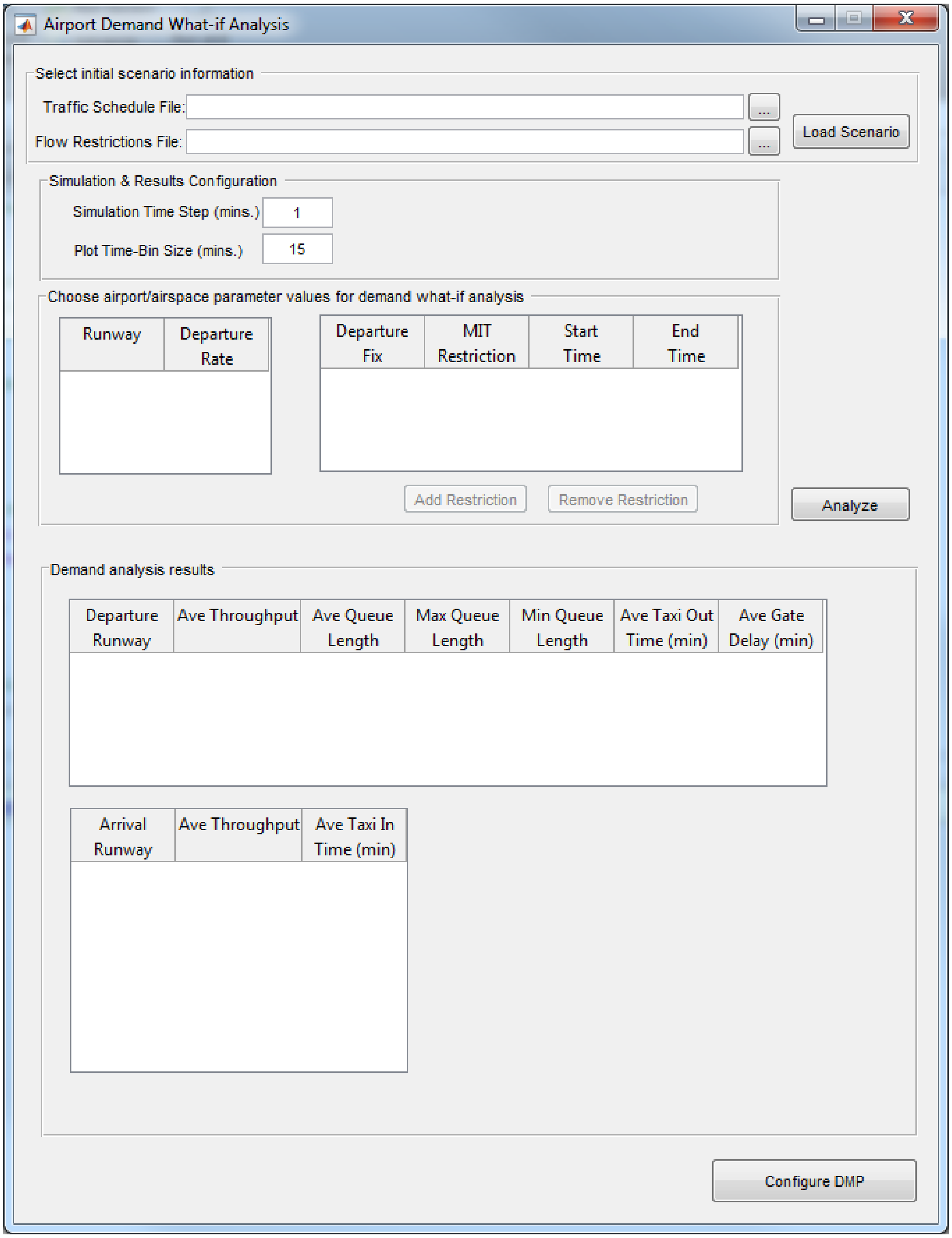


Figure 5-1. What-if Analysis Tool - Airport Demand Window.

5.2 Airport Demand What-if Analysis

This section describes how to use the Airport Demand What-if Analysis Window's features.

5.2.1 Select Scenario

The What-if Analysis Tool uses predefined scenarios. A deployed operational system would use live streamed data. A scenario consists of a traffic schedule and, optionally, traffic flow restrictions. A traffic schedule is a formatted input file compatible with the NASA SOSS airport traffic simulation software [WI2012].

The traffic flow restrictions can be loaded from a file, entered manually, or omitted. The fields in this comma separated variable (CSV) file are:

```
opType  category  categoryName  milesInTrail  timeStart  timeEnd
```

Where:

- `opType` is AZ for arrival or DZ for departure. Note only DZ is currently supported.
- `category` specifies the type of restriction. Note only `first_fix` is currently supported.
- `categoryName` specifies the name of restriction, e.g., the name of the fix.
- `milesInTrail` specifies the miles in trail value for the restriction
- `timeStart` specifies the start time of the restriction. The time is relative to the start of the traffic scenario file.
- `timeEnd` specifies the end time of the restriction. The time is relative to the start of the traffic scenario file.

To load the scenario:

1. Enter or use the browser to select the name of the `Traffic Schedule File` and, optionally, the name of the `Flow Restrictions File`.
2. Select the `Load Scenario` button

The scenario file(s) are then read in. As part of this step the runway rate table and departure fix table (if a Flow Restrictions file is specified) will be populated from the scenario data as shown in Figure 5-2.

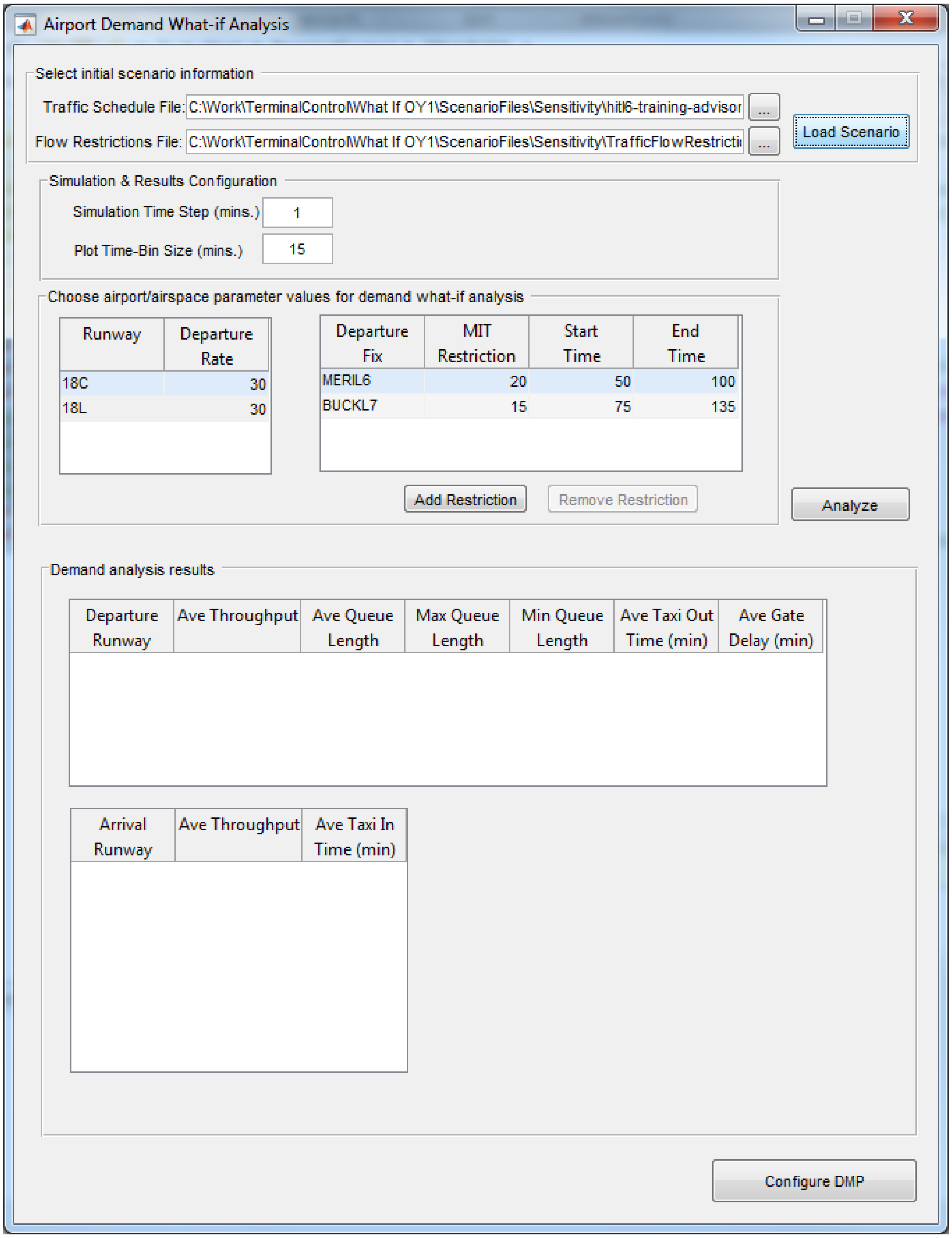


Figure 5-2. What-if Analysis Tool – After Loading a Scenario.

5.2.2 Change the Runway Rate

The hourly operations rate of each airport runway are read in with the traffic schedule file and loaded into the Departure Rate table. Any of the runway operations rate values can be changed by selecting the appropriate cell and entering a new value. Varying runway rates allows different potential conditions impacting individual runways to be evaluated as part of the demand analysis.

5.2.3 Change Flow Restrictions

Traffic flow restrictions can be read in from a file as described in the Section 5.2.1. Alternatively, and in addition to reading the restrictions in from a file, restrictions can be manually created, deleted, and modified. The ability to change flow restrictions allows different potential traffic flow management initiatives to be evaluated as part of the airport demand analysis.

To create a new restriction:

1. Select the `Add Restriction` button.
2. A list of departure fixes is displayed in a new window.
3. Select the departure fix name for the new restriction from the list and select `OK`. A new row is added at the bottom of the table.
4. For the new restriction, select the MIT cell and enter the desired value
5. Repeat for the restriction's start time and end time. Start and end times are specified as minutes from the start of the scenario.

To delete a restriction:

1. Select any cell in the row for that restriction.
2. Select the `Remove Restriction` button.

To modify a restriction:

1. Select the cell to be modified
2. Enter the new value

5.2.4 Configure Simulation and Result Parameters

To support development and evaluation of the What-if Analysis Tool it was desired to have a user-level of control over the underlying simulation and the analysis plots.

The time step for the underlying what-if analysis simulation can be changed from the default step size of 1 minute. The user may want to reduce the simulation step size for finer granularity in the timing of aircraft movements or to capture rapidly-changing traffic flow dynamics.

Likewise the bin-size used for the analysis plots can be changed from the default of 15 minutes.

5.2.5 Analyze Airport Demand

Once the scenario has been loaded and changes made to the airport/airspace parameters, an analysis can be started by selecting the `Analyze` button.

When the analysis is complete the aggregate metrics are displayed, per-runway, in two tables (one for departures, one for arrivals) as illustrated in Figure 5-3.

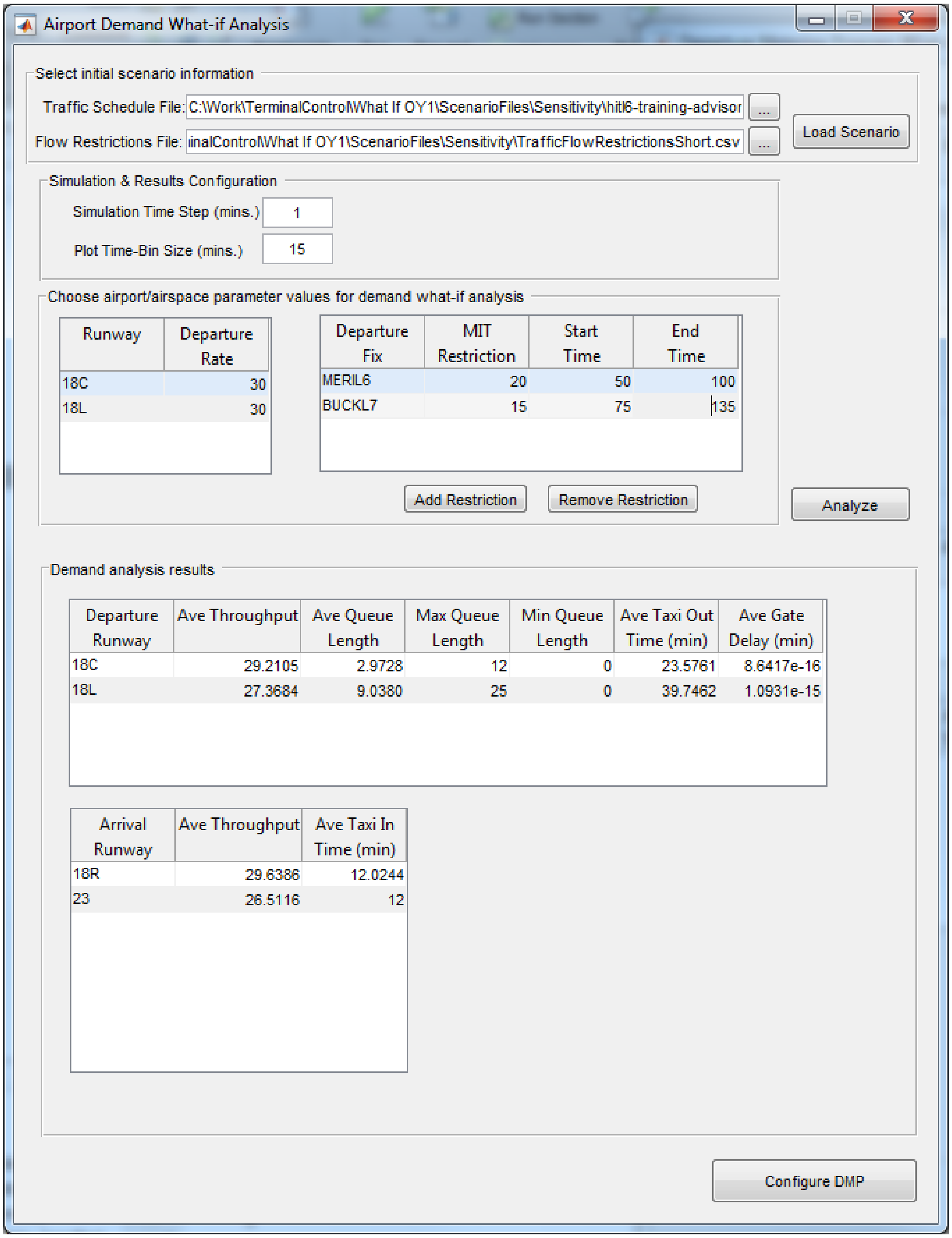


Figure 5-3. What-if Analysis Tool – Demand Analysis Results.

Additionally a set of time-series plots are generated and displayed in individual windows. The content of these plots and examples of them are provided in Section 2.3.

If the analysis shows the need for a departure metering program, e.g., a significant excess runway queue length, this is initiated by selecting the `Configure DMP` button.

5.3 Departure Metering What-if Analysis

When the need for a DMP has been detected using the Airport Demand Analysis capability described in Section 5.2, a DMP to resolve this condition is configured using the Departure Metering Program What-if Analysis Window shown in Figure 5-4.

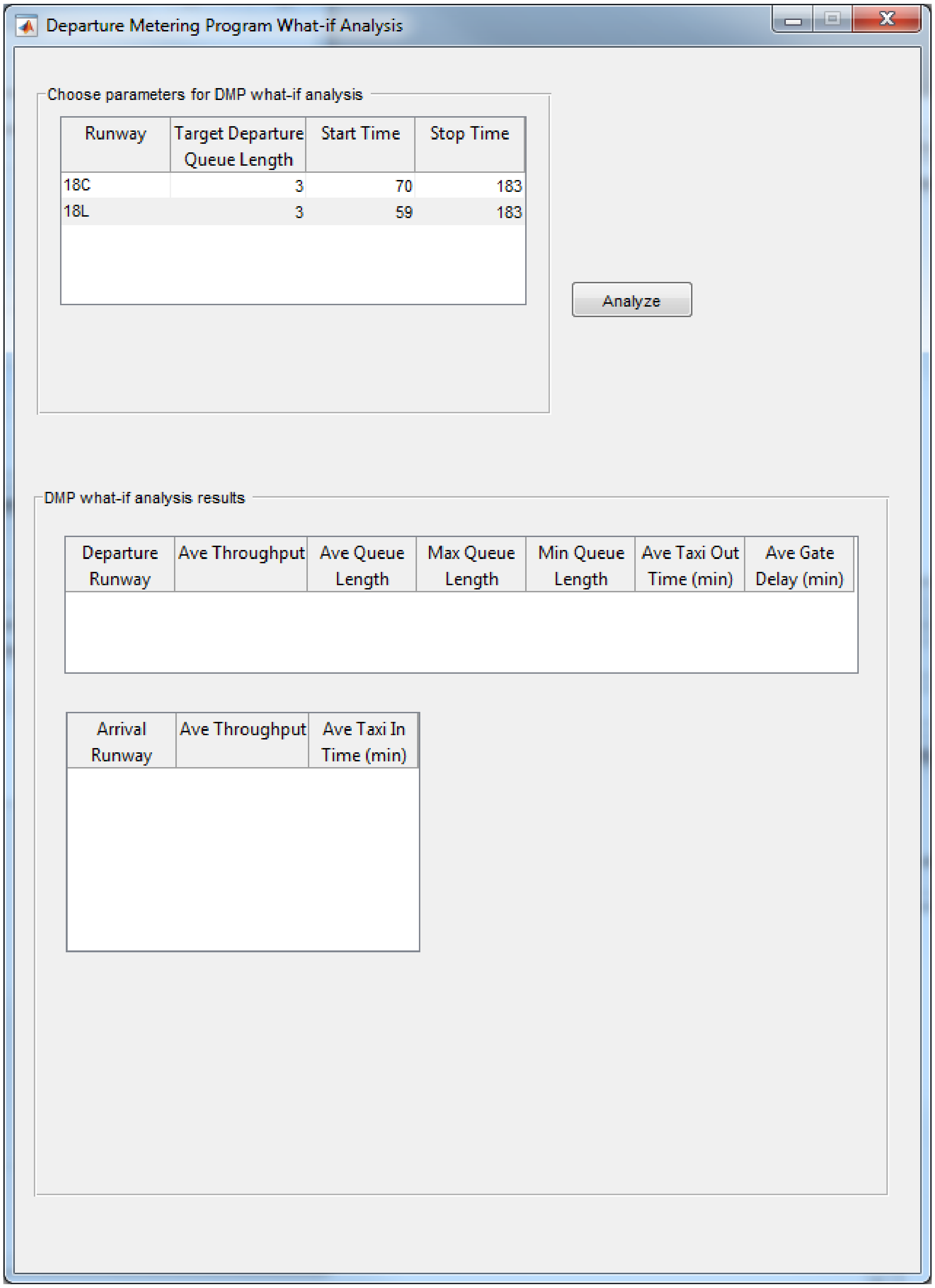


Figure 5-4. What-if Analysis Tool - Departure Metering Program Window.

5.3.1 Configuring a DMP

When a demand/capacity imbalance has been detected for a departure runway, initial computed values for the DMP – the target departure queue length (TDQL), DMP start time, and DMP stop time – are populated in the DMP parameters table. The values for the TDQL, start, and stop times can be modified by selecting the cell and entering the value. Start and stop times are specified in minutes from the start of the scenario.

5.3.2 Analyzing a DMP

Once the DMP parameters have been configured an analysis can be started by selecting the `Analyze` button. When the analysis is complete the aggregate metrics are displayed, per-runway, in two tables (one for departures, one for arrivals as illustrated in Figure 5-5. These are the same metrics computed and displayed by the Airport Demand What-if Analysis so a pre-DMP and post-DMP comparison can easily be made.

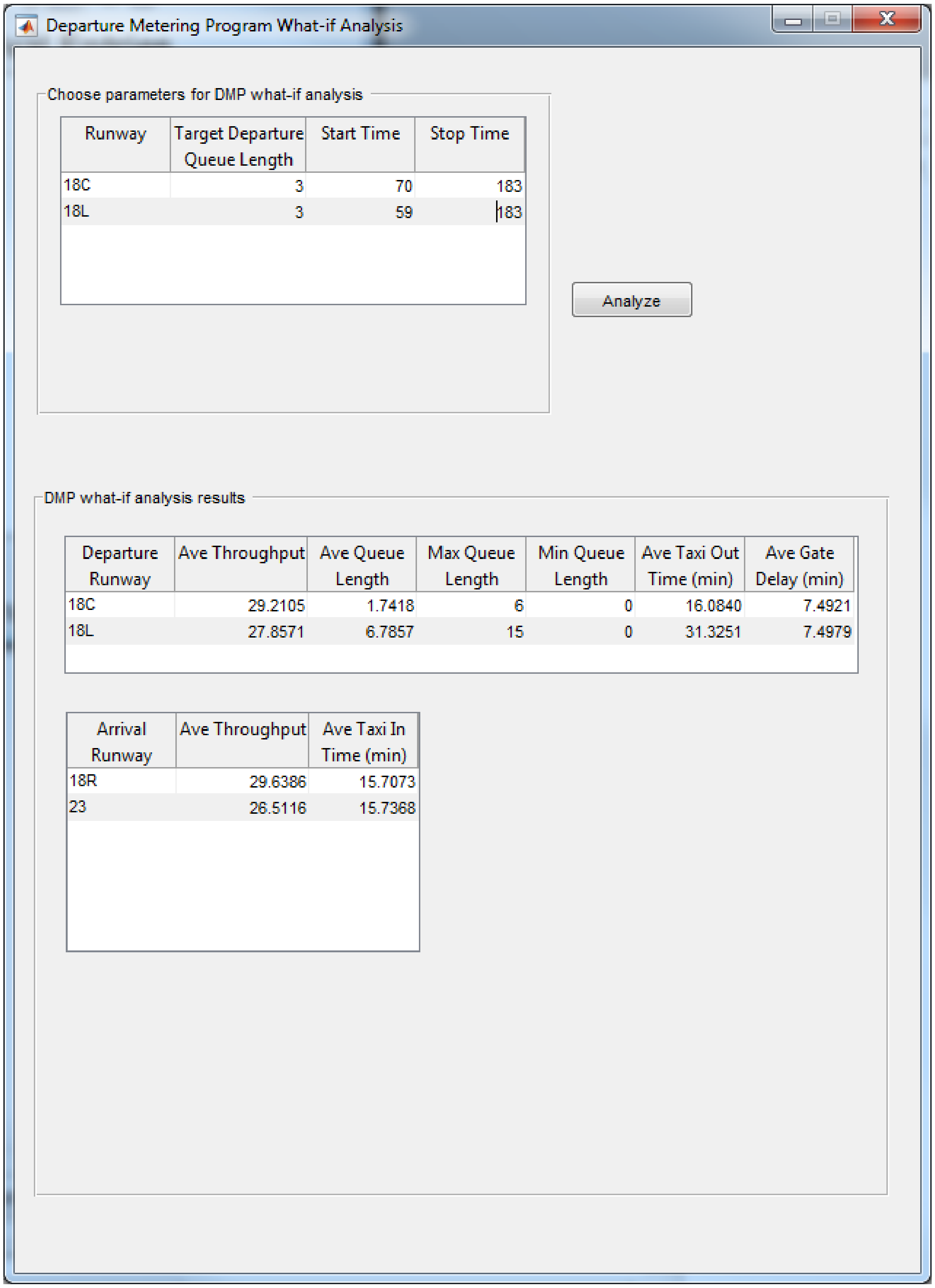


Figure 5-5. What-if Analysis Tool – DMP Analysis Results.

The DMP metrics are also saved to two Excel files:

- runwayDepartureMetrics.xls
- runwayArrivalMetrics.xls

Each file contains 2 sheets. The first sheet contains the metrics from the Airport Demand Analysis (pre-DMP). The second sheet contains the metrics from the DMP Analysis.

In addition to the aggregate metrics, the same set of time-series plots are generated and displayed in individual windows for the DMP analysis as the Airport Demand Analysis.

6 Recommendations for Future Work

The developments of the What-if Analysis Tool and process accomplished in the Base Year and Option Year 1 represent significant accomplishments. Nevertheless, numerous areas for expansion of the tool and process remain. This section provides extensive recommendations for future work across a broad range of areas for What-if Analysis Tool and what-if analysis process development. First and of foremost importance is exploring applications of DMPs to dynamic airport weather scenarios, the role of the What-if Analysis Tool and operations in planning those DMPs, and the inclusion of aircraft operators and airport stakeholders in planning DMPs. Other areas for future work focus on developing the What-if Analysis Tool to improve its utility, including refining the airport and airspace modeling and expanding the departure management program emulation for the What-if Analysis Tool, further identification and modeling of historical traffic and weather scenarios and enhancing and extending the user interfaces to support airport demand analysis and DMP analysis. The following subsections present recommendations in each area.

6.1 What-if Analysis Operations

There are important research gaps that have not yet been fully explored focusing on the use of DMPs to manage dynamic convective weather situations. While research conducted by Smith and his colleagues ([FS2015] [SW2012] [SF2011]) has characterized the nature of the challenges in managing such weather patterns and has demonstrated how decision support tools can improve the use of DMPs, there is still substantial work that needs to be done.

One of these gaps is the design of a What-if Analysis Tool that enables the DRC to address the following questions:

- What traffic flow management initiatives (such as MIT restrictions) could be put into effect in the future?
- How could a DMP, possibly in combination with other complementary traffic management initiatives, be used to manage such *forecast* TMIs?
- What should the parameters be for such a DMP? This is an especially rich decision if categorical DMPs need to be considered, as questions about what fixes to include alone or as one interact with decisions about how to manage different departure queues on the airport surface.

In short, some of the most important scenarios where departure metering would be beneficial require the *proactive* use of DMPS based on forecasts of upcoming TMIs, rather than reactive application once these TMIs have been put into effect. Below, we provide a notional example of a What-if Analysis Tool to support such decision making. Note that this is just a design concept. At this point it is not a carefully polished interface, and it has not been implemented. The numbers have been made up for the purpose of being illustrative.

6.1.1 Sample Scenario

Imagine a day at CLT where the weather pattern shown in Figure 6-1 developed. At 2045Z, the weather closes the airport and then continues to move east. Traffic scheduled to depart using Runway 18L is delayed not only for the duration of a departure stop from 2045Z to 2115Z, but also is impacted for an additional hour as the storm moves across the east gate departure fixes.

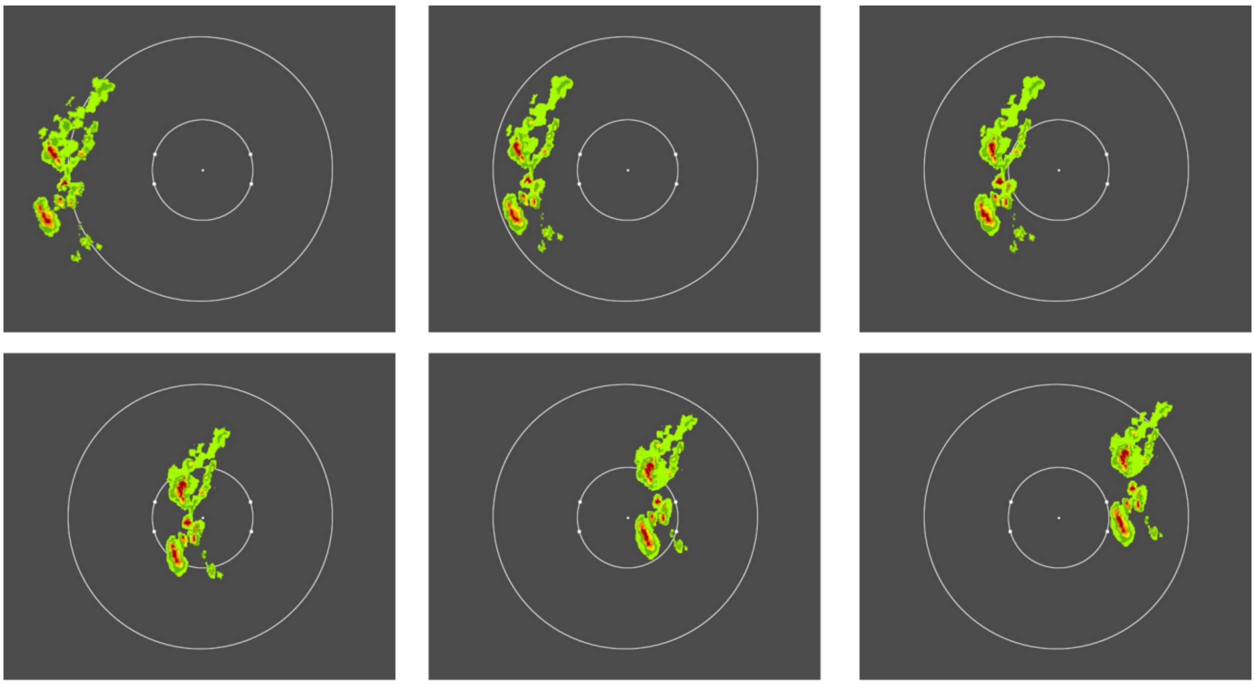


Figure 6-1. Weather Pattern Causing a Departure Stop at CLT.

South gate departures using 18L can depart unrestricted as soon as the departure stop ends at 2115Z, but there is a backlog of flights filed to depart these fixes because of the departure stop. Thus, to avoid an excessively long departure queue, even these south gate departures need to be controlled by a categorical DMP. East gate departures using MERIL and LILLS need to be more tightly controlled with categorical DMPs, however, as the storm cells are expected to continue to impact those fixes for an additional hour after the end of the departure stop (until 2215Z).

6.1.2 Managing Flights Using Categorical DMPs

Figure 6-2 shows a notional design of an interface for a What-if Analysis Tool to plan DMPs on this day. In this display, the current time is 2045Z, which is the beginning of the departure stop at CLT (see "Current Restrictions" at top).

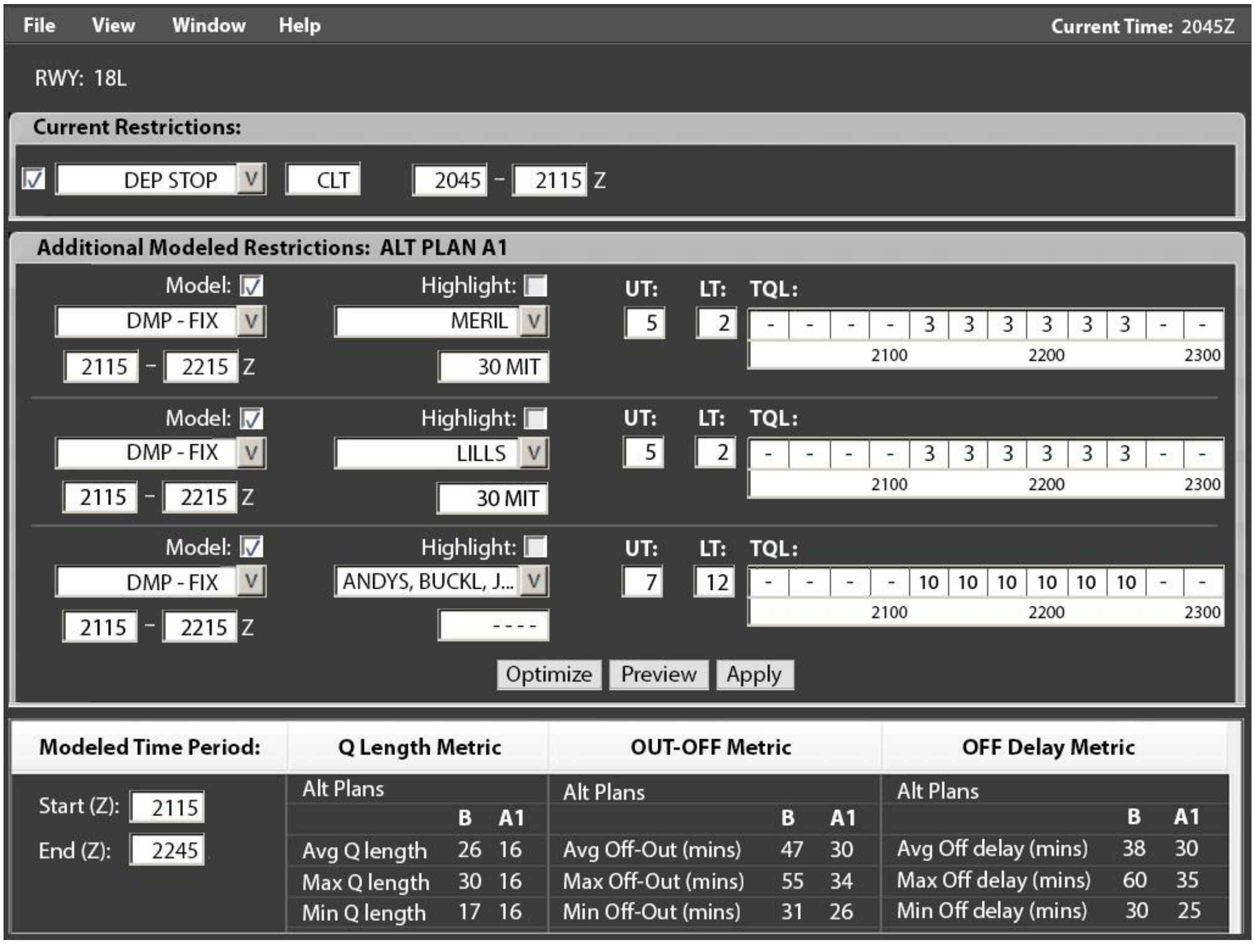


Figure 6-2. Notional What-if Analysis Tool Interface to Forecast TMIs and Identify Appropriate DMPs.

Figure 6-3 shows the location of aircraft on the airport surface at 2045Z. The turquoise flights are scheduled to depart 18L. The triangles are flights that have already pushed back at this time. Note that there is still a large number of flights at their gates (circles), so there is an opportunity to initiate an effective DMP even if it has a 15-30 minute static time horizon.

Figure 6-3. Location and Status of Flights at 2045Z.

Figure 6-4 shows the actual weather at 2045Z.

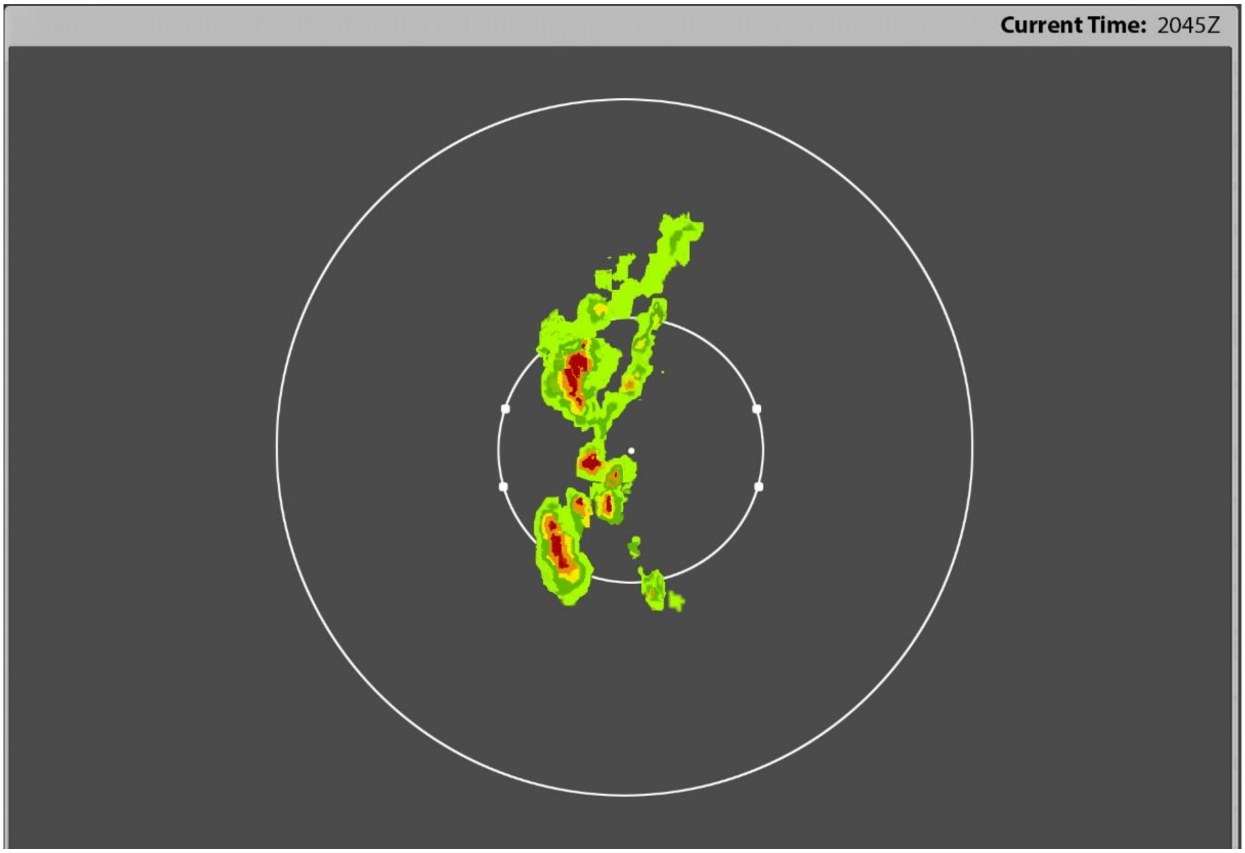


Figure 6-4. Actual Weather at 2045Z.

From a DRC perspective, the scenario plays out as follows:

- It is clear well before the departure stop at 2045Z that the airport will be closed for some period of time and that, once the storm moves east of the airport the east gate departure fixes will continue to be impacted.
- Participating in the traffic management telecons held involving traffic managers at the airport, TRACON, ARTCC and ATCSCC, the DRC asks for a 2 hour traffic management forecast. This has become a routine part of such telecons.
- The DRC is told that the departure stop is likely to last 30-45 minutes, and that departures using the east gate fixes will continue to be impacted for another hour after the end of the departure stop. A 30 MIT restriction is forecast for MERIL and LILLS for this additional hour. Since the storm will have cleared the south gate fixes, no restrictions are expected on those fixes once the departure stop ends.
- Based on this information from the traffic management telecon, the DRC decides to model –

- A categorical DMP to respond to the predicted 30 MIT restriction for MERIL from 2115-2215. Clicking on the Optimize button and indicating that he/she would like a target queue length of 3 with a upper threshold (UT) of 5 and a lower threshold (LT) of 3, the tool recommends setting the target queue length for flights to MERIL at 3 from 2115-2245. Note that this extends the DMP beyond the end of the MIT restriction in order to deal with the buildup of flights filed to depart MERIL.
- An identical categorical DMP is included for modeling for flights filed to depart LILLS.
- A third categorical DMP is set up for modeling for flights to the south gate departure fixes as one, but with a higher target queue length of 10 from 2115-2245 because those fixes are expected to have a much higher capacity (no MIT restriction).

- These three modeled categorical DMPs are shown in the middle pane in Figure 6-2. By default this modeled plan, which takes into consideration the current restriction (departure stop) that is in place as well as the 3 proposed DMPs, is labeled Alt Plan A1.
- The DRC looks at the predicted values of the performance statistics (bottom pane of Figure 6-2) and notes that the model predicts that the average departure queue length without the modeled DMP is 26 flights, while the average with Alt Plan A1 is 16 flights (3+3+10). This impact is communicated graphically in the additional window shown at the bottom of Figure 6-5.

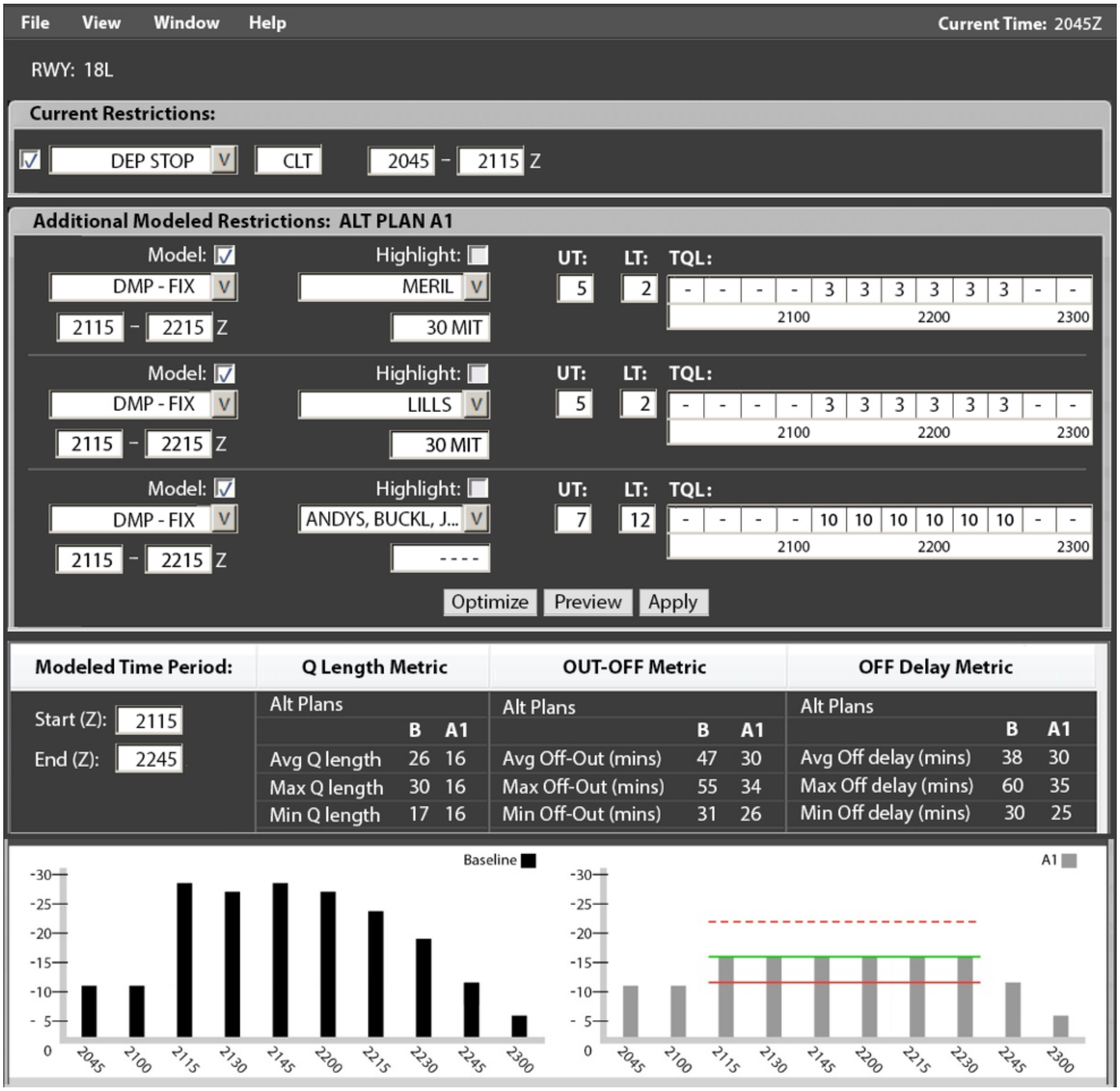


Figure 6-5. Bar Charts Comparing Predicted Queue Lengths for 18L With and Without the Implementation of the Modeled Categorical DMPs in Combination With the Implemented Departure Stop.

- The predicted average Off-Out times (in minutes) reflect a similar benefit, reducing average Out-Off time from 47 to 30 minutes. In addition, the modeled departure off time delay is reduced from 38 to 30 minutes. This latter benefit is in part made possible by assuming that the departure controller, supported by the NASA Spot and Runway Departure Advisor (SARDA) [JU2011], is able to optimize the sequencing of departures more effectively when the flights filed to MERIL and LILLS have been thinned in the queue.

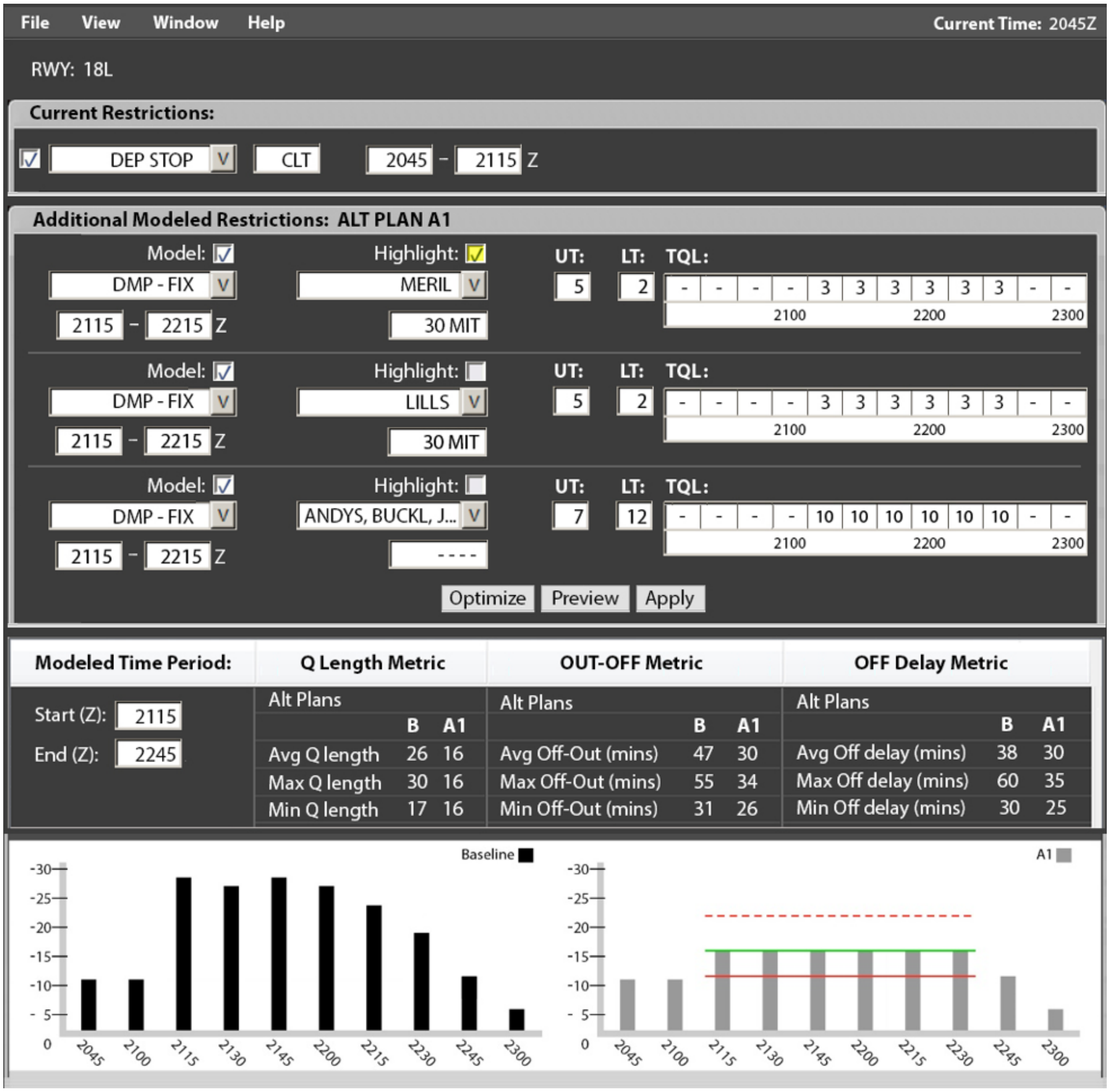


Figure 6-6. Highlighting flights to MERIL (indicated by the marked yellow check box for the MERIL DMP.

- Finally, the DRC highlights the flights to MERIL by checking the Highlight box associated with the MERIL DMP (see Figure 6-6) and looks to see where those flights are on the airport surface (see Figure 6-7). He/she sees that, by keeping the MERIL flights at their gates longer, it will be much easier to develop a more effective departure queue that minimizes the time between successive departures by "putting splitters" between the MERIL flights, e.g., sequencing flights to other departure fixes between MERIL flights.

Figure 6-7. Highlighting of the MERIL flights in yellow.

In short, if categorical DMPs are going to be used effectively, DMPs will have to be developed based on TMI *forecasts*. In addition, the computation necessary to determine the parameters for some combination of modeled DMPs is complex enough to require software support.

The above design concepts have not been fully explored, either in terms of the desirable functionality or the associated interface design. However, this notional example provides insights into important research questions that need to be addressed if DMPs are going to be used effectively to support a tool like the NASA SARDA in order to improve performance.

6.2 What-if Analysis Modeling

The operations modeling within the What-if Analysis Tool should be extended to account for additional traffic flow restrictions impacting departures, traffic flow interactions that impact airport performance, tail tracking of arrivals with departures to account for aircraft impacts, and modeling of traffic management methods to satisfy departure metering program TMATs.

6.2.1 Other Types of Departure Restrictions

Two additional types of traffic flow restrictions impacting departures include Expected Departure Clearance Times (EDCTs) and Call For Release/Approval Request (CFR/APREQ).

EDCTs specify takeoff times for departures to comply with Traffic Flow Management (TFM) Ground Delay Programs (GDPs) or Airspace Flow Programs (AFPs). GDPs or AFPs are implemented to balance traffic demand to capacity-constrained destination airports or airspaces. EDCTs are the result of the Air Traffic Control System Command Center (ATCSCC) estimating acceptance rates for airports and airspaces, and scheduling individual aircraft takeoff times using a Ration By Schedule (RBS) approach in order to satisfy the acceptance rate constraints of those airports and airspaces. EDCTs are an impactful and frequently occurring flow restriction on airport departures that should be included in the what-if analysis.

The What-if Analysis Tool may be extended with data inputs to explicitly model EDCTs for a given scenario, and logic to expedite departures with assigned EDCTs. However, for a what-if analysis over a forecast time horizon of, say, 2-hours, it is likely that the EDCTs for airport departures may not be specified, and that the acceptance rates of forecast weather or traffic events calling for the implementation of GDPs and AFPs may not be known. Estimating future EDCTs and/or their source flow restrictions, and incorporating those estimates into the what-if analysis, is a recommended area of future work.

CFR/APREQs specify the takeoff times for departures specified by the Time Based Flow Management (TBFM) Integrated Arrival Departure Capability (IDAC) functionality for merging departures into the en route traffic flow [LM2012]. The FAA Surface CDM Concept of Operations simply calls for departure management to allow departures to push back at their airline-scheduled gate pushback times. The flights will be issued takeoff times by TBFM once they have pushed back; thus departures subject to the CFR/APREQ process may not need to be explicitly modeled. However, if en route traffic flow congestion is sufficiently heavy, or traffic congestion due to other restrictions impacts management of these departures, they may need to be explicitly modeled in the What-if Analysis Tool. In turn, estimating takeoff times or equivalent departure rates for airport departures subject to these restrictions would be necessary.

6.2.2 Terminal Gates

Two areas for improving the gate modeling for the What-if Analysis Tool include modeling gate groups and introducing tail-tracking into the gate management model.

Current what-if analysis modeling is limited by fixed gate assignments for airport arrivals. The result is that simulated arrivals may be delayed unreasonably because their gate is occupied by a delayed departure, whereas in reality the ramp controller of the aircraft operator may assign the arrival to a different gate. To address this limitation, the gate groups may be introduced into what-if analysis modeling. Gate groups associate two or more gates as a single node. The queue size limit of the node equals the number of gates in the gate group. In turn, a simulated arrival in the what-if analysis may enter the gate group node if current occupancy state allows, regardless of the occupancy state of its specific gate.

Figure 6-8 presents a candidate model for the gate groups proposed for the What-if Analysis Tool modeling of CLT. The model groups gates by concourse region.

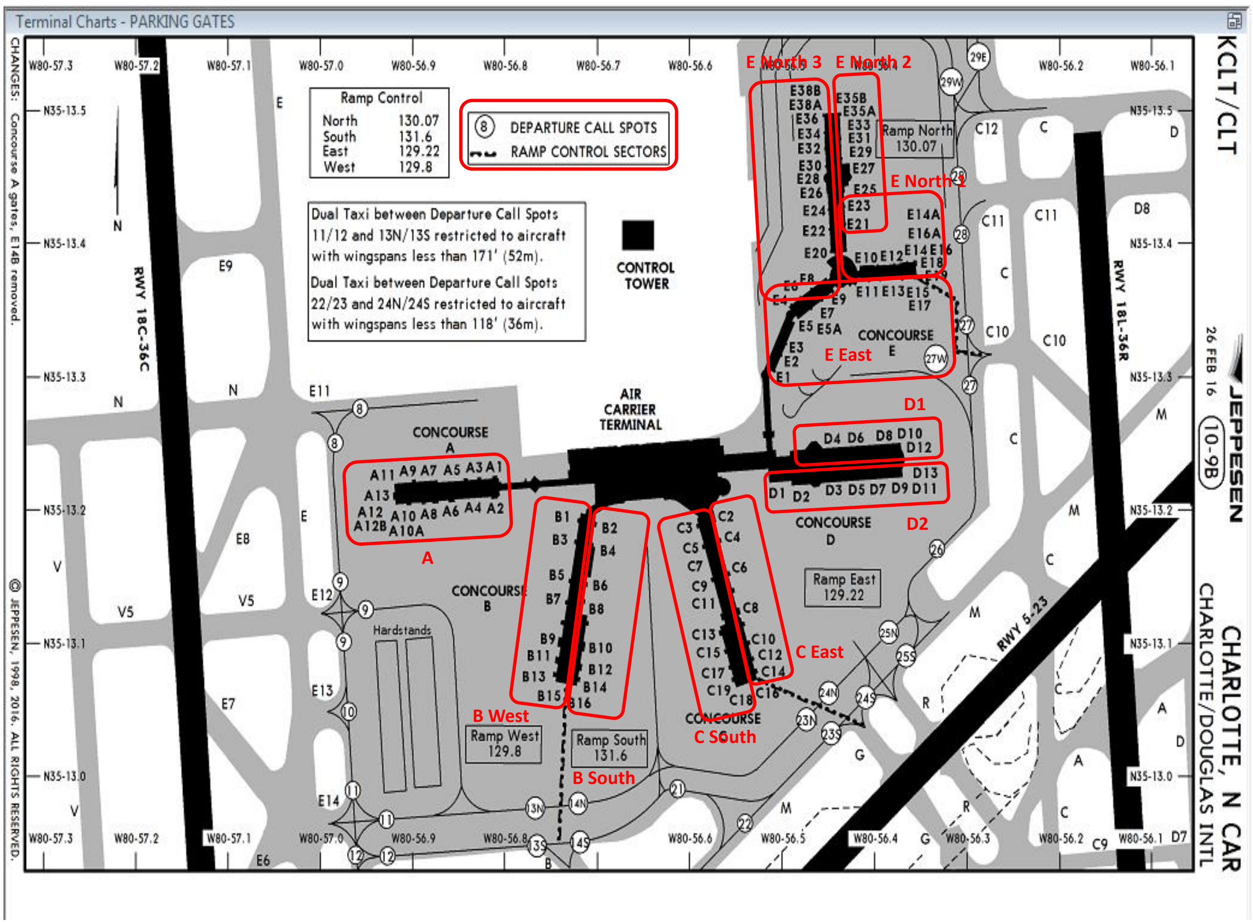


Figure 6-8. Candidate Model of Gate Groups for CLT.

The figure depicts gate groups A, B West, B South, C South, C East, D2, D1, E East, E North 1, E North 2 and E North 3. The gates comprising each gate group are visible in the figure and listed in Table 6.1.

Table 6.1. Gates and Capacities of Candidate Gate Group Model for CLT.

Gate Group	Gates	Capacity
E north 3	E: 4, 6, 8, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38A, 38B	14
E north 2	E: 35B, 35A, 33, 31, 29, 27, 25, 23, 21	9
E north 1	E: 10, 12, 14, 16, 16A, 18, 19	7
E east	E: 1, 2, 3, 5, 5A, 7, 9, 11, 13, 15, 17	11
D1	D: 12, 10, 8, 6, 4	5
D2	D: 1, 2, 3, 5, 7, 9, 11, 13	8
C east	C: 2, 4, 6, 8, 10, 12, 14	7
C south 1	C: 16, 18, 19, 17, 15, 13, 11, 9, 7, 5, 3	11
B south	B: 2, 4, 6, 8, 10, 12, 14, 16	8
B west	B: 1, 3, 5, 7, 9, 11, 13, 15	8
A	A: 1, 3, 5, 7, 9, 11, 13, 12, 12B, 10, 10A, 8, 6, 4, 2	8

While this candidate model proposes gate groups by physical proximity, gate groups may be modeled by the leasing airline or other criteria.

The current gate management model of the What-if Analysis Tool does not perform tail-tracking to model the airframe shared between an arrival and departure operations. The result is an inaccurate estimate of the impact of departure metering programs on individual flights, and the turnaround times and schedules of aircraft operators. Such impacts could determine whether an aircraft operator retains or cancels a flight, or the feasibility of a proposed program. The What-if Analysis Tool may be enhanced with traffic input schedules indicating which arrival and departure operations share a common airframe, and with gate management logic to propagate planned gate departure delays to the associated arrival.

6.2.3 Traffic Interaction Points

The current modeling of CLT surface routes neglects a number of the airport-specific factors complicating traffic management and impeding traffic flow at the airport. Such factors include interactions of traffic flows between the runways (runway-runway interactions), between the taxiways and runways (runway-taxiway interactions), and between the taxiways (taxiway-taxiway interactions). These interactions can limit throughput and affect the timing of traffic control. In particular, runway-

runway and runway-taxiway interactions are called out explicitly in the FAA Surface CDM Concept of Operations [FA2012].

Initial modeling and algorithm development work was done to address the interactions in the What-if Analysis Tool modeling; further implementation and troubleshooting remains. Complete models of the surface interaction nodes, the time separation rules and values for each node, link structures connecting the nodes, route structure descriptions and link transit time parameter variables were developed to represent three CLT runway configurations: the South Flow Straight and Converging, and the North Flow Straight. A description of the South Flow model is provided in this section.

Regarding runway-runway interactions, CLT-specific models were developed for the what-if analysis to capture the dependencies of arrival landings and departure takeoffs among the runways in the South and North flow runway configurations of the airport. The models capture the broadest possible uses of the runways in the South and North flow configurations. The specific runway usage of a particular traffic scenario is determined by the runway assignments of flights inherent in the traffic scenario.

Figure 6-9 depicts nine different traffic flow interaction points identified for CLT in the South Flow configuration of departures from runways 18L and 18C, and arrivals to runways 18R, 23 and 18C.

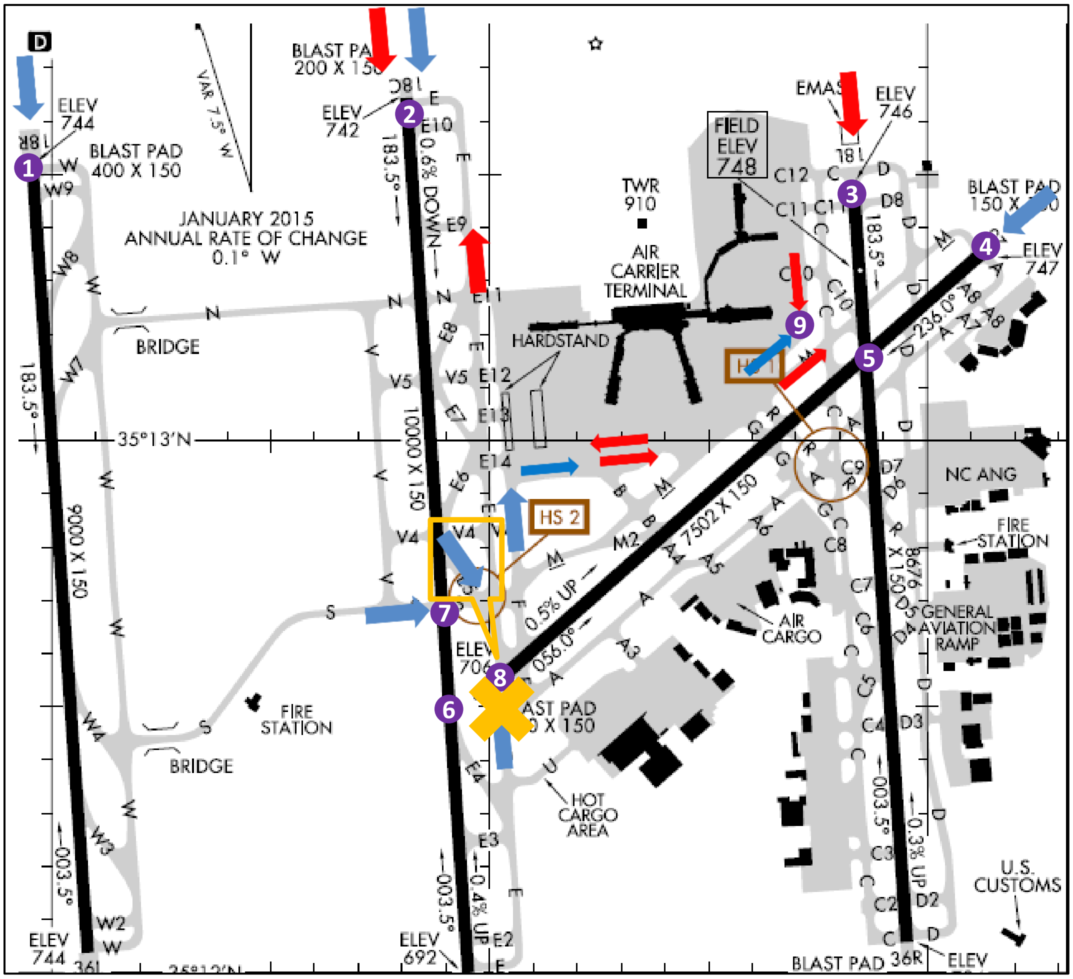


Figure 6-9. Surface Traffic Flow Interaction Points Identified for CLT in Generic South Flow Runway Configuration.

The nine different traffic flow interaction points are categorized as runway-runway, runway-taxiway and taxiway-taxiway interactions. These interactions are as follows in Table 6.2:

Table 6.2. Candidate Interaction Points for Modeling CLT South Flow Operations.

Interaction Point Number	Type	Interaction Description
1	Runway-Runway	Runway 18R arrivals sequenced with one another
2	Runway-Runway	Runway 18C departures and arrivals sequenced with one another
3	Runway-Runway	Runway 18L departures sequenced with one another
4	Runway-Runway	Runway 23 arrivals sequenced with one another
5	Runway-Runway	Runway 18L departures and Runway 23 arrivals sequenced with one another
6	Runway-Runway	Runway 18C departures and arrivals and runway 23 arrivals sequenced with one another
7	Runway-Taxiway	Runway 18C arrivals and departures sequenced with Taxiway S arrivals
8	Runway-Taxiway	Runway 18C arrivals sequenced with Taxiway E arrivals. Note this interaction may be excluded if runway 18C arrivals are assumed to exit via Taxiway E5.
9	Taxiway-Taxiway	Inner taxi lane Concourse D & E arrivals sequenced with inner taxi lane Concourse D & E departures. Taxiway C & M arrivals sequenced with Taxiway C & M departures.

This list captures some of the more significant interactions on the CLT surface. Additional interaction points may model the merging of multiple traffic flows, or other points of interest. Analysis via simulation results comparison to FAA ASPM or subject matter expert consultation is required to prioritize the interactions for modeling.

Tables specifying the minimum separation between the successor and predecessor aircraft crossing each interaction point were defined. Similar to the modeling approach undertaken in the NASA Airspace Concept Evaluation System (ACES) runway model [RA20015], each table is specific to a particular crossing sequence. Table 6.3 presents an example.

Table 6.3. Example Separation Table for Interaction Point 9.

Runway 18C-Runway 23	Arrival	Departure
Arrival	2.0 NM	Not applicable
Departure	2.0 NM	Not applicable

The data in the table indicate that an arrival or departure on runway 18C must be spaced 2.0 Nautical Miles (NM) behind an arrival on runway 23 [LO2016]. A separate table may be used to define spacing of an arrival on runway 23 following a departure or arrival on runway 18C.

Modeling of interaction nodes also includes specialized logic for controlling the traffic flow at interaction nodes, accounting for the interactions among the multiple traffic flows at the node. An initial version of the logic has been developed and implemented in the What-if Analysis Tool for the runway-runway interaction nodes. The key steps of the model are:

- Identify the next candidate flight to use each runway of the airport;
- Identify the predecessor to have used each runway of the airport;
- Determine the earliest feasible runway exit time of each runway candidate based on the interaction of its runway with the other runways as per spacing tables and the exit time of the predecessor of each of the interacting runways;
- Permit the candidate with the earliest runway exit time to takeoff from or land to the runway.
- The logic may have to be refined to ensure a particular aircraft is not excessively delayed.

Modeling of the surface traffic interaction nodes impacting traffic flow also requires a supporting link structure connecting the nodes. Figure 6-10 depicts the taxi route structure incorporating the interaction nodes.

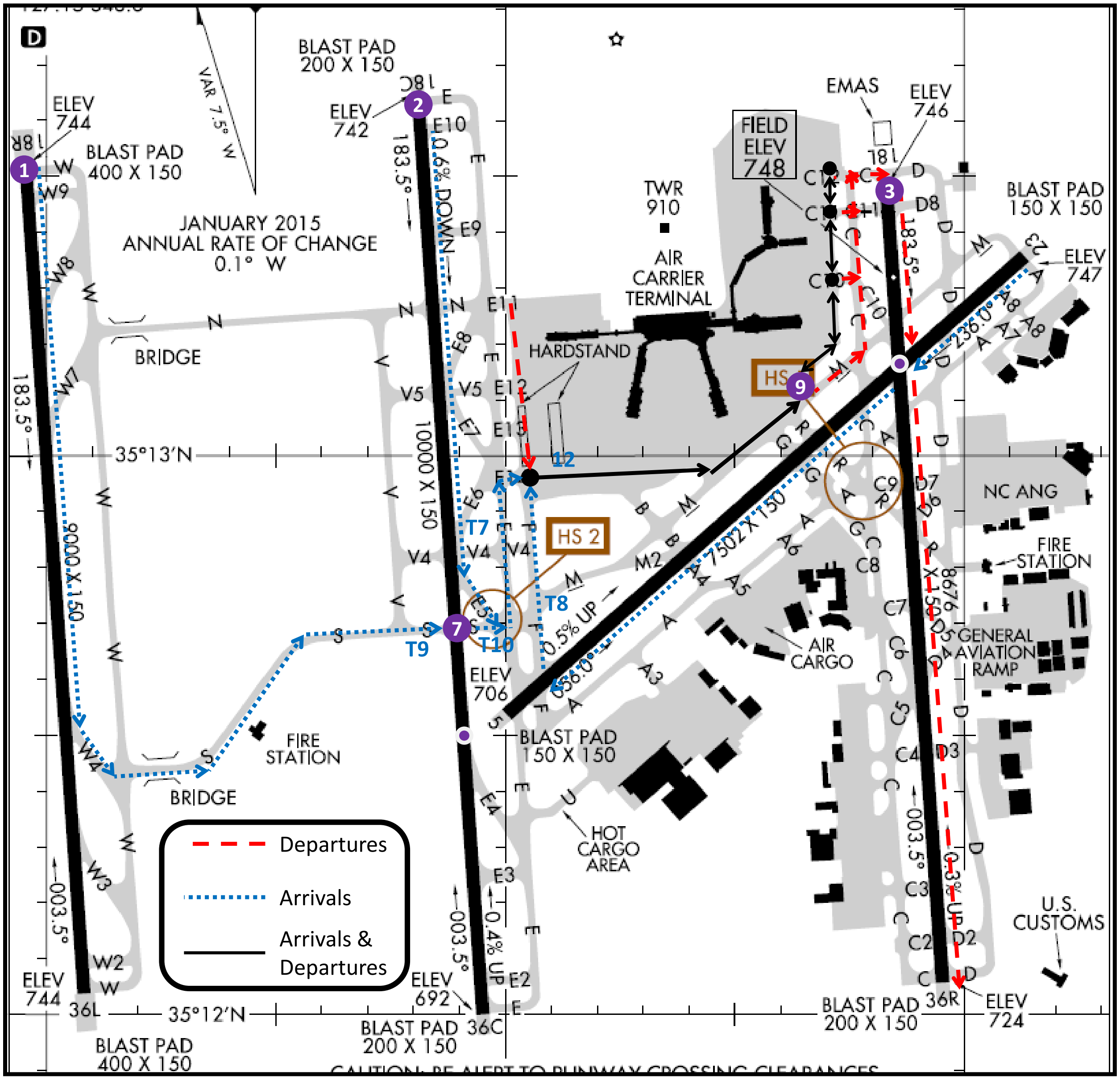


Figure 6-10. Taxi Routes Linking Interaction Nodes for CLT South Flow.

Based the taxi route structure and the node locations, the individual links connecting the gate, spot, spot-interaction points, interaction nodes are defined. An example of the taxi routes and the links connecting the nodes on the airport surface is given in Table 6.4.

Table 6.4. Subset of Taxi Routes for Runway 18C Departures.

Gate Group Node	Gate Group Node-Taxiway Interaction Node Link	Taxiway Interaction Node	Taxiway Interaction Node-Spot Node Link	Spot Node	Spot Node-Runway Interaction Node Link	Runway Interaction Node
E North 3	R1	9	R21	9	T5	18C (Point 2)
E North 2	R2	9	R21	9	T5	18C (Point 2)
E North 1	R3	9	R21	9	T5	18C (Point 2)
E east	R4	9	R21	9	T5	18C (Point 2)
D1	R5	9	R21	9	T5	18C (Point 2)
D2	R6	9	R21	9	T5	18C (Point 2)

In the table, R21 is the link connecting the Taxiway Interaction Node 9 to the Spot Node 9 in the surface model, and corresponds to a transit time to be specified as part of the model adaptation. Similarly, T5 is the link connecting the Spot Node 9 to the Runway Interaction Node 2 corresponding to runway 18C. The Figure 6-11 depicts the connection of the gate group nodes, taxiway interaction node, spot node and runway node presented in the table.

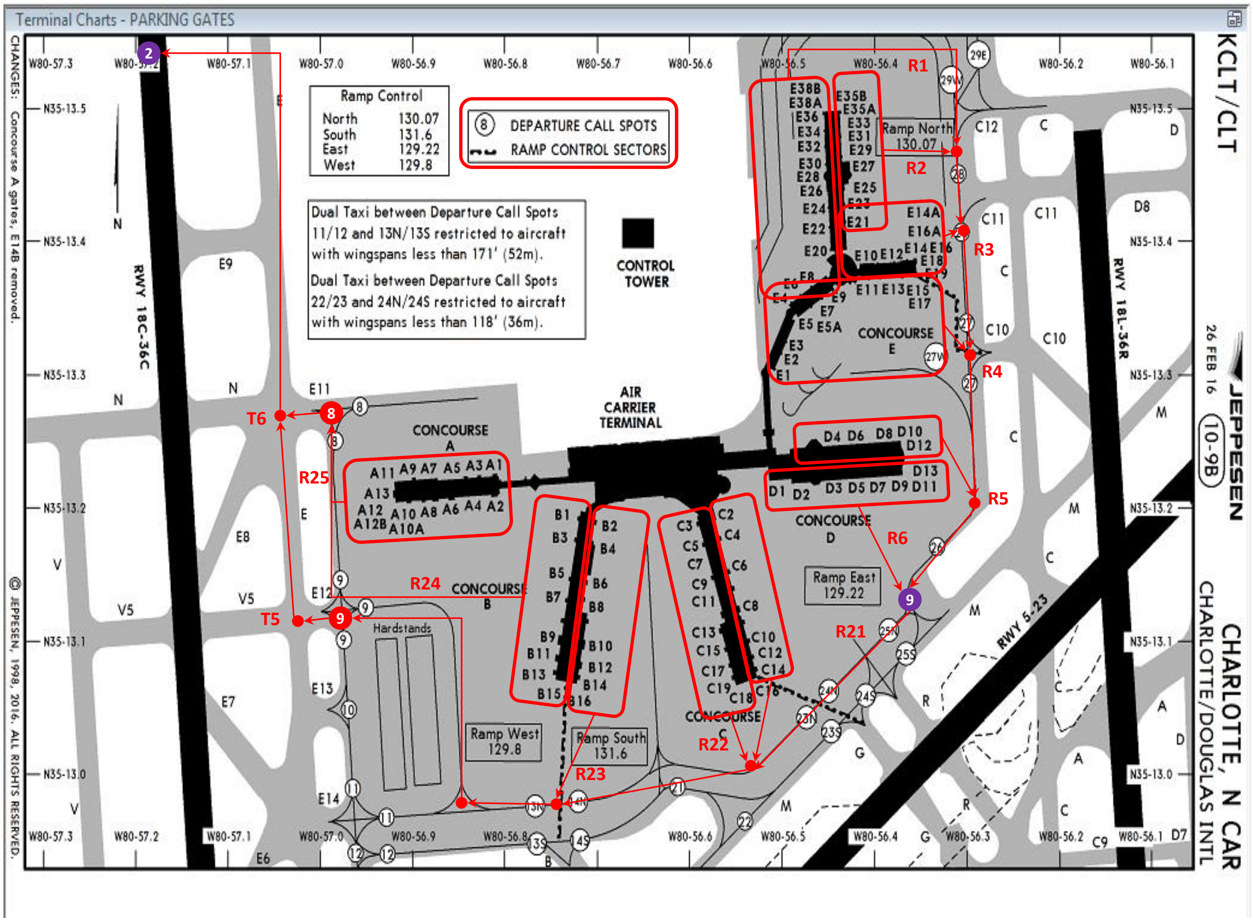


Figure 6-11. Example of Links R1 – R6, R21 – R25 and T5 – T6 Connecting Gate Group Nodes, Taxiway Interaction Node 9, Spot Nodes 8 and 9, and Runway Interaction Node 2.

The figure depicts the connection of gate group nodes to the Taxiway Interaction Node 9, the connection of gate group nodes to the Spot Nodes 8 and 9, the connection of Taxiway Interaction Node 9 to Spot Node 9, and the connection of Spot Nodes 8 and 9 to Runway Interaction Node 2 (runway 18C).

In this manner, entire models were developed for CLT in the South Flow and North Flow configurations to account for all key runway-runway, runway-taxiway, taxiway-taxiway interactions; associated spacing tables; and links connecting the interaction nodes with gate groups and other surface nodes.

6.2.4 Traffic Management Methods

The What-if Analysis Tool may be extended to account for traffic management methods that impact traffic throughput and taxi time, including runway sequencing methods and surface traffic holding practices.

The current implementation applies first-come, first-served sequencing and the runway node service rate to model runway operations. The logic could be extended to model some of the departure sequencing practices undertaken by the airport local controller, and afforded by the dual runway entry points, such as sequencing by aircraft weight class, departure fix or other departure restrictions.

The current implementation has simplistic modeling for distribution of delay for arrivals and departures taxiing on the airport surface. Departures leave their gates to transit unimpeded to meet their TMATs specified by the departure management program, and are delayed at the runway to satisfy runway spacing and departure restrictions. Arrivals are delayed in the non-movement area if their gate is occupied. The What-if Analysis Tool could be extended to model the delay reservoirs available to departures and arrivals—e.g., hardstands, taxiways—to distribute delay across the airport surface and to reduce gate conflicts. The delay reservoirs would be modeled as additional nodes, with maximum service rates, queue size limits, and sequencing rules, and management logic to enable independent entry and exit.

6.3 Departure Metering Program Emulation

The existing DMP Emulator has the ability to space departures at gates and runways while simultaneously satisfying flow restrictions at departure fixes. There are three main expansions to the functionality that are desirable. These are partial solution operations, mixed-use runway operations, and other types of restrictions.

6.3.1 Partial Solution Operations

When the current DMP Emulator is applied, it is given latitude overall the departure airport operations. However, there is a desire to be able to apply partial DMP solutions where only a subset of airport operations is impacted. For instance, it is desirable to apply a DMP to a single runway. However, partial DMP Emulator solutions are difficult because departure operations tend to be coupled. It is difficult to know how to appropriately decouple operations so that a partial solution would have validity. For example, flow restrictions create coupling of airport operations because flow restrictions are applied to departure fixes and are largely independent of runways. Therefore, a DMP that would apply to a single runway is by definition going to neglect certain fraction of flow restricted aircraft that are not using DMP controlled runway. Important questions must be answered in terms of how and when partial solutions are applied, and how generated spacing conflicts are handled.

6.3.2 Mixed-use Runways

A desirable extension would be the ability to manage the use of mixed-use runways, where arrivals and departures use the same runway. This addition is not inherently problematic as partial solution operations can be. Arrivals can be treated as an additional constraint on runway and gate usage. One important question to answer is to what extent (if any) arrivals should be given preferential treatment over departures, and if so, should it be an adjustable parameter within the DMP Emulator.

6.4 Traffic and Weather Scenarios

The recommendations are made based on lessons learned in the collection and collation of data for the simulations. Some apply to areas outside the project but should be considered.

6.4.1 Recording of Delay Metrics

It was not easy to identify which specific delays were allocated to specific flight by FAA. Sometimes MIT for an exit fix were applied to the flight but the actual flight departed through another exit fix. EDCT and CFR are allocated to flights based on destination or airspace penetrated. It was difficult to identify whether delay was caused by the restriction and if so what the attribution of delay should be. This leads to misleading statistics on the impact of TMIs.

It is recommended that actual delay metrics should be captured for each flight, identifying the source of external delay imposed and the type of delay. The planned and actual times will then show the actual delay. This information should be stored in the System Wide Information Management (SWIM) / Flight Information Exchange Model (FIXM) entry for the flight.

6.4.2 Recording and Use of Delay Metrics

Consideration should be given to comparison of actual taxi time for the scenario day to the what-if analysis results. This may be difficult if, as noted above, the allocation of delay is unclear or if the actual aircraft avoids the delay by leaving through another fix or airspace area. This avoidance of the delay penalty by rerouting should be added to the model as it is probably based on an airline operating procedure.

We plotted the taxi times (given to us in the OOOI data) for a couple of days, August 8th and August 18th. These taxi times are actuals, not based on scheduled OOOI times. A plot of the taxi times for the baseline day, August 8th, appears below in Figure 6-12.

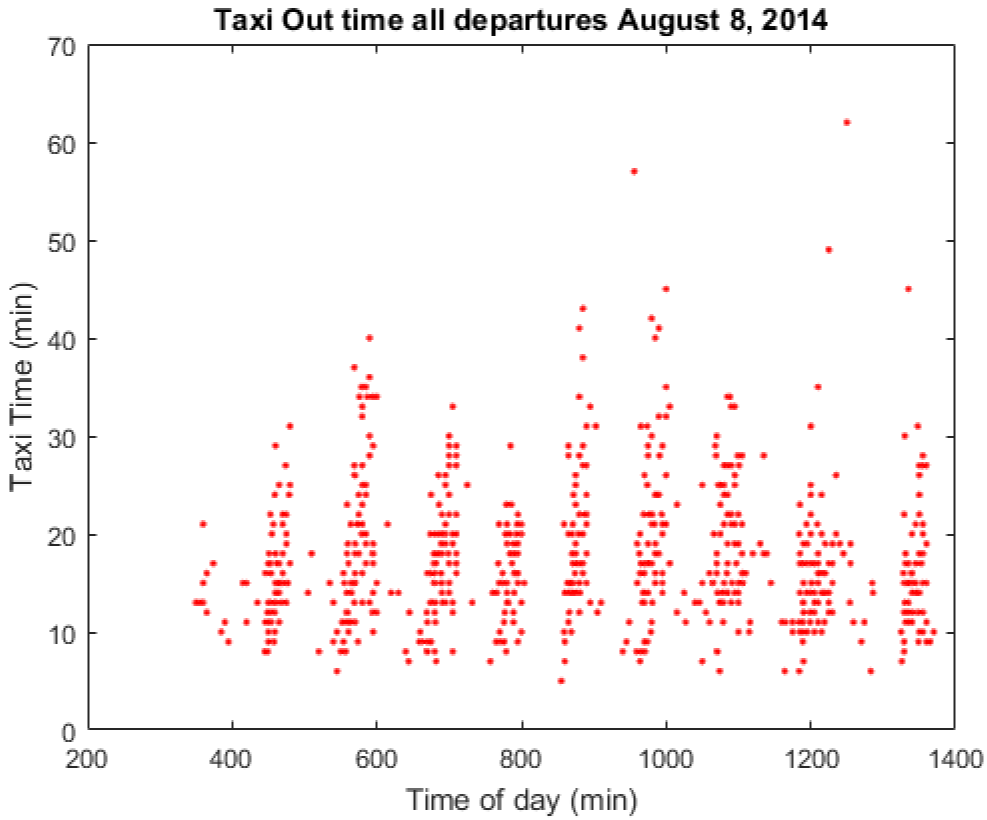


Figure 6-12. Taxi Times for All Runways.

It can be seen that taxi times increase during the banks, though most taxi times are less than 45 minutes. For a rough correlation between the departure banks and the taxi times, see Figure 6-13.

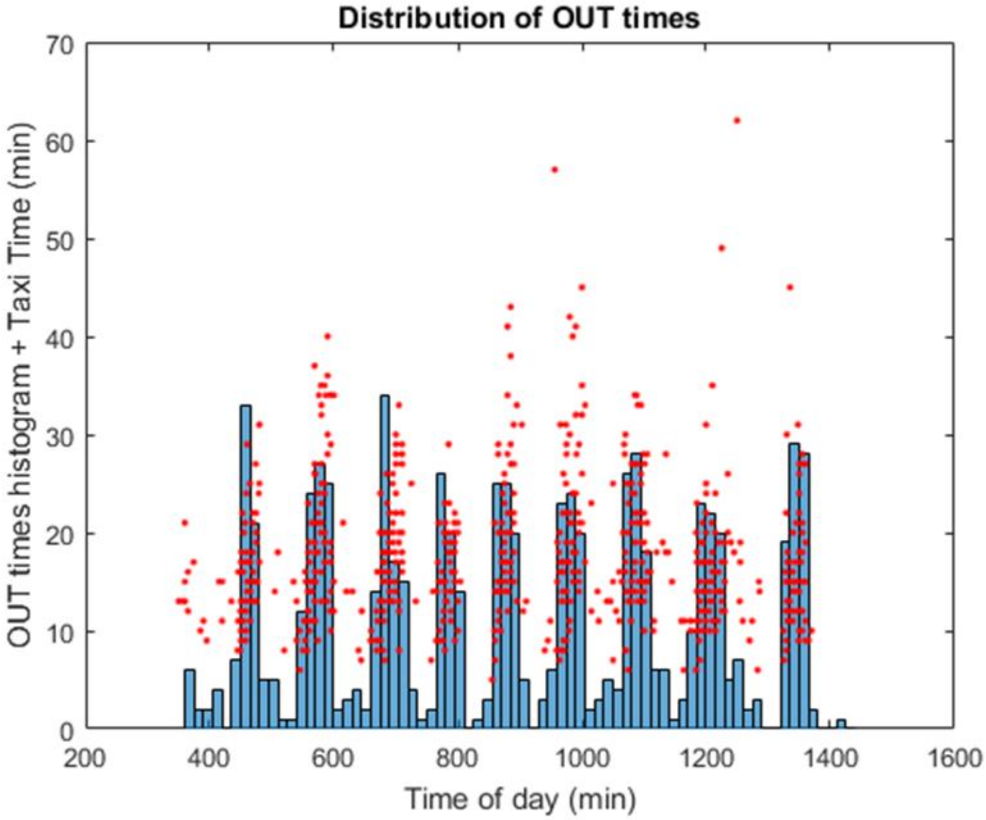


Figure 6-13. Overlay of Actual Departure Taxi-out Times with Scheduled Departure Pushback Times.

In future work, it should be possible to compare the taxi times resulting from the What-if Analysis Tool to the actual taxi times for a particular day. By analyzing the departure taxi times as a function of runway, we can generate plots by spot and runway. Recall that the departures traverse the ramp area to wait for FAA ground control at the departure spot. Departure spot is inferred from the gate and the departure runway, both of which are provided in the OOOI data. The scenario generation software applied the business rules received from the ramp controller to infer the spot.

From Figure 6-14, the minimum taxi time for CLT runway 18C is almost 10 minutes, owing to its distance from the ramp area. As might be expected, shorter taxi times are incurred from Spot 8 than from Spot 9.

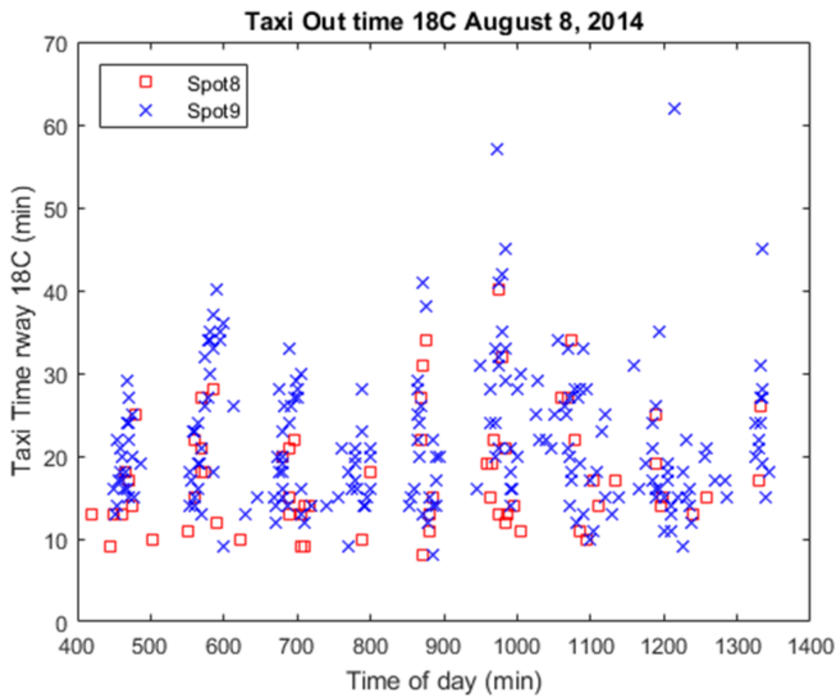


Figure 6-14. Taxi Times for CLT Runway 18C by Spot.

Departure spots for Charlotte as well as the departure runways are shown in Figure 6-15, below.

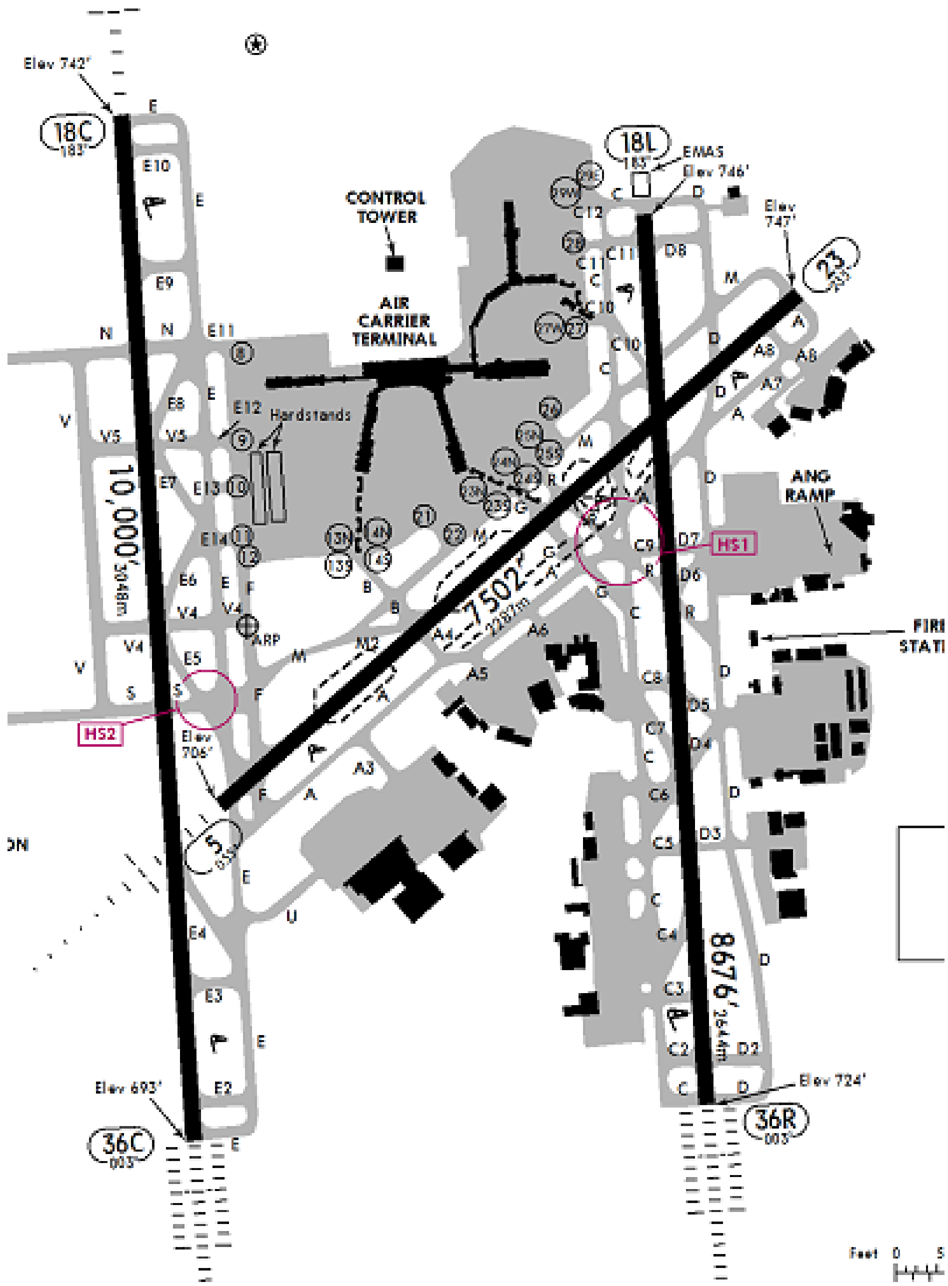


Figure 6-15. Departure Spots at CLT.

Figure 6-16 depicts the taxi times for runway 18L and 23. The taxi times for spot 29 are the shortest, because that departure spot is practically at the threshold of runway 18L. Overall the taxi times to runway 18L are a little shorter than for runway 18C, and as expected the minimum taxi times for spot 27 are longer than for spot 29. Spot 25 has the longest taxi times.

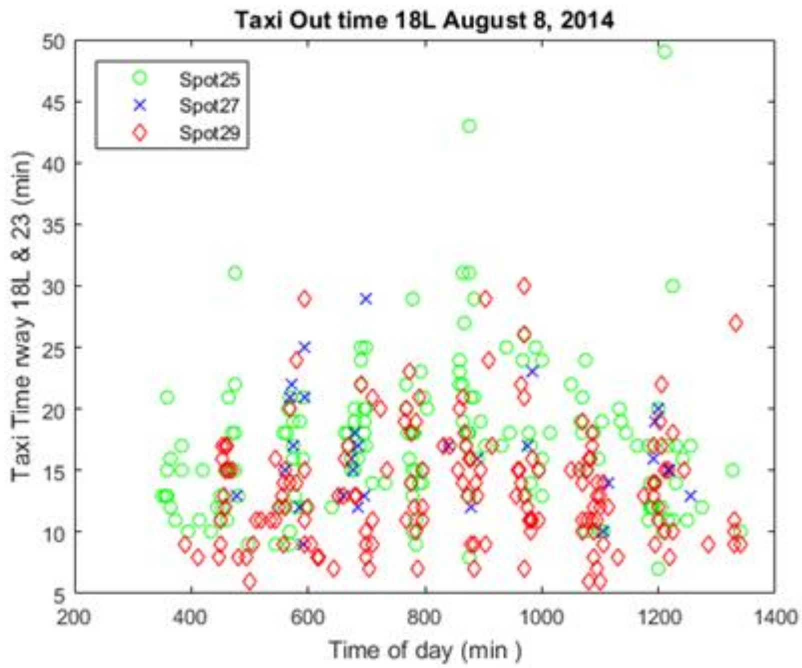


Figure 6-16. Taxi Times for CLT Runway 18L.

We created the same plots for actual pushback data from August 18th, which was the day that had so many restrictions. The histogram for the pushback times, based on actual OUT times, is shown below in Figure 6-17.

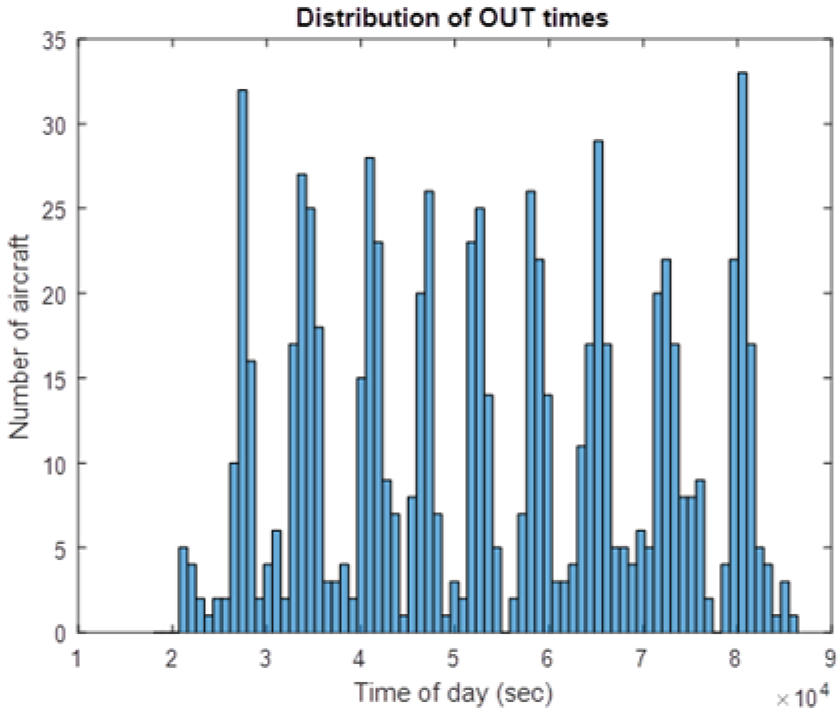


Figure 6-17. Histogram of Pushback Times for August 18, 2014.

The data in the figure indicate that the day starts out the same, but fewer flights go out in the third bank, and more flights go out in the 8^{th} and 9^{th} banks. Looking at the taxi times, there are many more flights with delays of 40 minutes, particularly late in the day.

6.4.3 Analysis

It is recommended that the following analyses and re-analyses of the traffic and weather data be considered:

- **Schedule vs Actual Comparison**. Compare scenario day what-if hold recommendations against airline gate holds delays and delay variability.
- **Extended Analysis**. Analyze the variability in initial climb to fix crossing times (i.e., Departure Fix crossing time – Runway Off time), by airplane type and operator.
- **Arrival and Departures**. Whole traffic patterns should be considered (i.e., arrival and departures) in the definition of the scenario and the utility of Decision Support Tool (DST).
- **Expanded Analysis**. Consider expanding analysis scenarios with conditions such as:
  - Lower visibility weather conditions at CLT;
  - North Flow runway operations;

- Recovery from Ground Stop.

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