Final Report
for
"Methods of Increasing Terminal Airspace Flexibility and Control Authority"

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1 Introduction

This is the 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 September 1, 2014 through October 31, 2015.

The original objectives of this project were to (i) develop concepts and algorithms for making tactical adjustments (e.g., path modifications such as path-stretches or temporal trajectory modifications such as speed adjustments) to strategically planned arrival and departure trajectories, and (ii) test these algorithms in a terminal airspace-airport surface simulation environment modeling real-world instances of an arrival-departure interactions. To support these objectives, the research team first conducted a background literature review of precision methods of arrival and departure management in the terminal area. Then the team reviewed literature and consulted with subject matter experts to identify five high-priority arrival-departure interaction cases that create inefficiencies in today’s air traffic operations. Three interaction cases were from the New York metroplex and two others were from Charlotte Douglas Airport (CLT) and Los Angeles Airport (LAX). The team selected one of the New York metroplex problems for modeling and evaluation, and presented its findings and justifications in a briefing to NASA.

Following identification of the real-world problems, the team was directed to shift its focus to more closely align with the NASA Airspace Technology Demonstration-2 (ATD-2) project. The team was directed to investigate candidate real-world problem at a site other than the New York metroplex, and to focus on planning and management of airport departures, accounting for interactions with arrivals at points on the airport surface and in the terminal airspace. While NASA was considering potential sites for ATD-2 evaluations, the team investigated departure management issues at the Dallas-Ft. Worth metroplex.

NASA ultimately confirmed its focus on the ATD-2 Concept of Operations and its integration with the Federal Aviation Administration’s Surface Collaborative Decision Making (CDM) Concept of Operations, and Charlotte-Douglas International Airport (CLT) as the site for initial ATD-2 evaluations. In consultation with NASA, our team identified a new research objective to develop and evaluate a prototype tool for what-if analysis of candidate Departure Metering Programs (DMPs). The Surface CDM Concept of Operations [5] calls for managing imbalances between scheduled airport traffic and available airport and local airspace capacity through the use of DMPs. During a DMP, departure flights are assigned and managed to Target Movement Area Entry Times (TMATs) to control airport surface traffic levels and improve the transit efficiency of departures. The Surface CDM ConOps calls for a Departure Reservoir Coordinator (DRC) to identify demand-capacity imbalances, to collaborate with stakeholders to design and implement a DMP, and to monitor and adjust DMPs as the airport surface traffic situation evolves. The what-if analysis capability supports the DRC in evaluating and collaborating with stakeholders to specify DMP start and end times, target departure queue lengths, unscheduled demand buffers and other parameters that constitute a particular DMP.

The remainder of Year 1 focused on evaluating three use cases of the what-if analysis capability to specify key DMP parameters: 1) start and end times, 2) target departure queue length, and 3) unscheduled demand buffer. The team specified the use cases for the what-if analysis capability; developed a prototype what-if analysis tool that includes a discrete-time, link-node metroplex simulation capability of departure traffic for the Charlotte metroplex and an emulation of the

ATD-2 scheduling algorithms; incorporated the DMP parameters for the use cases into the ATD-2 scheduling paradigm; and used the prototype what-if analysis tool to conduct initial evaluations of the use cases.

The use case evaluations confirmed that the what-if analysis tool can be extremely useful in detecting forecast traffic level-capacity imbalances, identifying and evaluating the impact of candidate values for different parameters of the DMP, and ultimately designing and implementing a DMP. The use case evaluations also confirmed that the implementation of DMPs leveraging the ATD-2 departure planning and management concepts and tools is effective in reducing average departure delay. In our case, we designed a single DMP of 3 hours to span two distinct, successive demand-capacity imbalance periods, each approximately 1 hour in duration. The DMP was effective in maintaining the total number of departures in the movement and non-movement areas at or below 20 aircraft, in reducing average total departure delay from 11.7 minutes to 5.2 minutes; average taxi delay from 9.9 minutes to 1.9 minutes, and average airborne delay from 1.4 minutes to 0.5 minutes from the baseline condition.

Additional work remains to explore the design of DMP parameters under different traffic and airport conditions; to evaluate the impact of traffic uncertainty on the effectiveness of a DMP; to explore the minimum necessary modeling fidelity for the what-if analysis capability to still be useful; performance metrics and interfaces useful for DMP specification; incorporation of stakeholder considerations in DMP design; policies for managing traffic if DMP thresholds, such as target departure queue length upper and lower bounds, are violated; operational considerations for instituting a DMP; and others.

This report is structured as follows. Chapter 2, Literature Review, summarizes the key findings from the project literature review under the original scope. Chapter 3, Real-world Problem Selection, summarizes the real-world arrival-departure interaction problems recommended for study under the original scope. Chapter 4, Project Direction Change, summarizes the transition to the new scope of work. Chapter 5, What-if Analysis for Departure Metering At Charlotte Airport, describes the new project scope and summarizes the background. Chapter 6, What-if Analysis Tool, describes the what-if analysis tool technical components. Chapter 7, What-if Analysis Use Cases, details the what-if analysis use cases evaluated in this study. Chapter 8, What-if Analysis Evaluations, describes the methodology for and results of using the what-if analysis tool prototype to evaluate the use cases. Summary and future work summarizes the findings and proposes areas for future investigation.

2 Literature Review

The purpose of the literature review was to determine the gaps in current and researched precision methods of arrival and departure management in the terminal area (i.e., methods for tactical control to support real operations in conjunction with NASA's strategic scheduling tools). We reviewed 45 documents in areas including scheduling concepts, schedule conformance, off-nominal situations, evaluations of tools and gaps identified, technological requirements for tools, management of arrival-departure interactions, airport surface traffic management and metroplex operations. A detailed Literature Review Report [1] was developed. The main conclusions from the literature review report are summarized in this section.

2.1 Scheduling Concepts

We reviewed existing strategic scheduling concepts, with a particular focus on the scheduling algorithm within Terminal Sequencing and Spacing (TSAS). Scheduling-based concepts, tools and operations for managing terminal arrivals including a range of navigation capabilities have been studied extensively and are quite mature. Additional research and development is required to extend these methods with path modifications for arrivals in the terminal area to afford a greater range of flexibility and robustness, and to investigate the spacing buffer reductions and resulting throughput benefits that path modification methods might afford. In addition, the concepts are isolated to managing arrival flights; they can be extended to address coordinated scheduling and management of arrivals and departures. To this end, there is a need to investigate operational concepts and scheduling methods for coordinating arrivals and departures, methodologies and criteria for specifying scheduler parameters including scheduling point spacing buffers and flight regime delay distribution, while accommodating the range of aircraft navigation capabilities and performance characteristics in both the arrival and departure flight phases.

2.2 Schedule Conformance

We reviewed existing method and tools for schedule conformance, with particular focus on the Controller Managed Spacing tools within TSAS. Aircraft conformance to terminal arrival schedules depends on a number of factors, including metrics and criteria for assessing conformance; assumptions, design and modeling errors in scheduling; controller tools for monitoring and controlling conformance; operational procedures including phraseology and route structure; and aircraft navigation characteristics and precision. Development of schedule conformance tools and procedures has focused on arrival operations, with speed advisories as the control mechanism for managing conformance. Work remains to extend conformance management methods for arrivals with 3D path-based methods in the terminal area; to develop tools and procedures for managing conformance of departures to scheduled times of arrival and planned trajectories; and to integrate management of arrival and departure trajectories to conform to schedules at arrival-departure coordination points.

2.3 Off-nominal Situations

We reviewed existing NASA tools for managing off-nominal situations in the terminal airspace. Their effect is to severely disrupt the resource utilization schedule and planned trajectories of aircraft. This requires automation tools, in conjunction with operational procedures and controller decision-making, to formulate and adapt to a new schedule with new aircraft trajectories. Further research is required to develop operational frameworks and automation algorithms and methods for addressing off-nominal conditions in a robust manner, which still permits maximizing throughput and flight efficiency, while maintaining reasonable controller workload, under the given conditions. Arrival-departure interactions and required coordination may arise as a result of off-nominal conditions, or approaches for managing nominal arrival-departure interactions may have to address off-nominal conditions. Identifying the off-nominal conditions in either case is a first step.

2.4 Evaluation of Tools

We reviewed human-in-the-loop simulation and field trial based evaluations of these tools. Evaluations of tools to control the trajectories of aircraft to meet time of arrival and inter-aircraft spacing goals have focused on arrival management. Design issues include the impact of the tools on own-ship and proximate traffic flows, including conflicts and flow dynamics; usability of tools from a controller perspective; and tools appropriate for each controller position involved in managing the flight. Significant work remains to investigate appropriate scheduling and conformance management tools for departures in the terminal airspace; to integrate these with airport surface and Center advisory tools; and to integrate these with arrival management tools for coordinating arrivals and departures in the terminal airspace.

2.5 Technological Requirements for Tools

We reviewed technological requirements for enabling the operation of these NASA tools and comparison with today's available technology. Trajectory prediction is fundamental to the model-based predictive control approach to planning and managing air traffic and aircraft trajectories. A significant source of the uncertainty to be addressed in developing scheduling and tactical control methods to coordinate arrivals and departures in the terminal airspace is modeling error. Work remains to compare and contrast the nature of trajectory prediction errors for arrival and departure flights, and to understand their combined effect and resulting requirements on integrated arrival-departure scheduling and conformance management.

2.6 Management of Arrival-departure Interactions

We reviewed recent, ongoing research on strategic and tactical management of arrival/departure interactions. Extensive research has developed optimization-based algorithms for scheduling arrival and departure traffic to shared airspace resources. While research has accommodated uncertainty either in the original formulation or as tactical speed-based adjustments within the framework of the scheduling solution, work remains to evaluate use of these algorithms in a decision support tools used in a dynamic traffic planning and management environment, under a broader range of uncertainties and disturbances. Simpler, heuristic-based scheduling approaches which find near-term opportunities for tactical adjustments to coordinate arrivals and departures, and propose trajectory adjustments for doing so, are more immediately amenable to implementation and evaluation. Tactical speed-based control techniques could be extended with simple local path adjustments to expand the tactical adjustment range. The integration of strategic planning and tactical adjustment systems for coordinating arrivals and departures needs to be explored in greater detail.

2.7 Airport Surface Traffic Management

We reviewed airport surface traffic management research and its relationship with the terminal airspace control authority. Extensive research has been conducted into developing and extending concepts and tools to manage airport surface traffic, in particular to manage departures to reduce the taxi times. Scheduling and management of departure takeoff and terminal airspace transit is an emerging field. Further work remains to more closely integrate airport surface and terminal airspace planning and management of departures. While methods of departure terminal airspace trajectory planning and management to automate the Call For Release procedures have been developed and demonstrated, further work remains to apply and extend these methods to address arrival-departure interactions. Another significant area for further research is planning and management of departure aircraft trajectories in the terminal airspace, and integration with terminal airspace arrival and airport surface traffic planning and management concepts and tools.

2.8 Metroplex

We reviewed multi-airport traffic flow interactions for the metroplex, and proposed concepts and methods for managing those interactions. Methods comprise spatial segregation and time-based coordination. Spatial approaches provide procedurally deconflicted traffic flows, and eliminate the additional operational tools and controller workload of time-based approaches. However, spatial deconfliction methods may introduce significant flight inefficiency. This may be sufficient to justify the operational complexity of time-based coordination. Prototype real-time tools for tactical time-based coordination of multi-airport traffic flows have been evaluated in human-in-the-loop simulations and have shown promise. Strategic scheduling-based tools have also shown promise, although the scheduling algorithms need to be sufficiently robust to trajectory uncertainty.

3 Real-world Problem Selection

The objective of this task was to select five high-priority arrival-departure interaction-cases that create inefficiencies in today's air traffic operations. These would become the candidate problems for which we would develop tactical air traffic management solutions. We were asked to select at least two interaction cases from the New York metroplex along with three others from either metroplex or single-airport environments. The Selection of Real World Problem Report [2] describes the methods used to select high-priority arrival-departure interaction-cases at the top metroplexes and busy airports within the U.S. A summary of this report is provided is this section.

3.1 Methodology

We used a two-step process for comparing and prioritizing arrival-departure interaction-cases at metroplex and single-airport sites within the U.S.

The first step used data analysis to prioritize and down-select metroplexes and airports that together contain a variety of airport/airspace geometry features and operational characteristics suited to the study goals. Special consideration was given to features relevant to arrival-departure-surface interactions. The outcome of this first step was a spreadsheet quantifying the various features by airport and metroplex area. Using this data we identified five sites that were of interest to our study—the New York metroplex, the Charlotte International Airport, the Southern California metroplex, the Atlanta International Airport (along with its neighboring smaller airports), and the Northern California metroplex.

The second step involved identifying and down-selecting candidate interaction-cases from these five areas. Methods used include literature review, SME consultation, operational data-analysis and consideration of work scope and modeling complexity. The literature review summarized problematic traffic flow interaction cases from 17 reports for New York, Charlotte, Southern

California, Atlanta, and Northern California. Reports included site visit notes and FAA Metroplex Program study team reports. SME consultation was supported by distributing a survey document followed by discussions. The survey document provided an overview of the project, the objective of the consultation, a list of questions, and a description of example interactions assembled from literature. The categories of questions included problem verification and identification, problem ranking, problem information, and thoughts on potential problem solutions. Individual questionnaires were created for each site, posing the general questions and listing the problems identified in literature for each site. Based on the literature review and outcomes of the SME consultation, we categorized the candidate interaction-cases by the type and potential impact of interaction and by location. Candidate interaction-cases were then evaluated according to numerous criteria in order to down-select to high priority interaction cases for each site.

3.2 Findings

Table 3-1 summarizes the five interaction cases that were selected as the most significant/relevant.

Table 3-1. Top-Priority Interaction-Cases.

Priority	Interaction-Case Description	Reason for Selecting
1)	**JFK 22R departures interacting with JFK 22L/22R arrivals.** *When JFK uses runway 22R for departures and runways 22L/22R for arrivals, JFK departures have to tunnel under the JFK arrival flow at 5000 feet for 20-25 miles, causing inefficient level-offs for both arrivals and departures.*	• Involves a commonly used runway configuration at JFK. Identified as a medium-priority problem by New York SME • Involves arrival-departure interaction in the airspace • Allows for a potential solution involving time-delay and path-change control authority degrees of freedom relevant to the goals of our project • Ranked first because it is from New York and is a single-airport interaction, which is easier to model in Year 1
2)	**JFK Arrivals on VOR 13L, interact with LGA 13 ILS arrivals and LGA 13 departures.** *When JFK uses VOR 13L approach, the Coney airspace is delegated to this arrival flow 3,000' and below. LGA has to release departures with coordination to the Coney airspace. Coordination is difficult. So, LGA departures usually take an indirect route (turn left and make a full circle) to avoid Coney airspace. Moreover, JFK arrivals from the west have to make a long loop and stay high for longer than optimum to reach runway 13L.*	• Involves arrival-departure interaction in the airspace • Identified as a high-priority problem by New York SME. Solution will provide significant benefit to LGA. For example, when N90 ran this configuration for 5 hours on November 6th 2014, LGA experienced an average delay of 120 min. • Allows for a potential solution involving time-delay and path-change control authority degrees of freedom • Ranked second because it is a two-airport interaction which will involve significant modeling effort and can be better addressed in Year 2 (we will not have literature review and interaction selection tasks in Year 2)
3)	**EWR Arr-22L, Dep-22R; TEB Dep-19: TEB departures interact with EWR arrivals.**	• Involves similar types of problems and potential solutions as the first two problems. • Occurs less frequently.

	TEB departures from runway 19, the longest runway, use a "noise friendly" departure procedure which routes the flight path over an industrial area. This creates interactions between EWR arrivals and TEB departures. In Instrument Flight Rules (IFR), controllers have to build big (~10 nmi) gaps in EWR arrival flows to accommodate TEB departures, which is difficult to achieve. A Visual Flight Rules (VFR) departure procedure was also created (TEB DALTON2) to allow aircraft to depart with less of a spacing requirement (5 Miles) but it still impacts EWR arrivals.	
4)	**CLT runway 18C coupled operations—a truly integrated arrival-departure-surface interaction** *When CLT is in its south-flow configuration, runway 18C is mixed-use. 18C departures have to be coordinated with arrivals on virtually crossing runway 23 besides arrivals on 18C itself. Moreover, arrivals on 18R have to cross active runway 18C to reach their gates. Furthermore, 18C departures have to adhere to call-for-release windows in order to fit into appropriate overhead en route streams. Today's operations involve loose manual coordination for controlling the sequence of operations on 18C. The FAA has recently suspended operations to runway 5/23, reducing the arrival capacity at CLT.*	• Involves multiple types of airspace/runway system interactions—arrival-arrival, arrival-departure, departure-overhead stream • Commonly used configuration at CLT (used ~70% of the time). Interactions severely restrict the optimum usage of available runway capacity • Different type of interaction as compared to all others listed in this table and studied by NASA in the past —a truly integrated arrival-departure-surface interaction • Allows for a potential solution involving time-delay and path-change (in air and on surface)—the control authority degrees-of-freedom relevant to the goals of our project • NASA has interest in analyzing IADS problems at CLT
5)	**LAX runway system interactions** *LAX lacks taxi holding areas between the runways in each of its parallel runway pairs. LAX usually uses inboard runways for departures and outboards for arrivals. But, large aircraft are forced to land on inboard runways due to the lack of space to hold them between parallels. This causes the operations on the two runways in each pair to be coupled to one another. Also makes the LAX flows highly sensitive to disruption.*	• Involves two types of runway system interactions—arrival-arrival, arrival-departure • Common problem in all runway configurations at LAX. Interactions severely restrict the optimum usage of the available runway capacity and also cause safety concerns • Different type of interaction as compared to all others listed in this table and studied by NASA in the past • Allows for a potential solution involving time-delay and path-change (in air and on surface)—the control authority degrees-of-freedom relevant to the goals of our project

Our recommendation for selecting three cases were based on NASA research goals.

- For a goal of developing a higher Technology Readiness Level (TRL) solution and progress to human-in-the-loop (HITL) simulations by the end of this three year project, we recommended selecting interactions 1), 2), and 3). These three are similar in terms of the nature of the involved interaction and potential solution(s). This approach would allow extra time to focus on increasing the TRL of the proposed solution.

- For a goal of evaluating a comprehensive solution that can address multiple types of interaction cases, which will result in a lower TRL, we recommend the selection of three dissimilar interaction cases: 1), 4), and 5). In this case, the focus would be on generating innovative and comprehensive trajectory control concepts rather than a higher-level TRL solution.

4 Project Direction Change

At this point in the project NASA requested a change in direction in order to ensure better alignment with NASA's near-term goal of field-testing an integrated arrival-departure-surface (IADS) traffic management capability under the ATM Technology Demonstration-2 (ATD-2) project. This change in direction included two areas of focus: (1) select a candidate site for real-world problem selection that aligned with ATD-2, and (2) investigate strategic and tactical planning of airport departures while accommodating arrivals as a scheduling constraint. Because the initial site for NASA's ATD-2 efforts was unknown, we were directed to Dallas-Ft. Worth as a surrogate site for investigating candidate problems of the tactical control of departures.

We conducted supporting research and then held a series of interviews with Greg Juro of the Dallas-Ft. Worth TRACON (D10) to identify candidate tactical departure control problems to focus our research and development efforts. Types of problems considered in the interviews coincided with the categories identified as part of the NASA IADS concept: out-bound tactical departure scheduling problems, including merging departures from multiple airports at departure fixes and major airport departures merging into busy en route traffic flows; inbound tactical departure scheduling problems, including destination airport arrival scheduling constraints; Traffic Management Initiatives (TMIs) including Miles-In-Trail (MIT) restrictions and national TMIs such as Ground Delay Program (GDP) Expected Departure Clearance Time (EDCT) time windows and Traffic Flow Management (TFM) reroutes; arrival-departure or departure-departure crossing or interacting flows; and airport surface traffic management, including surface congestion and interactions with arrivals.

The detailed findings from this series of interviews are documented in [3]. The interviews identified a broad range of complexities in managing departures in the D10 TRACON. Regarding out-bound departure scheduling, merging departures into en route traffic flows is managed by Call-For-Release (CFR) implemented by D10, Miles-In-Trail restrictions, or a specified departure time controlled by the ARTCC. Departure fixes are shared among Dallas-Ft. Worth airport (DFW), Dallas Love (DAL), Addison (ADS), Meecham (FTW) and Alliance (AIA). Manual management of departures to merge at fixes is inefficient from throughput, flight efficiency and controller workload facets; a tool to specify takeoff times to merge departures would be very helpful. Regarding TMIs, manual coordination to fill slots as per a given MIT is challenging. Resolving multiple MIT restrictions, EDCTs and other restrictions impacting a single flight, and coordinating different MIT restrictions among different flights in managing departures is also challenging.

Following the investigation of real-world tactical departure control problems at DFW, Charlotte Douglas International Airport (CLT) was selected as the focus site for ATD-2 evaluations. At this point we collaborated with NASA to focus our work on CLT and to develop a tactical decision support capability to perform real-time what-if analyses to support the functioning of the ATD-2 traffic management tools.

5 What-if Analysis for Departure Metering at Charlotte Airport

ATD-2 aims to improve predictability and operational efficiency of air traffic in metroplex environments by enhancing existing and developing new arrival, departure and surface prediction, scheduling and collaborative decision making systems and integrating them in a single, state-of-the-art traffic management system [4]. The eventual objective is to demonstrate this state-of-the-art traffic management system via human-in-the-loop (HITL) simulations and/or field evaluations, and transfer the component technologies to the FAA. The operational environment for ATD-2 IADS metroplex traffic management concept includes a primary TRACON (CLT TRACON), consisting of a major, well-equipped airport and multiple satellite airports that are less-equipped. A well-equipped airport will typically have sophisticated automation aids such as surface traffic surveillance in the FAA towers as well as in ramp towers, and would be subject to heavy traffic demand including flights from multiple major airlines. The less-equipped airports will typically not have surface surveillance and are subject to smaller demands with smaller percentage of commercial air traffic from the major air carriers.

Within this operational environment, the ATD-2 traffic management tools' focus is on improving the coordination between departures to enable efficient merging and metering of departure flows at the key exit-points of the TRACON (departure-fixes) and merge points into overhead en route traffic streams. In addition, the tools will enhance adherence to metered departure times from the primary TRACON airports, where the metered departure times are provided by a time-based metering system such as Traffic Management Advisor (TMA) at destination airports outside the TRACON (perhaps even multiple centers away from the TRACON). The control points for the ATD-2 traffic management tools may include gate pushback (by providing Target Off Block Times, TOBTs, to airline ramp controllers), movement area entry (by providing Target Movement Area Entry Times, TMATs, to the Ground Controller(s)) and runway takeoff (by providing Target Takeoff Times, TTOT, to the Local Controller) at the well-equipped airport and runway takeoff at the less-equipped airports (by providing TTOTs to the Local Controller).

In addition to NASA's research into new IADS traffic management tools, the FAA has also developed a Surface Collaborative Decision Making (CDM) concept [5], which will enable U.S. airports to make optimal use of available airport capacity. This concept addresses the need for timely sharing of relevant operational data among Surface CDM Stakeholders to improve situational awareness and predictability through a common understanding of "real" airport demand and continuous predictions of demand/capacity imbalances. At the core of this concept is a set of well-defined capabilities and procedures which facilitate the proactive management of airport surface traffic flows and runway departure queues to equitably optimize local airport capacity and shared NAS resources. Although the FAA's Surface CDM concept specifically addresses improvements in the way traffic is managed on the airport surfaces, it can be applied to traffic management tools such as ATD-2 that control traffic on the airport surface with the objective of improving terminal airspace traffic efficiencies. NASA plans to develop, test and deploy the ATD-2 tools while adhering to the concept of operation outlined by the FAA.

One of the key capabilities included in the FAA's Surface CDM Conops is the efficient strategic management of departure queues and flows on the airport surface. This capability leverages improved situational awareness via data exchange (which is another capability included in the Surface CDM concept) for accurate prediction of demand and capacity imbalances, notification of predicted imbalances to stakeholders, and implementation of Departure Metering Procedures or Programs (DMPs) to equitably allocate constrained NAS resources among stakeholders. DMPs include a specific set of functions, such as assignment of Target Movement Area entry Times (TMATs) and all associated processes and procedures. Conceptually, a DMP is very similar to a Ground Delay Program (GDP), which is currently implemented by the FAA's System Command Control Center (ATCSCC) in order to manage arrival traffic flows into constrained airports. The objective of a GDP is to absorb as much delay as possible on the surface at the origin airport rather than in the air (because that is more safe and fuel-efficient), while at the same time not creating unnecessarily large delays and under-utilization of available arrival airport capacity. Similarly, the objective of the DMP is to absorb as much delay as possible at the gates (or at a holding location in the ramp or movement area) rather than in a departure taxi queue because it is more fuel efficient (since the engines are off) and convenient (because passengers can wait in the airport terminal area rather than inside an aircraft).

As in a GDP, the DMP is characterized by multiple tactical parameters such as:

- DMP start and end times,
- Target Departure Queue Length (TDQL—when a DMP is active metering times are assigned to all flights included in the DMP in order to maintain the length of the departure queue at TDQL so that sufficient pressure is maintained on the departure runway) and associated upper and lower thresholds,
- Unscheduled Demand Buffer (UDB—in order to account for uncertainty, future departure demand predictions include estimates of the amount of unscheduled demand still unknown to the system in the form of UDB. UDB represents an estimate of the number of unscheduled departures expected every hour while the DMP is active), and
- Other including planning horizon, TMAT compliance window strategic parameter, etc.

Inherent to the concept of a DMP is a new controller/coordinator position called the Departure Reservoir Coordinator (DRC). The DRC will typically decide when departure metering should be in effect and will also determine appropriate values for the parameters of a DMP in real-time.

A key component of the Surface CDM Conops is a what-if analysis capability which allows all stakeholders to perform automated analyses to determine the impacts of the decisions that the stakeholders are considering. Since the DRC has to evaluate many different factors while making real-time decisions about the values of different DMP parameters, the DRC will significantly benefit from an automated what-if analysis capability for determining the impact of using different candidate values for DMP parameters, such as the TDQL and UDB, on the DMP's performance. The main decisions from the perspective of the DRC are related to the choice of appropriate values for the DMP parameters. For example, before accepting or rejecting a recommended DMP, the DRC may be interested in testing out the impact on key performance indicators (such as taxi times, gate delays, runway throughput, fuel consumption, and others) of implementing a DMP with different start-times or different Target Departure Queue Lengths, or not implementing the DMP at all.

The revised goal for Year 1 of this project was to develop a what-if analysis capability to help the DRC in determining optimal choices for certain parameters of the DMP, under which ATD-2 tools will actively manage the traffic on the surface of the CLT airport and also exercise coarser control on neighboring satellite airport departures. The concept for the What-if Analysis capability is described in the Concept Description Report [6]. In addition to developing the what-if analysis capability, we tested it under three use cases. The use cases capture key parameters, among others, that the DRC will have to specify in designing a DMP:

- Use case #1: DRC determines the appropriate start time and end time for a DMP, before accepting (or rejecting) the DMP.
- Use case #2: DRC determines the appropriate Target Departure Queue Length (TDQL).
- Use case #3: DRC determines the appropriate Unscheduled Demand Buffer (UDB).

In each use case, the DRC uses the what-if analysis capability to evaluate the airport traffic impact of a particular parameter value (or range of values) based on appropriate performance indicators. The DRC iteratively specifies, evaluate and adjust the DMP parameter until settling on a value which he/she, in collaboration with other stakeholders, determines to give reasonable airport traffic flow performance. Each use case is described in the following section.

6 What-if Analysis Tool

The objective of the what-if analysis tool is to allow the DRC to evaluating airport traffic under baseline conditions over a prescribed future time horizon, detect demand-capacity imbalances, evaluate the impact of different DMP parameters, communicate findings to stakeholders, and ultimately design a DMP to efficiently manage the demand-capacity imbalance.

The what-if analysis tool is a fast-time simulation including four technical components: (i) airport surface and terminal airspace departure traffic simulation, (ii) emulation of ATD-2 departure scheduling algorithms, (iv) automatic evaluation over multiple combinations or ranges of parameters, and (v) performance metrics calculation and display. To enhance the modeling fidelity of the fast-time simulation platform, physics-based high-fidelity modeling of departure airborne trajectories provides accurate representation the transit time and fuel burn variability of departure flight from the airport runway to the departure fixes.

The figure below depicts the core components of the what-if analysis tool: the airport surface and terminal airspace departure traffic simulation, the ATD-2 scheduling algorithms, along with the what-if analysis process: Simulation of baseline traffic, ATD-2 traffic scheduling under specified DMP parameters, and simulation of traffic under the DMP.

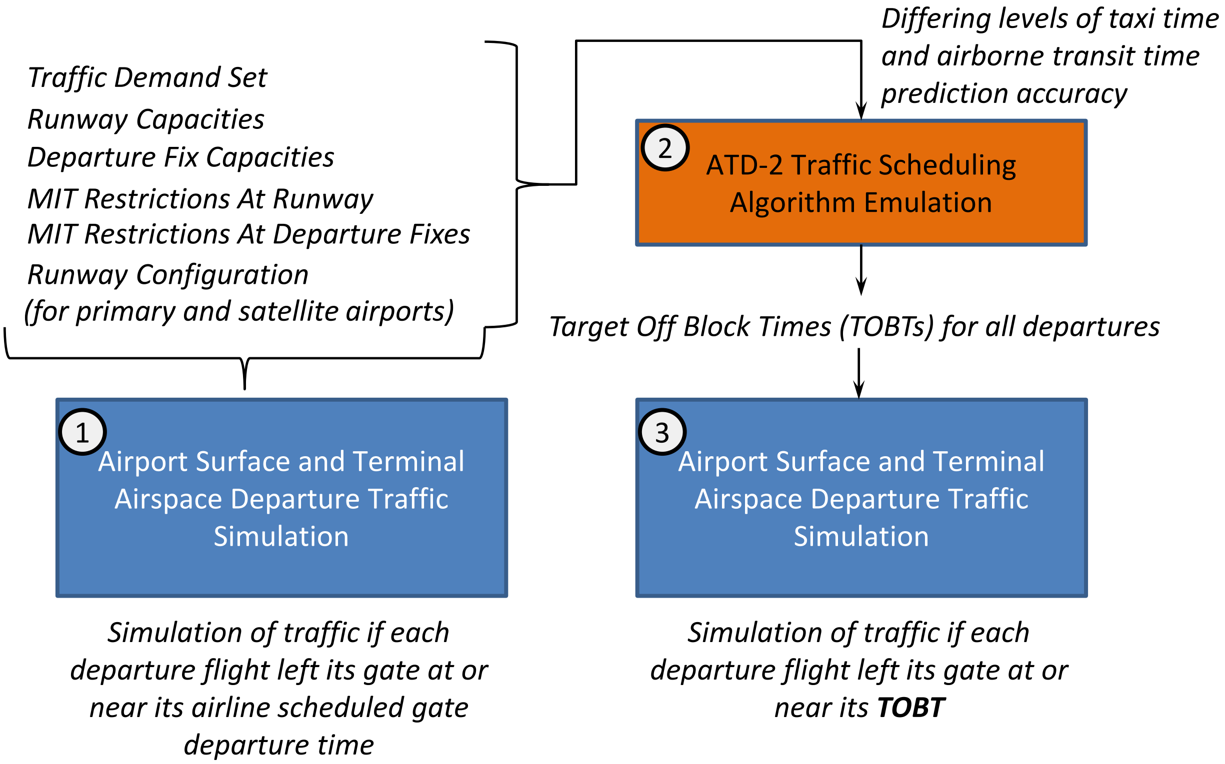

Figure 1. What-if Analysis Capability Components and Process.

What-if analysis relies on numerous input parameters for the ATD-2 primary airport and its interacting satellite airports to obtain accurate estimates of departure traffic over the prescribed time horizon. These include scheduled traffic, including scheduled gate departure times and destination airport or route information; anticipated airport runway configuration and departure rates; and anticipated departure fix separation minima and Miles-In-Trail restrictions at the fix and the runway.

In Step 1 of the what-if analysis process, the DRC uses the airport surface and terminal airspace departure traffic simulation to evaluate airport traffic under baseline conditions over a prescribed future time horizon. In the baseline simulation, aircraft push back near their scheduled gate departure times, and traffic management is performed on a first-come, first-serve basis. Performance metrics calculation and display helps the DRC evaluate departure traffic performance, detect demand-capacity imbalances, and specify initial DMP parameter values. In Step 2, the DRC applies the emulation of the ATD-2 scheduling components to compute Target Off Block Times (TOBTs) for departures under specified DMP parameters. The TOBTs account for the breadth of downstream constraints and traffic impacting each departure. In Step 3, the DRC uses the fast-time airport surface and terminal airspace departure traffic simulation to evaluate airport traffic under the DMP, which applies the ATD-2 scheduled gate pushback times to those flights in the DMP. Automatic evaluation over multiple combinations or ranges of parameters supports evaluating a range of DMP parameter values. Performance metrics calculation and display helps the DRC evaluate departure traffic performance and to select the optimal DMP parameter values.

6.1 **Airport Surface and Terminal Airspace Departure Traffic Simulation**

The objective of the airport surface and terminal airspace departure traffic simulation is to provide a fast-time simulation of the surface and terminal airspace traffic for the ATD-2 primary airport and its interacting satellite airports over a prescribed future time-horizon. This provides the means for the DRC to evaluate, in real-time, the airport traffic under baseline conditions, detect demand-capacity imbalances, evaluate the impact of different DMP parameters, and ultimately design a DMP.

The current implementation of the airport surface and terminal airspace departure traffic simulation is a discrete-time simulation using link-node models. Spatial routes for departures from their gates to their entry points to the en route airspace are modeled as sequences of nodes and links. Link transit time models propagate flights to successive nodes. Node queue management models manage the entry and exit of flights into and out of the nodes. Each element is described in the following sections.

6.1.1 Link-Node Models

Link-node models provide a low-to-medium fidelity representation of the airport surface including the gate, ramp, movement area and runway system; the terminal airspace including the terminal area departure fixes and en route traffic stream merge-points; and interactions with satellite airport departure traffic. The models can be tailored to adjust the level of modeling fidelity required for a particular what-if analysis. For example, two parallel, independent departure runways could be modeled as individual runway nodes with representative runway departure capacities, or could be modeled as a single runway node with a representative airport departure capacity.

For each airport model, the route of each flight is modeled as a sequence of four nodes connected by three links. The nodes and links are depicted in the figure below.

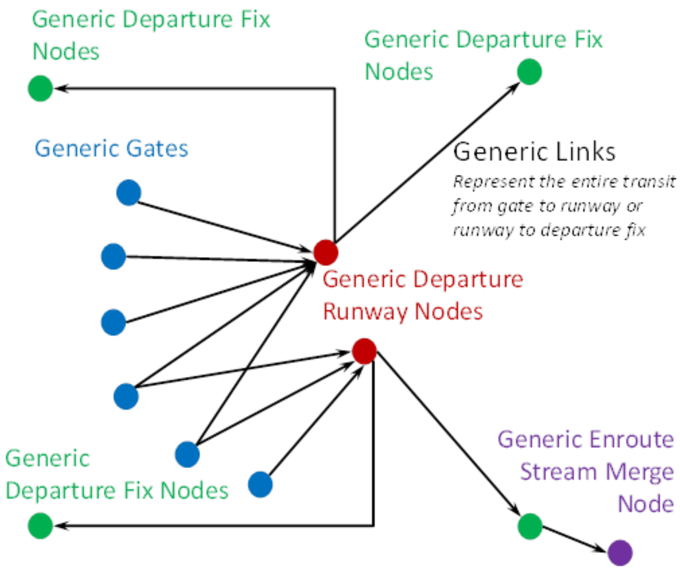

Figure 2. Generic Representation of Airport-Terminal Model.

The four nodes are (1) one complex node representing a group of gates, (2) one simple node representing the departure runway, (3) one simple node representing the departure fix, and (4) one simple node representing the en route merge point. The three links are (1) one link connecting the gate-group node to the departure runway node, (2) one link connecting the departure runway node to the departure-fix node, and (3) one link connecting the departure fix node to the en route stream merge point node.

Flight movement along the links is governed by transit time models, and flight movement through nodes is governed by queue management models. The sequence of link transit time and node queue management models is depicted in the figure below.

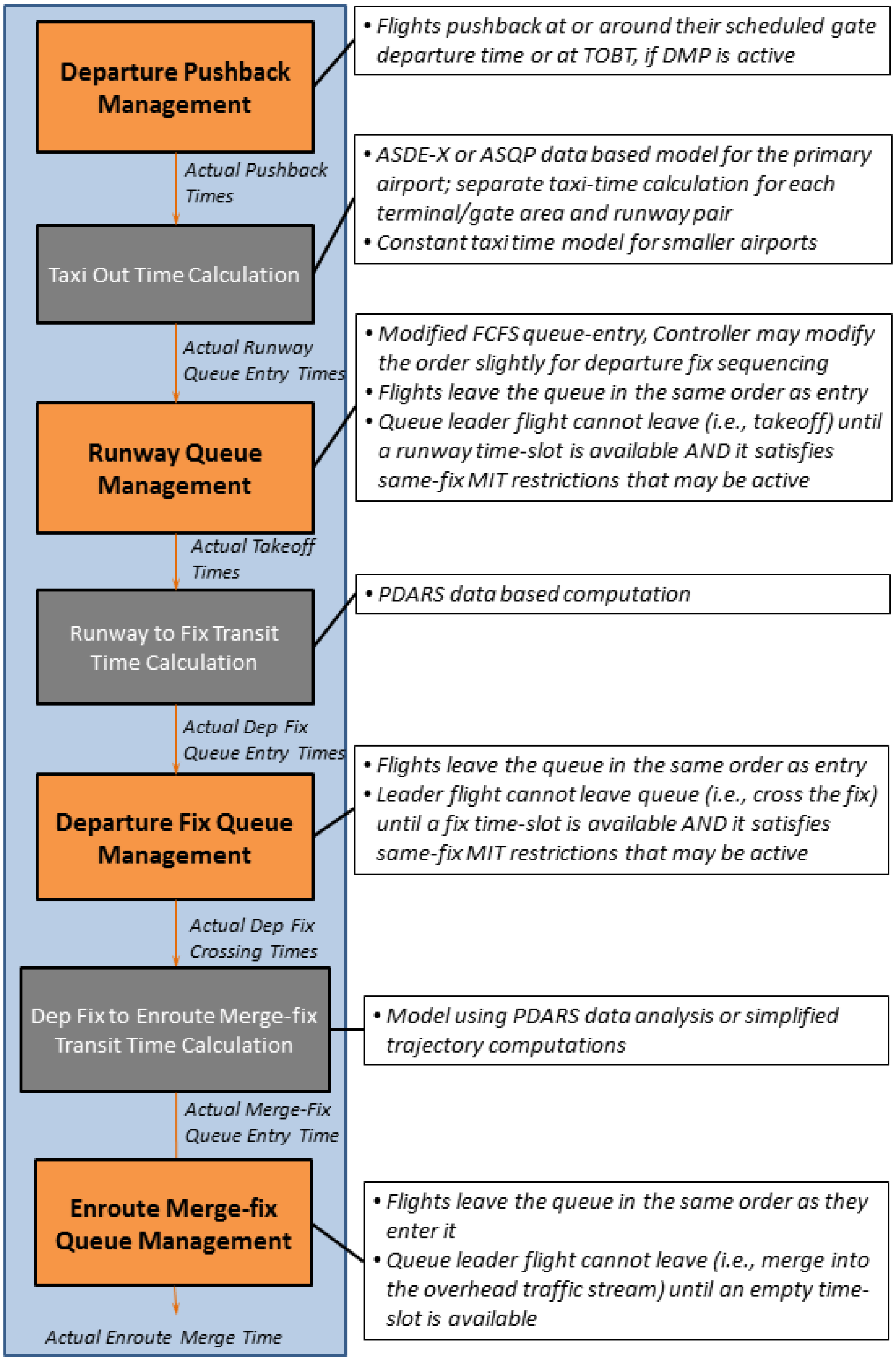

Figure 3. Sequence and Key Features of Link Transit and Node Queue Management Models.

Queue management models apply minimum separation criteria, traffic flow gap availabilities, and traffic control mechanisms particular to each node. These separation criteria, gaps and control mechanisms determine flight entry into and exit from the queue, hence the propagation of each flight through the simulation. Pre-defined time slots are the basis for modeling the minimum separation and gaps at each node. The transit time and queue management models are described in the following sections.

6.1.2 Link Transit Time Models

Each link has a distinct transit time model. Taxi-out transit time models apply to the link joining each gate-group node to the departure runway node. Departure trajectory transit time models apply to the link joining the departure runway node to the departure fix node. En route transit time models apply to the link connecting the departure fix to the en route stream merge point.

Two taxi-out transit time models are currently implemented: a “Fixed” lower-fidelity model and a “X Percentile” higher-fidelity model. The Fixed model applies to satellite airports which do not have surface surveillance and do not report taxi times to the Bureau of Transportation Statistics (BTS) for inclusion in the Airline Service Quality Performance System (ASQP) database. For the Fixed model, each airport departure is assigned the same fixed taxi-out time. The X Percentile models apply to major airports with historical recorded taxi-out time data recorded in the ASQP database. Using airline as a proxy for gate groups, the X-th percentile taxi-out time is computed from the distribution of taxi-out times obtained from the ASQP database for the respective gate-group and departure runway pair.

Two departure trajectory transit time models are currently implemented: a low-fidelity model and a high-fidelity model. The low-fidelity model is derived from the straight-line airport-to-fix distance, with a scaling factor to model the indirect flight path, and assumed transit speed of 250 knots. The high-fidelity model is derived from high-fidelity simulations of the departure trajectories of a Boeing aircraft under various conditions. The high fidelity simulations and approaches to implementing the high-fidelity model are discussed in Section 6.1.5.

One low-fidelity enroute transit time model is currently implemented. The low-fidelity model is derived from the straight-line departure fix-to-merge point distance and assumed transit speed of 250 knots.

6.1.3 Node Queue Management Models

Each node has a distinct queue management model. The queue management model at each of the four key control points—the gate (gate group), the departure runway, the departure fix, and the en route stream merge fix—manages the entry and exit of individual flights to and from the queue, and their resulting entry and exit times. These queue management models are departure gate pushback, runway queue, departure fix queue, and en route stream merge point queue. In each queue, flights are first-in, first out.

Departure gate pushback management assigns the actual gate pushback time (gate queue exit time) of a flight. The model identifies which flights are ready for pushback in a given time step based on their pushback readiness times. Under simulations of baseline operations, a flight’s pushback readiness time is its airline scheduled gate departure time, perturbed according to a stochastic model of the pre-pushback process. Under simulations of the DMP, a flight’s pushback readiness time is its Target Off Block Time (TOBT)—the gate pushback time scheduled by the ATD-2 departure scheduling capability. Currently this time is not perturbed by a scheduled gate departure meet time accuracy model. Flights with pushback readiness times in this time step are assigned an actual gate pushback time and exit the gate group node queue.

Runway queue management determines the actual runway queue entry time and actual runway queue exit time (takeoff time) of each flight. A flight's actual runway queue entry time is the later of (1) its gate exit time plus its taxi out time, or (2) its Approval Request (APREQ) time. Runway queue management models the APREQ process for merging departures into en route streams of traffic at the modeled en route merge points. Slots for departures in the en route streams are modeled according to a user-specified slot availability rate and a Poisson process to identify available slots as per this rate. For a flight subject to an APREQ, runway queue management searches for the first available time slot for the flight at its en route merge point, and back-propogates this via the link transit time models to estimate its actual runway queue entry time.

Runway queue management assigns a flight an actual runway queue exit time according to (1) separation at the runway and (2) separation as per the departure fix. Separation at the runway corresponds to the user-specified airport departure rate. Separation at the departure fix corresponds to user-specified Miles-In-Trail (MIT) restrictions applied to consecutive flights from the same runway to the same departure fix. While each successive flight in the runway queue in a given time step satisfies these criteria, each is assigned an actual queue exit time (runway takeoff time).

Departure fix queue management determines the actual departure fix queue entry time and actual departure fix queue exit time of each flight. A flight's actual departure fix queue entry time is either (1) its takeoff time plus its departure trajectory transit time, or (2) the earliest time after that to satisfy minimum in-trail spacing with the previous flight to have crossed the same fix. In turn, once the flight enters the queue, it is assigned an actual departure fix crossing time.

En route merge fix queue management determines the actual en route merge fix queue entry time and actual en route merge fix queue exit time of each flight as per slot availability. Slots are available as per the user-specified slot availability rate and a Poisson process to identify available slots as per this rate. Once flights exit the en route merge fix queue, they have completed their simulated transit.

6.1.4 Adaptation to Charlotte Metroplex

Adaptation of the what-if analysis capability to the Charlotte metroplex included generating link-node models that capture the gates and runways of the airports and the departure fixes and the en route merge points of the airspace as nodes, and the transit times of the associated links.

The current implementation of the what-if analysis capability includes CLT as the primary airport and seven other satellite airports identified from the FAA Optimization of Airspace & Procedures in the Metroplex (OAPM) Study Report on the CLT metroplex [7]. The satellite airports are Concord Regional (JQF), Charlotte-Monroe Executive (EQY), Spartanburg Downtown Memorial (SPA), Hickory Regional (HKY), Gasontia Municipal (AKH), Rock Hill (UZA) and Statesville Regional (SVH).

Departure fixes were defined based on review of literature and evaluation of the Standard Instrument Departure (SID) procedures for CLT [5]. In the evaluation of the SIDs, the departure fixes were selected as the last point in the SID, and/or as a waypoint common among the SIDs of multiple airports. For example, for the Charlotte metroplex, each departure fix was selected as the last waypoint in the Area Navigation (RNAV) SID for CLT. These departure fixes also had the same name as the SID.

Each departure flight was assigned to the departure fix closest in bearing to its destination airport, relative to the origin airport. The bearings of the departure fix and of the flight's destination airport, relative to the origin airport, were computed using a method described and demonstrated in [8]. This method uses a reference latitude/longitude for the origin airport, and the latitude/longitude for the fix or a reference latitude/longitude for the destination airport, to compute the bearing of the fix or destination airport relative to the origin airport. The coordinate system assumes true north as the zero reference and clockwise as positive for bearing. A bearing is computed for each fix a priori. Then the bearing of each flight's destination airport is computed, and the departure fix closest in bearing to that of the flight's destination airport is assigned to the flight.

The transit time for each departure flight from its takeoff runway at the airport to its assigned departure fix was computed from the distance between the airport and the departure fix and an assumed transit speed. The distance between the airport and the departure fix computed as the product of the fundamental geometric distance and a distance scaling factor. The fundamental geometric distance was based on a straight-line ground track from the reference point for the airport to the fix, and a geometric vertical flight profile to reach 10,000 feet Above Ground Level (AGL) at the particular fix. The distance scaling factor was a user-configurable parameter, the value of which was specified by comparing the cumulative distance of the flight legs of the longest route in a SID to the measured straight-line distance from the airport reference point to the end point of the SID. A scaling factor of 1.2 was used based on the CLT MERIL7 SID, for which the cumulative distance was 91.2 nautical miles and the straight-line distance was 78.1 nautical miles. For each combination of origin airport and departure fix, the transit distance was computed as the product of the geometric distance for the given airport-fix pair and the distance scaling factor of 1.2. The transit speed between the airport and the departure fix was assumed to be 200 knots, an intermediate value between the takeoff speed and the speed limit of 250 knots at or below 10,000 feet in terminal airspace.

En route merge points could not readily be determined from literature review. Merge point(s) were allocated to a location corresponding to a point15 minutes away (based on the transit time model) from one or more heavily used departure-fixes.

The table below summarizes the modeling characteristics for the Charlotte metroplex:

Table 6-1. Charlotte Metroplex Modeling Assumptions.

Primary Airport	Satellite Airports	Departure Fixes	Enroute Merge Points	Departure Fix-Merge Point Mapping	Airport-Merge Point Mapping	Taxi-time Model
CLT	JQF	NALEY, MERIL, LILLS, ANDYS,	CLT_GATE	MERIL – CLT_GATE	CLT – CLT_GATE	CLT – airline specific, Others -

		ZAVER				simple

In addition, constraining miles-in-trail restrictions were modeled on certain departure fixes. The table below summarizes the departure fix constraints modeled for the Charlotte metroplex.

Table 6-2. Departure Fix Capacity Constraints and Miles-In-Trail Restrictions for the Charlotte Metroplex.

Airport	Departure Fixes Impacted By MIT Restrictions Per Metroplex	MIT Restriction Details
CLT	MERIL and NALEY*	10 MIT for CLT 60 MIT for satellite airports**

*50% departure fix capacity degradation modeled from 17:00 to 21:00 UTC

**All MIT restrictions active 17:00 to 21:00 UTC

6.1.5 Departure Trajectory Modeling

The trajectories of departure aircraft transiting the TRACON airspace can be difficult to predict and exhibit great variability [10]. Inaccurate trajectory prediction and variability in trajectory execution can be detrimental to the effectiveness of the ATD-2 time-based scheduling approaches to planning and managing departure traffic. We conducted high-fidelity simulations under varying conditions to capture and model the transit times between the airport departure runway and the departure fix or departure gate, including the variability in those transit times. The resulting departure trajectory models serve to assess the impact of transit time variability on the effectiveness of ATD-2 scheduling and DMPs, and to develop scheduling approaches robust to departure trajectory uncertainty.

We used the avionics test benches of Boeing to model the departure trajectories of an aircraft at a high level of fidelity, with proprietary aerodynamic and engine data, coupled with a input/output (I/O) system that interfaces with the avionics hardware suite (e.g., the Flight Management System (FMS), Displays, Autopilot, Traffic Collision Avoidance System (TCAS), and other components). The models were used to assess the primary effects on departure trajectory transit times, speed and altitude profiles, and fuel burn.

We selected the MERIL7 Area Navigation (RNAV) Standard Instrument Departure (SID) published at Charlotte/Douglas International airport (CLT) and the Boeing 737NG aircraft platform as the basis for departure flight simulations. Simulations evaluated departure flight long MERIL6 runway transitions for RW18L and RW18R, which leverage Course-to-Fix (CF) and Direct-to-Fix (DF) flight legs, respectively. The SID is depicted in the figure below.

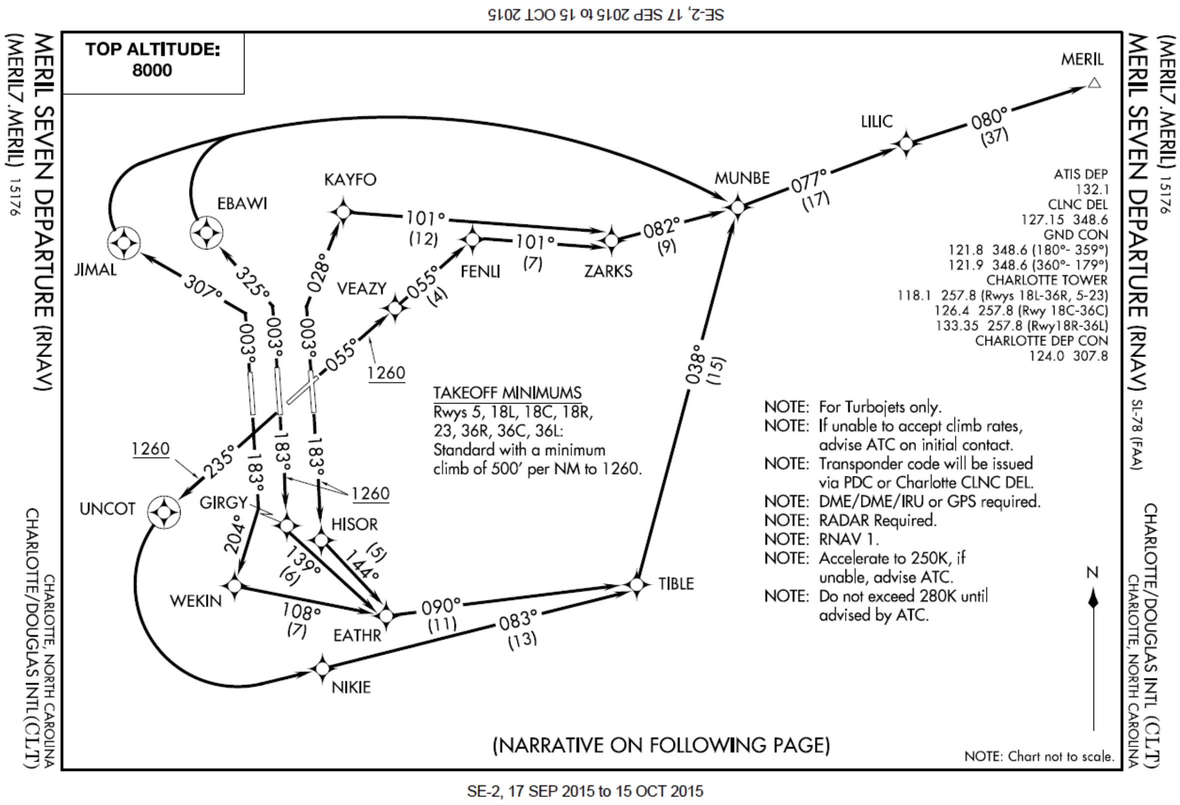

Figure 4. The MERIL 7 SID.

We evaluated the impact of the following operational parameters on the departure trajectories: Aircraft weight, power derate setting (derates or “quiet” settings), cost index (for Vertical Navigation (VNAV) departures), winds (actual and predicted, if entered in the FMS), temperature, flight procedure (e.g., landing gear and flap deployment schedules), and vertical/speed guidance mode (e.g. Flight Level Change (FLCH), vertical speed, VNAV). The maximum weight was for the maximum takeoff weight (MTOW) and the minimum weight was based on a representative light payload based on low load factor (e.g., 30%) with corresponding fuel for a short-leg flight. The cost index was based on typical airline procedures for using fast, economical and nominal settings.

We evaluated the departure trajectories of 94 separate permutations of departure conditions from initial runway departure through achievement of cruise altitude at 35,000 feet. For each run, aircraft state data of transit time, altitude, calibrated airspeed, ground speed, rate-of-climb and fuel burn were recorded at each major waypoint and archived at 1 sec intervals. Table 6-3presents an example of the aircraft state data captured at the HISOR waypoint for the run condition of aircraft initial weight of 133,000 pounds (a medium weight condition) and cost index of 500 with the aircraft departing from runway 18L and executing a 10-minute level off (per the SID).

Table 6-3. Example Aircraft State Data at Waypoint HISOR for One Evaluation Case.

Waypoi	Time, Second	Altitude	Calibrat ed Air	Ground Speed,	Fuel Burn,	Ground Distanc	Flight path	Rate of Climb,

nt	s	, Feet	Speed, Knots	Knots	Pounds	e, Nautical Miles	Angle, Degree s	Feet Per Second
HISOR	115.0	4087.7	168.5	177.0	526.	3.9	8.0	42.1

The aircraft state data obtained from the high fidelity simulations is the basis for modeling departure trajectory uncertainty in the airport surface and terminal airspace departure traffic simulation and the traffic simulation and the ATD-2 departure traffic scheduling emulation. In the simplest implementation, the transit time may be modeled as a Gaussian process with a mean and standard deviation derived from the extent of the simulation results, simply to model departure trajectory variability and assess its impact on scheduling and traffic management. A histogram of the transit time data obtained from the departure trajectory simulations, depicted below, indicates a more complex probability distribution, such as log-log, is required to more accurately model the transit times:

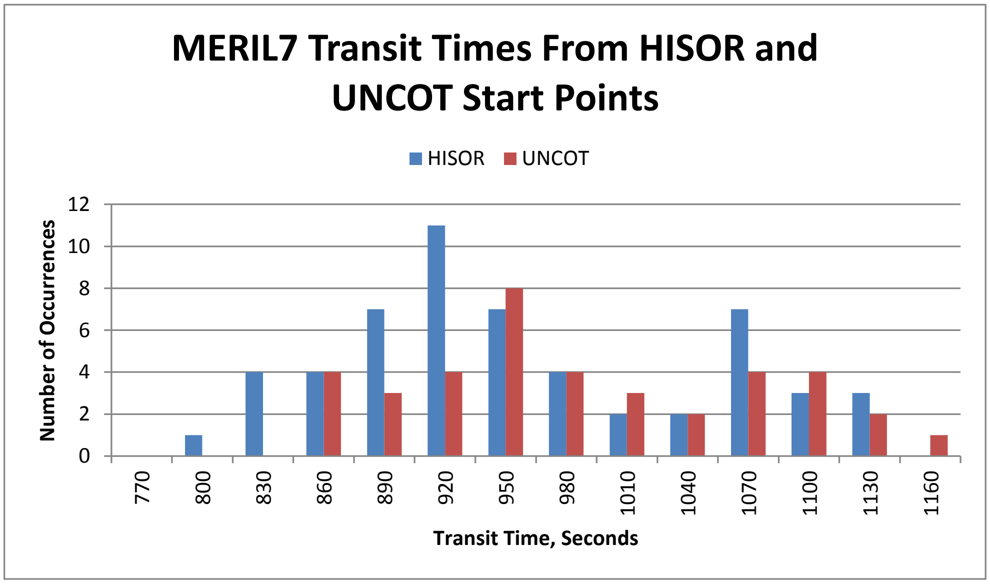

Figure 5. Histogram of MERIL 7 Transit Times From Departure Trajectory Simulations.

In turn, the transit time results for the MERIL 7 SID may be scaled to the other SIDs to distinctly model the transit time and variability to each departure fix. The table below depicts a simple distance-based approach to scaling the mean and standard deviation of the MERIL7 SID transit time data to other waypoints

Table 6-4. Distance-based Approach to Scaling MERIL7 Transit Time Results to Model Other SIDs.

SID-Starting Waypoint	Flight Leg Distance, nmi	Distance Ratio	Transit Time Mean, Seconds	Transit Time Standard Deviation, Seconds
MERIL7-HISOR	88.99	1.00	943.2	87.4

MERIL7-UNCOT	94.34	1.06	999.9	92.7
ANDYS8-GIRGY	51.82	0.58	549.2	50.9
ZAVER3-HISOR	72.47	0.81	768.1	71.2
JACAL7-HISOR	100.96	1.13	1070.0	99.2
LILLS7-HISOR	52.5	0.59	556.4	51.6

6.2 **ATD-2 Scheduling Algorithm Emulation**

The ATD-2 scheduling algorithm emulation performs metroplex-wide departure scheduling control of flight-timings at multiple departure runways, multiple commonly-shared departure fixes, and multiple en route stream merge points. With a focus on practicality rather than optimality, the scheduling algorithm is based on that used in NASA's Terminal Management Advisor (TMA) decision support tool [11]. The *arrival* scheduling principles in TMA are equally applicable to the metroplex *departure* scheduling problem. That is, traffic flows originating from multiple source metering locations (runways for departures; arrival-fixes for arrivals) converge at multiple sink metering locations (departure fixes for departures; runways for arrivals).

For the sake of practicality and fairness, we use Ration-by-Schedule (RBS) scheduling method which uses airline-scheduled times to assign time-slots for each flight at the runway, the departure fix and the en route merge fix. The scheduling algorithm uses a sequence-conserving scheduling strategy to compute Target Takeoff Times (TTOTs), Target Fix Crossing Times (TFXTs) and Target Enroute Merge Times (TEMTs). Departure aircraft Estimated Takeoff Times (ETOTs) are first spaced with respect to each other by allocating one aircraft to one runway time slot to create a sufficiently spaced schedule of departures from each of the interacting airports. The next step is to fix the order and timing of departure fix crossings for each of these departure aircraft. The aircraft enter the departure fix scheduling process based upon an Order of Consideration (OOC). To compute the OOC, aircraft with similar scheduling characteristics (engine type, departure runway and assigned departure fix) are first classified into groups called stream classes. Aircraft within a single stream class are sequenced at the departure fix in the same order as the order in which they are predicted to depart from the runway. Aircraft belonging to different stream classes, however, may be resequenced with respect to each other between the runway and the departure fix. The OOC algorithm selects flights one by one based on their order in the runway departure queues and departure fix crossing queues. When a flight is selected for processing in the OOC, its TTOT and target TFXT are finalized by separating them sufficiently with respect to earlier runway departures or earlier fix crossings, and to satisfy any miles-in-trail restrictions that may be active. This allocation of TTOTs and TFXTs continues for each next flight select in the order prescribed by the OOC computations until all the flights have TTOTs and TFXTs assigned.

For simulating the air traffic with this scheduling algorithm, we back-compute TOBTs from the TTOTs assuming unimpeded taxi times and prescribed target departure queue length(s). The TOBTs are then input to the simulation platform described in a previous section.

7 What-if Analysis Use Cases

This section documents the three use cases developed to guide Year 1 development and testing of the what-if analysis capability and the Surface CDM concept of operations. The use cases are 1) assessing options for the DMP start and end times, 2) assessing options for the DMP Target Runway Queue Length (TDQL) and its upper and lower bounds, and 3) assessing options for the DMP unscheduled demand buffer. Prior to the use cases, the demand-capacity imbalance is detected by a Surface CDM monitoring system or the DRC, and it is recommended that a DMP be implemented. In turn, the use cases are performed sequentially, such that the value for the parameter specified in each prior use case is included in the what-if analysis of the current use case. The uses cases are described in the following sections.

7.1 Use Case 1: Assess Candidate DMP Start and End Times

This use case evaluates how a DRC will use the what-if analysis capability to determine start and end times for the DMP. The major events/steps for this use case are:

- A demand-capacity imbalance is detected.
- The DRC analyzes the Departure Queue Graph, Departure fix Load Graphs and the Enroute Merge-point Load Graph. The Departure Queue Graph displays predicted departure queue length for each active departure runway over a certain future time-horizon. The Departure fix Load Graph displays predicted departure-fix loadings from interacting airports. The En route Merge point Load Graph displays en route merge fix loadings from different interacting airports; that is, the number of departures from the primary ATD-2 TRACON trying to merge into the en route stream gaps per time-bin.
- The DRC analyzes these plots to determine a set of start and end time options to evaluate (e.g., 09:00 to 10:30, 09:00 to 11:00). Alternatively, the DRC may decide to evaluate a range of start times (09:00-09:30) and a range of end times (10:30-11:30). The DRC inputs these start/end time evaluation options or ranges in the what-if analysis tool.
- The what-if analysis tool simulates airport surface and terminal airspace traffic under a DMP for each of the start and end time pairs in the prescribed choice set, or for a range of times in the prescribed range. The what-if analysis tool uses the current “state” of the TRACON as the starting point and then simulates the traffic as controlled by (an emulation) of the ATD-2 scheduling tools for a time-period covering the DMP active time. It simulates ATD-2 control via TOBTs or TMATs computed for each impacted flight.
- For each pair of start and end time options, the what-if analysis tool conducts multiple simulations, each time adding perturbations to actual gate pushback times and actual spot crossing times to simulate imperfect adherence to prescribed controlled times (non-compliance limited to within the TMAT Compliance Window, and possibly outside of it) based on a model of gate turnaround and ramp taxi uncertainty. Based on the multiple simulations, the what-if analysis tool can compute a mean value as well as confidence bounds for performance metrics such as taxi times, gate delays, fuel utilization, and others, for each parameter option.

- The what-if analysis tool displays key relevant metrics, including their confidence bounds, in an easily understandable manner to the DRC.
- The DRC uses these performance metrics to make a decision on the start and end time of the DMP.

7.2 Use Case 2: Assess Candidate DMP Target Runway Queue Length and Upper/Lower Bounds

This use case evaluates how a DRC will use the what-if analysis capability to determine the Target Departure Queue Length and its upper and lower bounds for each impacted departure runway, after the start and end times of the DMP have been finalized. The DRC could optionally determine what actions should be taken in the event that the actual departure queue length exceeds the upper bound or reduces below the lower bound. The major events/steps are:

- The DRC has already made a decision to implement a DMP and has finalized its start and end times.
- Now, the DRC wants to determine what TDQL and upper/lower bounds he/she should use for the duration of the DMP. DRC inputs some specific values of TDQL and upper/lower bounds that he/she wants to test (e.g., TDQL = 8, 9, 10, Upper Bound = +1, +2, +3, Lower Bound = -1, -2, -3). Alternatively, the DRC prescribes test-ranges for thse parameters (e.g., TDQL = 8 - 10, Upped Bound = +1 - +3, Lower Bound = -1 - -3). The DRC inputs these specific values or ranges in the what-if analysis tool.
- The what-if analysis tool simulates airport surface and terminal airspace traffic under a DMP for each of the TDQL parameters in the prescribed choice set or for a range of values in the prescribed range. The what-if analysis tool uses the current "state" of the TRACON as the simulation starting point and then simulates the traffic as controlled by (an emulation) of ATD-2 scheduling tools, the DMP being active between the pre-determined start and end times. It simulates ATD-2 control via TOBTs or TMATs computed for each impacted flight.
- For each combination of TDQL parameter options, the what-if analysis tool conducts multiple simulations, each time adding perturbations to actual gate pushback times and actual spot crossing times to simulate imperfect adherence to prescribed controlled times, based on a model of gate turnaround and ramp taxi uncertainty. Based on these multiple simulations, the what-if analysis tool can compute a mean value as well as confidence bounds for performance metrics such as taxi times, gate delays, fuel utilization, and others, for each parameter option.
- In simulating the traffic, the what-if analysis tool assumes a number of different policies (e.g., TMAT-reassignments or Runway Departure Rate adjustments) for handling situations where the actual departure queue length exceeds the upper bound or reduces below the lower bound. The exact policies are to be determined.
- The what-if analysis tool displays key relevant metrics in an easily understandable manner to the DRC, so that the DRC can compare the impact of different choices.

- The DRC uses these performance metrics to make a decision on the TDQL and its upper/lower bounds for the DMP. In addition, the what-if analysis tool metrics display can also be used to determine the best policy (e.g., TMAT reassignment) in the event of excessive mismatch between actual and target departure queue length.

7.3 Use Case 3: Assess Candidate DMP Unscheduled Demand Buffer

This use case evaluates how a DRC will use the what-if analysis capability to determine the Unscheduled Demand Buffer parameter, after the DRC has already made a decision to implement a DMP and the start and end times of the DMP as well as the TDQL and its upper/lower bounds have been finalized. The major events/steps are:

- The DRC wants to determine what UDB to use for the duration of the DMP. The DRC inputs discrete values (e.g., UDB = 6, 8, 10 unscheduled departures per hour) or ranges (e.g., UDB = 8 – 10 unscheduled departures per hour) for the UDB parameter, in the what-if analysis tool.
- The what-if analysis tool simulates airport surface and terminal airspace traffic under a DMP for each of the UDB parameters in the prescribed choice set or for a range of values in the prescribed range. The what-if analysis tool uses the current “state” of the TRACON as the simulation starting point and then simulates the traffic as controlled by (an emulation) of ATD-2 scheduling tools, the DMP being active between the pre-determined start and end times with the pre-determined TDQL and upper/lower bounds. It simulates ATD-2 control via TOBTs or TMATs computed for each impacted flight.
- For each UDB parameter option, the what-if analysis tool conducts multiple simulations, each time adding perturbations to actual gate pushback times and actual spot crossing times to simulate imperfect adherence to prescribed controlled times, based on a model of gate turnaround and ramp taxi uncertainty. Based on these multiple simulations, the what-if analysis tool can compute a mean value as well as confidence bounds for performance metrics such as taxi times, gate delays, fuel utilization, and others, for each parameter option.
- The what-if analysis tool displays key relevant metrics in an easily understandable manner so that the DRC can compare the impact of different choices.
- The DRC uses these performance metrics to make a decision on the UDB choice for the DMP.
- The order of use cases 2 and 3 can be interchanged, i.e., UDB can be finalized before the TDQL, or vice versa.

8 What-if Analysis Evaluations

We developed a prototype of the what-if analysis tool to conduct preliminary evaluations of the three what-if- analysis use cases of evaluating and selecting from candidate values of DMP start and end times, target departure queue length, and unscheduled demand buffer. The use case evaluations exercise the what-if analysis process of 1) simulations of departure traffic to identify demand-capacity imbalances, 2) ATD-2 traffic scheduling to compute TOBTs for departure flights, and 3) simulations of departure traffic in conjunction with their TOBTs to evaluate the impact of the DMP on airport traffic flow.

8.1 Modeling and Evaluation Methods

Our evaluations of the use cases employed definition and modeling of the DMP parameters for each use case. The DMP start and end times correspond to the time period for aircraft to push back at their ATD-2 scheduled TOBTs, accounting for all other current and forecast traffic. In the evaluations, ATD-2 scheduling is performed for all flights in the traffic demand set. In turn, only those with TOBTs within the start and end times of the DMP are scheduled to push back at their TOBTs. The other flights push back at their airline-scheduled gate departure times.

The DMP Target Departure Queue Length (TDQL) is defined in the evaluations as the number of minutes of departure delay shifted from gate holding to taxiing during the DMP. This is based on the approximation that an extra flight in the runway departure queue is equivalent to one extra runway time slot of delay, which is approximately 1-minute. So, for a TDQL of X, the TOBT of each flight in the DMP time window is hastened by X-minutes to allocate that portion of each flight’s gate delay to its taxi phase of flight. The upper and lower bounds for the TDQL were not modeled or evaluated.

The DMP Unscheduled Demand Buffer reduces airport departure quarterly capacity during the DMP to accommodate unscheduled traffic. The portion of departure capacity to be allocated to unscheduled flights may be apportioned in different ways. In our evaluations, we apportion the quantity of unscheduled demand equally among the quarter hour periods within the DMP time period.

The departure traffic schedules used in the evaluations were obtained from different sources. For CLT, a traffic schedule from July 18, 2010, obtained from an input file for the NASA Surface Operation Simulator and Scheduler (SOSS), was used. The departure traffic schedules for the other satellite airports EQY, HKY, JQF, SPA and SVH were derived from data obtained from the Federal Aviation Administration Air Traffic Organization–Planning (ATO-P) for use on the Analysis of Choke Points in the NAS Project (NASA Research Announcement (NRA) Contract # NNA13AB95C, LMI Prime Contractor). Specifically, the traffic schedules used for the satellite airports were those created for the 2020 forecast year which were derived from May 13, 2012 traffic demand data. For the evaluations, the data sets were adapted by changing the date of each flight’s scheduled airline departure time from May 13, 2020 to July 18, 2010.

To model unscheduled demand, 5% of the flights were extracted at random from each airport traffic schedule prior to ATD-2 scheduling. The ATD-2 scheduling was performed without these flights to represent the unscheduled demand not accounted for in the DMP. These flights were included in the simulation of airport surface and terminal airspace departure traffic to evaluate the impact of the unscheduled traffic on the effectiveness of the DMP.

The simulations of baseline and ATD-2 traffic employ the following modeling of runway, departure fix and en route fix time slot availability for realism. Time slots at the runway are constant at 8 departures per 15-minute time period. Time slots at the departure fixes correspond to 7 nautical miles with an assumed transit speed of 250 knots, corresponding to approximately 9 fix crossings per 15-minute period. This number is reduced to 4 crossings per 15-minute period for simulation time steps 25 to 40. Time slots at the en route fixes correspond to 8 nautical miles with an assumed transit speed of 450 knots. The availability of time slots at the en route fixes was specified to be 3 of every 5 (3/5) for the first 24 time slots, 2/5 for the next 16 time slots, and 3/5 for the remaining time slots.

The primary metrics in the evaluations for detecting demand-capacity imbalances and assessing the effectiveness of particular DMP parameters were the number of departures active on the airport surface and the number of departures in the runway queue. The number of departures active on the airport surface is equal to the number of departures which have pushed back from their gates (i.e., exited the gate queue) and have not yet taken off (i.e., have not yet exited the runway queue) in a given simulation time step. The number of departures in the runway queue is equal to the number of departures which have entered the runway queue however have not yet taken off (i.e., exited the runway queue) in a given simulation time step. The former metric provides a measure of surface traffic congestion, while the latter provides a measure of runway utilization.

The primary metrics for assessing the impact of the DMP on airport departure traffic performance, in addition to the queue length measurements, were average gate, taxi and airborne delay relative to their unconstrained trajectories initiating from their airline-scheduled gate departure times. The relative values of these parameters indicated the effectiveness of the DMP in achieving the ideal departure profile as per the ATD-2 Concept of Operations while efficiently using airport resources. The ATD-2 ideal departure profile is delay at the gate, unimpeded taxi and continuous climb to cruise. Efficient use of the airport resources is particularly focused on maximizing use of the airport's system of departure runways while the number of active departures is high.

8.2 **Results**

This section presents the results of the airport traffic performance for the baseline condition of aircraft pushing back at their airline scheduled gate departure times, and for the scheduling condition of aircraft pushing back at their ATD-2 scheduled TOBTs in conjunction with the DMP parameters for the particular use case.

8.2.1 Baseline

The figure below depicts the number of active departures and the number of departures in the runway queue at each 1-minute time period in the simulation for the baseline traffic condition.

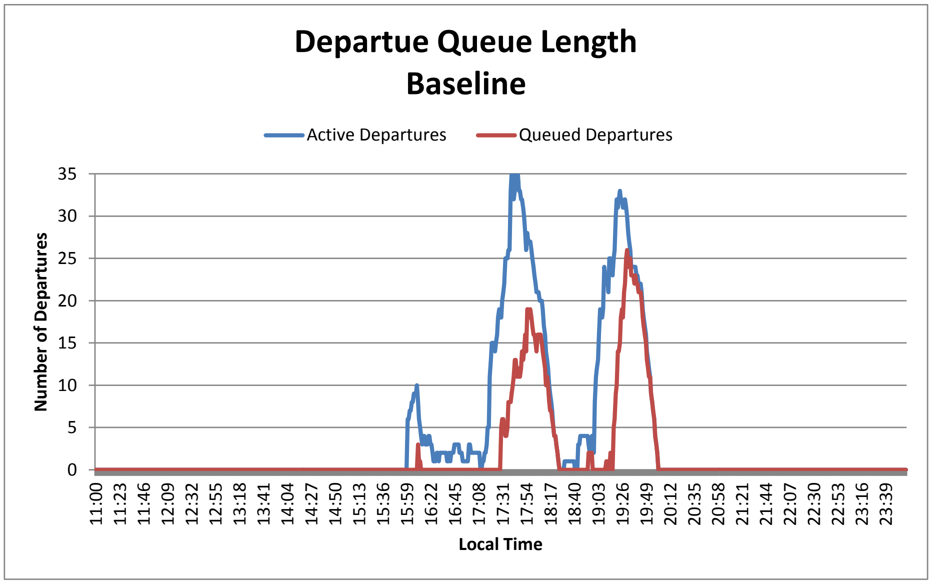

Figure 6. Number of CLT Departures Active and in Runway Queue in Baseline Condition.

The results indicate two periods of demand-capacity imbalance inherent in the Charlotte departure traffic: One during 17:00 –18:30, and another during 19:00 – 20:00. During those periods, the number of departure aircraft active on the CLT airport surface exceeds 15, and the number of aircraft in the runway queue also exceeds 15 aircraft, signaling a demand-capacity imbalance.

The figure below depicts the average gate, taxi and airborne delay of departures in the baseline condition.

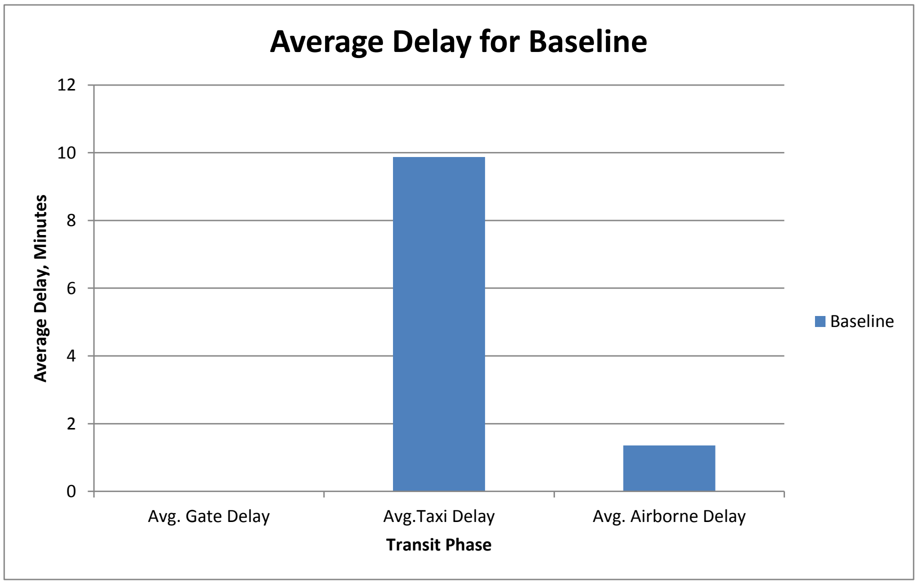

Figure 7. Average Gate, Taxi and Airborne Delay for CLT Departures in Baseline Condition.

The results indicate flights are pushing back at their airline scheduled gate departure times, hence no delay is taken at the gate and average gate delay is zero. Average taxi delay of 10-minutes indicates surface traffic congestion is an issue, with resulting fuel burn and emissions impacts on the aircraft operators and airport environment. Average airborne delay is 1.4 minutes, potentially requiring some vectoring to absorb. Average total delay for departures is 11.4 minutes.

8.2.2 Use Case 1: DMP Start and End Times

In this use case, there are options for specifying the quantity of DMPs to implement (one or two) and the start and end times of one or both DMPs, to address the two demand-capacity imbalance periods. One option is to implement single DMP spanning the duration of the anticipated demand-capacity imbalance. Another option is to implement two shorter DMPs, one for each identified demand-capacity imbalance period.

The considerations in specifying the number of DMPs to implement and the start and end times of those DMPs include the operational complexity of starting and stopping the DMP. The workload of coordinating with stakeholders and shifting airport operational paradigms may preclude having two DMPs in close succession. The time required to initiate and conclude the DMP could result in having two DMPs overlap—one DMP concluding while another begins. The operational impact of these alternatives needs to be understood. Avoiding the possibility of artificially starving the airport runways due to a DMP spanning a period of low traffic levels, and possibly having to conduct a DMP compression, is another consideration. These are just a few of the considerations in designing a DMP to balance departure trajectory efficiency with airport throughput that need to be explored and better understood.

For our initial evaluations of DMP start and end time, we consider a single DMP of different start and end times. The DMP start and end times are 16:00 – 20:00, 17:00 – 20:00, 17:00 – 19:00 and 17:00 – 18:00. These times correspond to initiating the DMP before or at the start of the demand-capacity imbalance, then gradually shortening the DMP to avoid excessively constraining or controlling departure traffic. While we explore only hour-long increments for the DMP duration, previous experience with the Saab Sensis Departure Management system at JFK airport indicate 15-minute time period increments are sufficiently long [12].

The figure below depicts the number of active departures and the number of departures in the runway queue at each 1-minute time period in the simulation for different DMP start and end times.

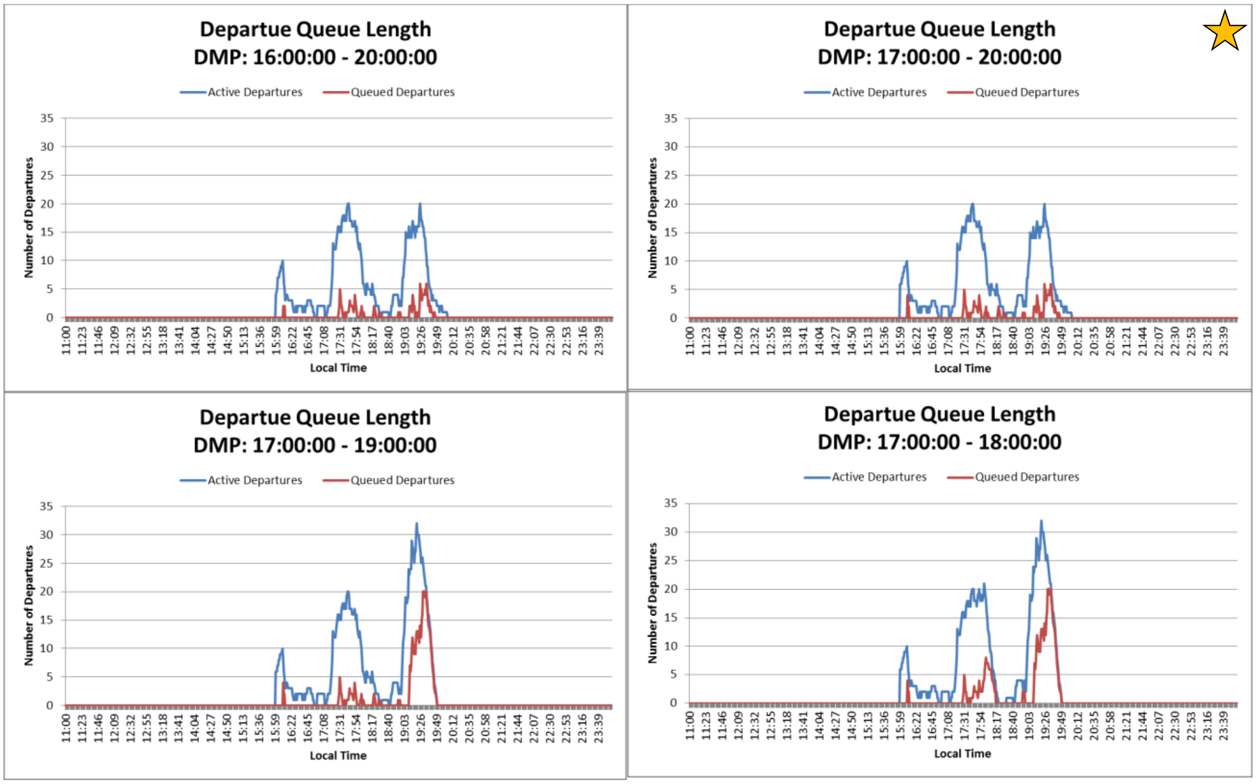

Figure 8. Number of CLT Departures Active and in Runway Queue for Different DMP Start and End Times.

The results indicate that the initial DMP start-end time of 16:00-20:00 reduces the maximum number of active departures to 20 aircraft, an acceptable level. However, the runway departure queue is sometimes empty, even while there are active departures at CLT, indicating some loss of runway efficiency. As the DMP is shortened by delaying the start time to 17:00, there is no observable increase in the number of active or queued departures. As the DMP is shortened by changing the end time from 19:00 to 18:00, the number of active and queued departures increases to an unacceptable level. A DMP initiating at 17:00 and ending between 19:00 and 20:00 seems to be the best option. As a conservative design, we consider DMP start and end times of 17:00 and 20:00, respectively, indicated by the star icon.

As another point of consideration for specifying the DMP start and end times is the average gate, taxi and airborne delay of departures, depicted in the figure below.

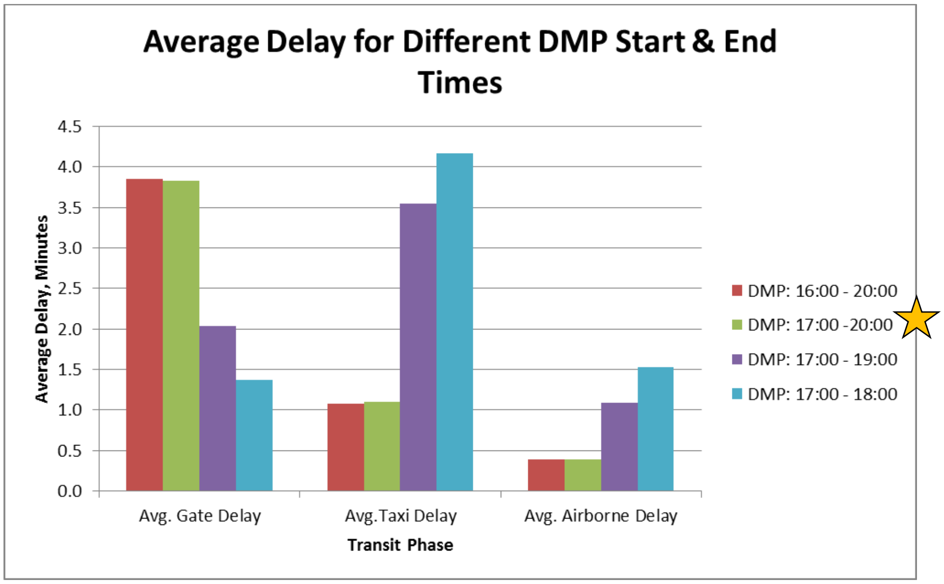

Figure 9. Average Gate, Taxi and Airborne Delay for CLT Departures for Different DMP Start and End Times.

The results indicate that the ATD-2 scheduling employed in the DMP is effective in shifting the taxi delay to the gate and reducing total delay: For the candidate DMP time period of 17:00-19:00, average gate delay is 3.8 minutes, while average taxi and airborne delays have reduced to 1.1 and 0.4 minutes, respectively, and average total delay has reduced to 5.8 minutes. As the DMP end time is hastened to 19:00, average taxi and airborne delays increase dramatically.

8.2.3 Use Case 2: Target Departure Queue Length

Having specified the start and end times of the DMP to be 17:00 – 20:00, the second use case concerns the DRC specifying of the Target Departure Queue Length (TDQL). The objective is to specify a queue length that avoids both excessive taxi delays and starving the departure runway of flights.

The figure below depicts the number of active departures and the number of departures in the runway queue at each 1 minute time period in the simulation for different DMP start and end times.

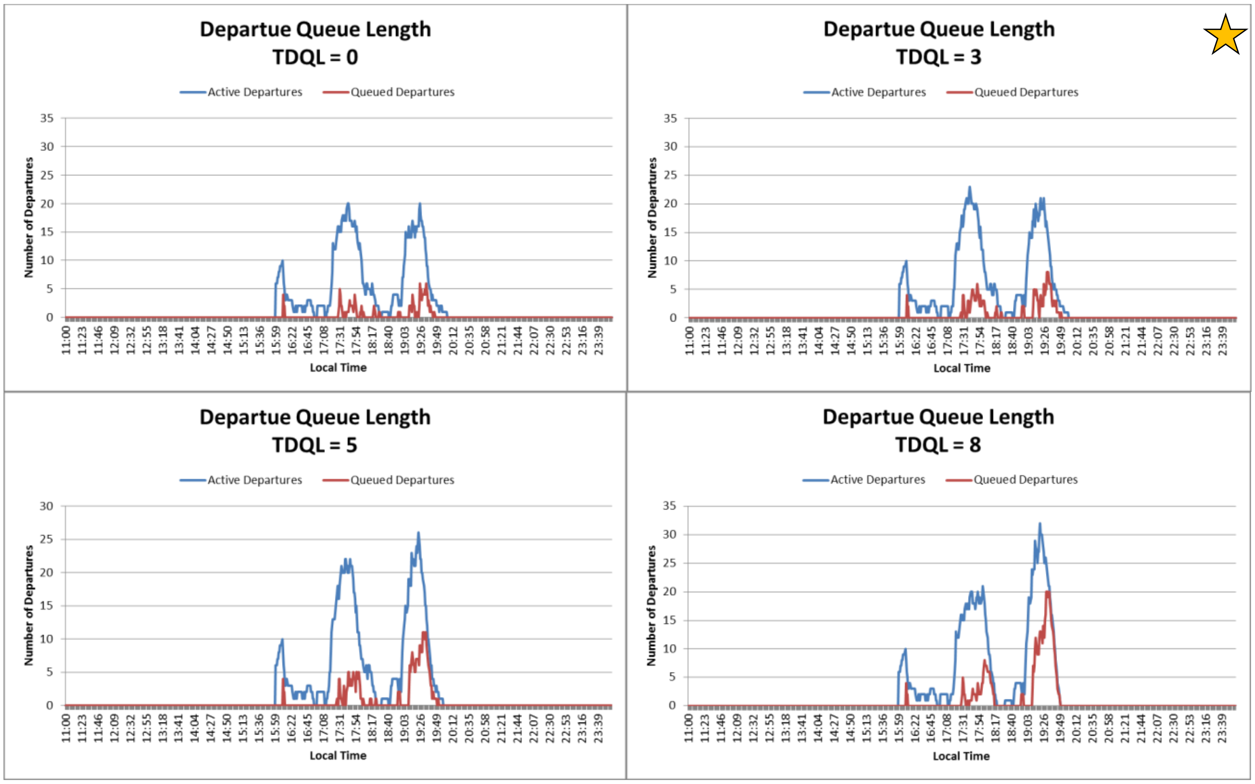

Figure 10. Number of CLT Departures Active and in Runway Queue for Different Target Departure Queue Lengths (TDQLs).

The results indicate that the initial DMP TDQL of 0 (that is, no portion of ATD-2 scheduled gate delay apportioned to the taxi phase of flight) may starve the runways of departures; during some time periods where departures are active on the airport surface, the departure queue length is zero, and the average queue length is 0.8 aircraft during the DMP time period. As the TDQL values are increased to 3, 5 and 8 minutes of delay apportioned to the taxi phase of flight, the runway is more consistently supplied with departure flights for takeoff, as indicated by the departure queue length profiles and the average queue lengths of 1.4, 2.0 and 3.0 aircraft during the DMP time period. However, the departure queue length and the number of active departures on the airport surface increases to excessive levels. A TDQL of 3 seems to provide a reasonable balance of maintaining a sufficient departure queue to avoid starving the departure runways of flights while maintaining reasonable airport surface traffic levels.

We also evaluate the DMP TDQL according to the average gate, taxi and airborne delay of departures, depicted in the figure below.

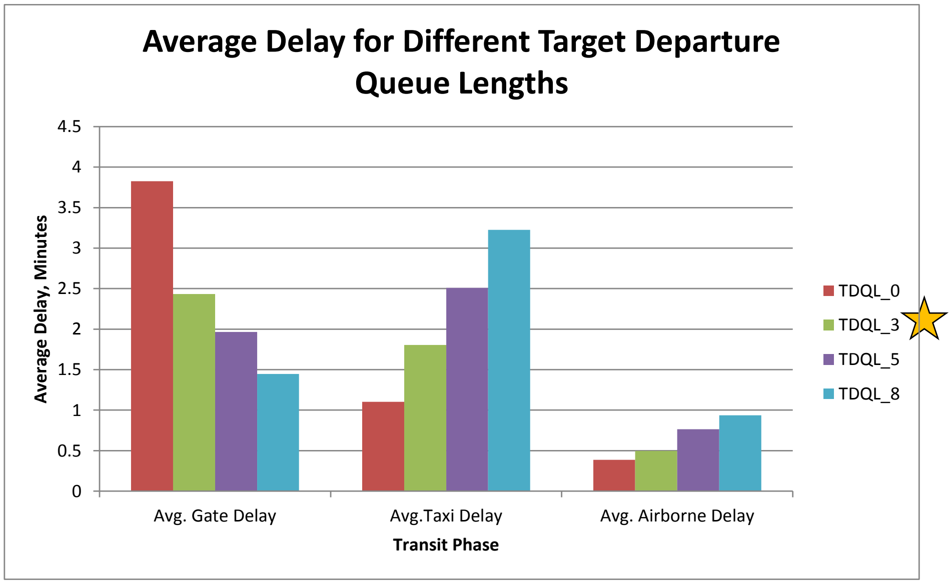

Figure 11. . Average Gate, Taxi and Airborne Delay for CLT Departures for Different TDQLs.

The results indicate that the TDQL is effective in shifting the portion of the gate delay to the taxi transit phase. For the candidate TDQL of 3, average gate delay is reduced 2.4 minutes, while average taxi and airborne delays have increased to 1.8 and 0.5 minutes, respectively. Average total delay is minimally reduced to 5.4 minutes. As the TDQL is increased to 5 and 8, average taxi and airborne delays increase dramatically. A TDQL of 3 seems to retain a reasonable level of gate delay while ensuring the runway is supplied with flights.

8.2.4 Use Case 3: Unscheduled Demand Buffer

Having specified the start and end times of the DMP to be 17:00 – 20:00, and the TDQL to be 3, the third use case concerns the DRC specifying of the Unscheduled Demand Buffer (UDB). The objective is to specify an unscheduled demand buffer which accommodates flights not included in the ATD-2 scheduling with minimal disruption to the traffic under the DMP, without reducing the capacity such that delays are increased or the runways are starved of departures. Discussions with Michael Smith, Ramp Manager of American Airlines at CLT confirmed that unscheduled traffic is minimal, so UDB would not be a significant parameter in the design of the DMP.

The figure below depicts the number of active departures and the number of departures in the runway queue at each 1-minute time period in the simulation for different DMP start and end times.

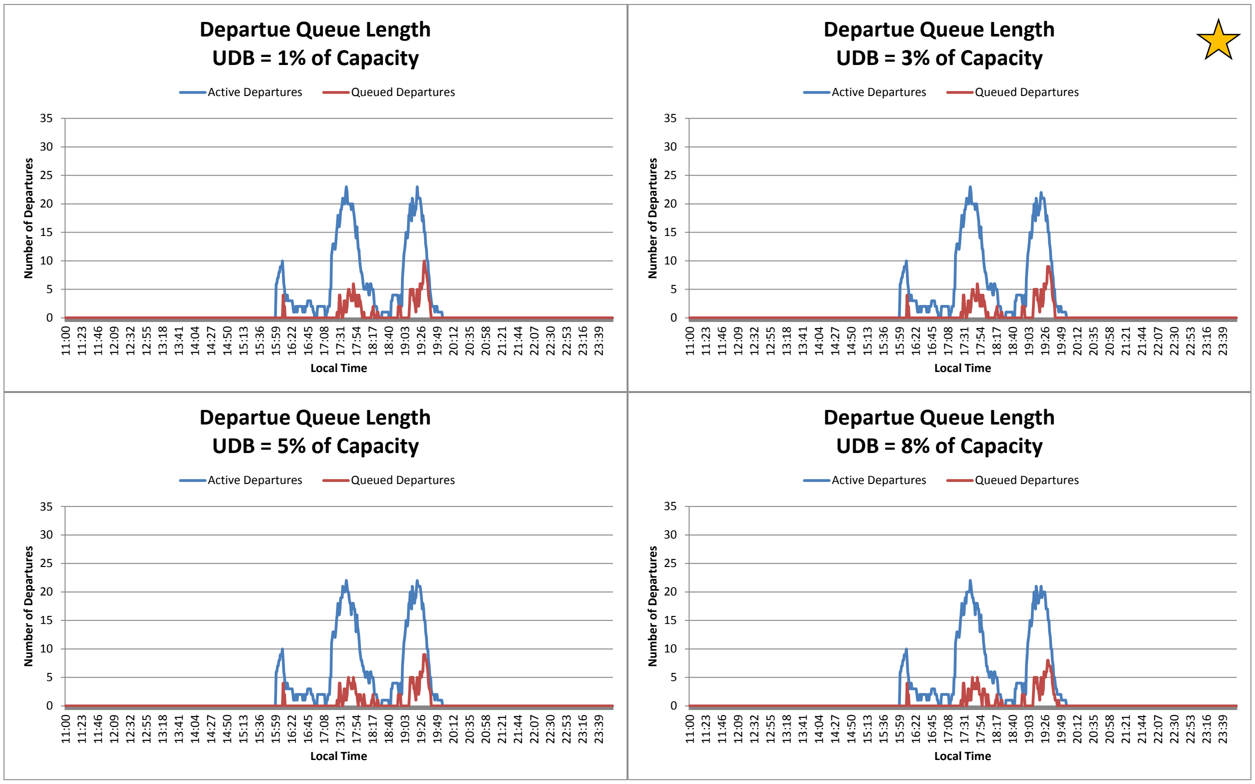

Figure 12. . Number of CLT Departures Active and in Runway Queue For Different Unscheduled Demand Buffers (UDBs).

The results indicate that the different unscheduled demand buffers, even at 8% of airport departure capacity, have minimal impact on the number of active departures or the departure queue length.

We also evaluate the DMP UDB according to the average gate, taxi and airborne delay of departures, depicted in the figure below.

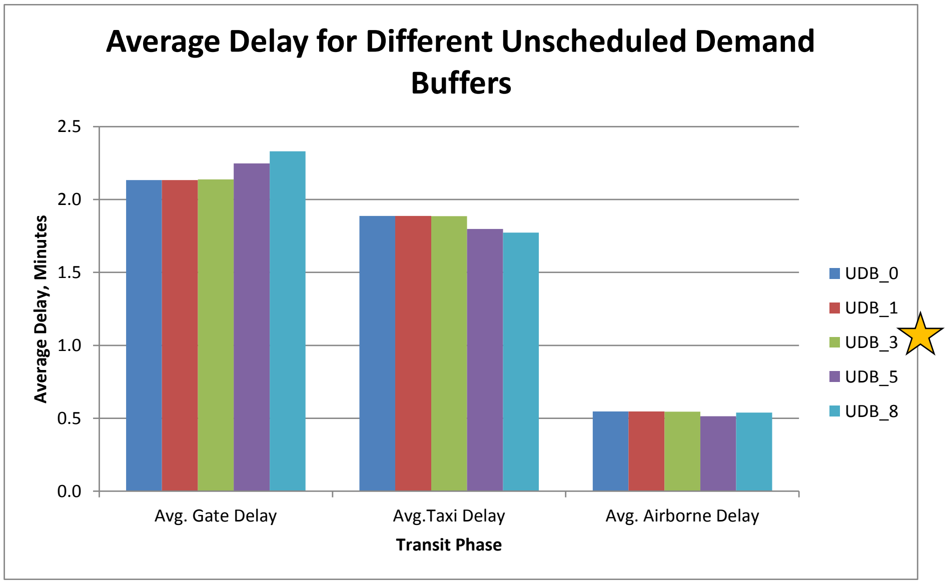

Figure 13. Average Gate, Taxi and Airborne Delay for CLT Departures For Different UDBs.

The results indicate that the UDB has some minimal impact on the gate and taxi delay realized, but does not appear to significantly impact the airport traffic performance under these conditions. We select a UDB of 3% of airport departure capacity, which appears to be the point at which UDB is maximized before the delay distribution is influenced.

The resulting design for the DMP for this particular scenario is DMP start-end times of 17:00-20:00, a target departure queue length of 3, and an unscheduled demand buffer of 3% of airport departure capacity. Under these parameters, the DMP is found to reduce average total departure delay from 11.7 minutes to 5.2 minutes; average taxi delay from 9.9 minutes to 1.9 minutes, and average airborne delay from 1.4 minutes to 0.5 minutes from the baseline condition.

8.2.5 Impact of Uncertainty

Differences between the transit times of aircraft as they are modeled in the what-if analysis simulation platform and occur during implementation of the DMP can impact the effectiveness of the DMP in meeting the performance goals of airport and metroplex traffic. As an initial evaluation of the impact of transit time uncertainty on effectiveness of a designed DMP, we incorporated transit time uncertainty models into CLT surface traffic simulation and conducted Monte-Carlo simulations of CLT traffic under the DMP to assess the collective impact of the transit time uncertainties on the performance of CLT surface traffic including the number of active departures, departure queue length and average transit delay of aircraft.

Uncertainty models for the surface taxi, terminal airspace and en route airspace transit times were modeled as Gaussian distributions. The mean and standard deviation of each transit time distribution for each link in the link-node simulation were estimated from data analysis as described below.

- For the taxi transit time, the airline-specific taxi time mean and standard deviation were estimated from Airline System Quality Performance (ASQP) data for CLT for that airline. The mean transit time for each airline at CLT was estimated as the 5th percentile of the ASQP taxi-time data. The standard deviation for each airline at CLT was estimated as the standard deviation of the subset of the ASQP taxi-time data range up to the 10th percentile.

- For the terminal airspace transit time, the departure fix specific mean and standard deviation were modeled from the transit time data obtained from high-fidelity simulations of departures from takeoff to the departure fix for the MERIL7 SID. For the transit time to departure fix MERIL, the mean and standard deviation were estimated from all the transit times obtained for all simulation runs. For the transit times to the other departure fixes, the mean and standard deviation for each was estimated by distance based scaling of the mean and standard deviation of the MERIL 7 SID to the SID of each of the other fixes. The cumulative distances of the MERIL 7 SID and the other SIDs were computed as the cumulative length of the flight legs the SID. The SID data were obtained from National Flight Data Center (NFDC) data, and the flight leg lengths measured using the FAA’s Terminal Area Route Generation and Traffic Simulation (TARGETS) software.
- For the en route airspace transit time, the mean transit time between the departure fix and the en route merge point were estimated to be 10 minutes. The standard deviation was estimated from the mean and standard deviation of the transit time for the MERIL 7 SID. That is, we computed the ratio of the standard deviation to the mean—the coefficient of variation—for the MERIL 7 SID transit data. This coefficient of variation was multiplied by the assumed mean en route transit time to estimate the standard deviation for the en route transit time.

A Gaussian distribution of unit standard deviation and zero mean, bounded between +/- 3 standard deviations, provided the core uncertainty model. Individual values sampled from this model were scaled according to the uncertainty parameters of the applicable transit time distribution to estimate an individual link transit time at each simulation time step. One hundred runs of the simulation were conducted to sufficiently capture the extent of the Gaussian distributions for uncertainty analysis of the airport surface traffic performance.

The results of the simulations are presented as the maximum and minimum values of the number of active departures, the number of departures queued for takeoff, and the flight-averaged delay of flights at the gate, during taxi transit, and during airborne transit. Figure 14 below depicts the maximum and minimum values of the number of active departures on the surface of CLT from among the 100 simulation runs.

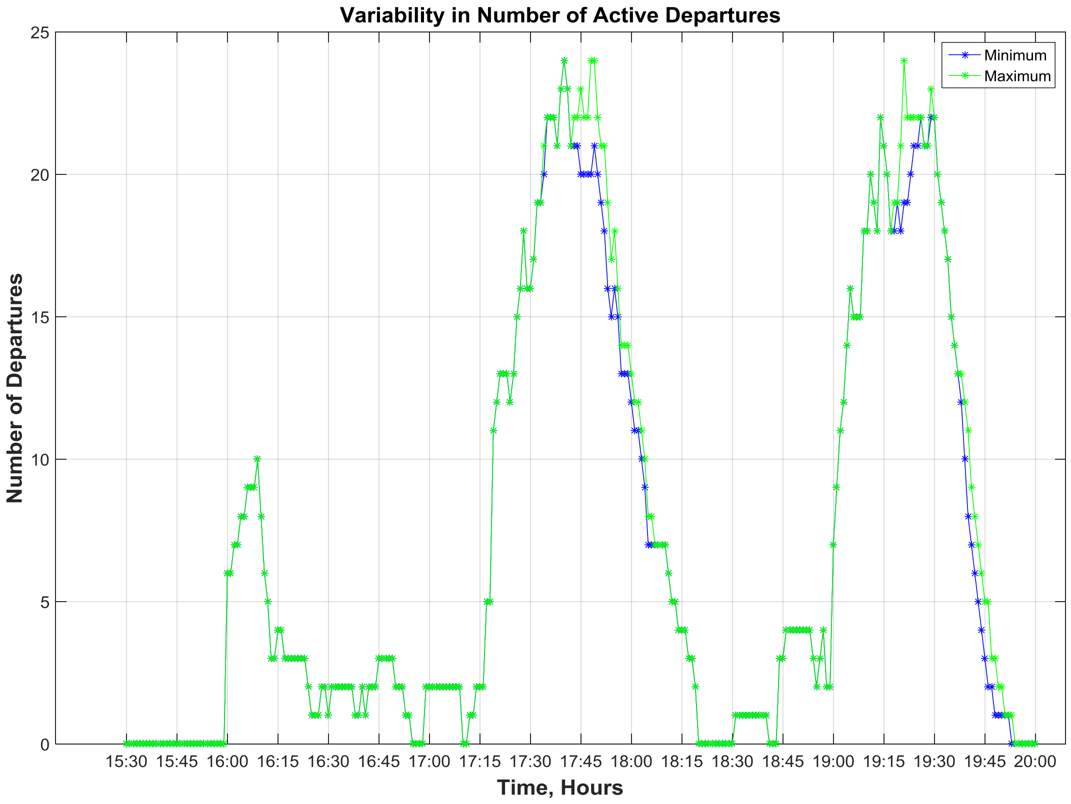

Figure 14. Maximum and Minimum Number of Active Departures From Among the Multiple Simulation Runs.

The results demonstrate that the transit time uncertainty yields a modest range in the number of active aircraft on the airport surface with differences of ~3-5 aircraft during peak demand periods. The tolerance for the variability in the number of active departures could be determined from such results.

Figure 15 depicts the maximum and minimum values of the number of departures queued for takeoff on the surface of CLT from among the 100 simulation runs.

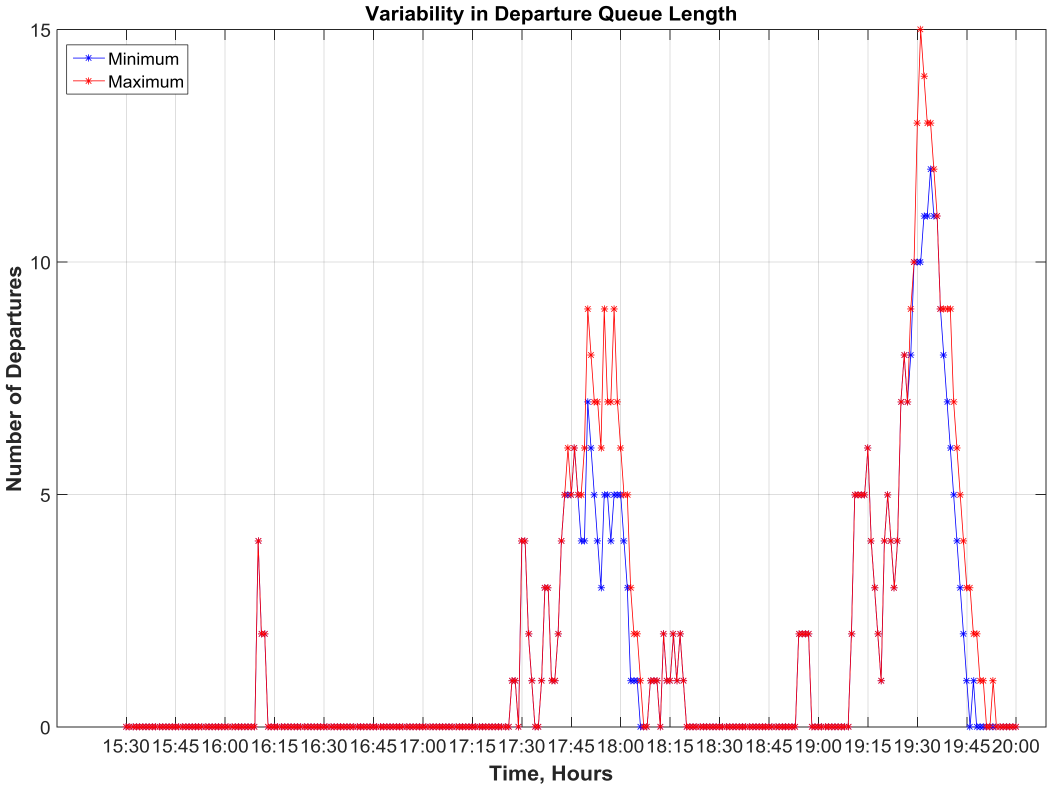

Figure 15. Maximum and Minimum Number of Departures Queued for Takeoff From Among the Multiple Simulation Runs.

The results demonstrate that the transit time uncertainty yields a modest range in the number of departures queued for takeoff among the simulations with differences of ~2-5 aircraft during peak demand periods. The tolerance for the variability in the departure queue length, specified as the lower and upper bounds of the Target Departure Queue Length DMP parameter, could be determined from such results.

Figure 16 depicts the maximum and minimum values of the flight-averaged gate delay, taxi time delay, and en route transit time delay from among the 100 simulation runs.

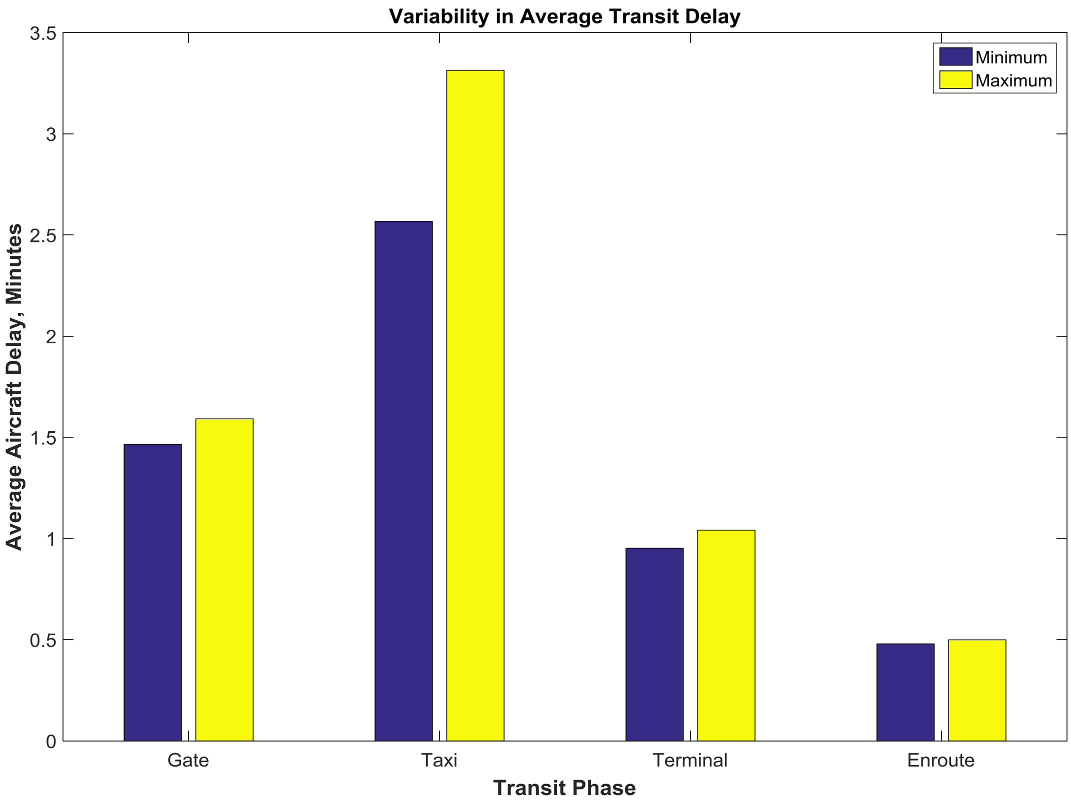

Figure 16. Maximum and Minimum Flight-Averaged Delay by Transit Phase From Among the Multiple Simulation Runs.

The results demonstrate that the transit time uncertainty yields a modest range in the taxi delays experienced with differences of ~1.0 minutes in mean taxi delay of aircraft during peak demand periods. The tolerance for the variability in the aircraft surface traffic performance could determine the particular parameters selected for a DMP.

8.3 Conclusions

The design of a DMP is an iterative process of evaluating individual DMP parameters and conducting what-if analysis to assess the impact of the DMP on airport traffic performance.

The number of active departures (that is, the number of aircraft in the ramp and movement area) is a valuable indicator of a demand-capacity imbalance and when to start and end a DMP. When this value is above a certain threshold is a good indicator of when to start a DMP, and when it is below a certain threshold is a good indicator of when to end a DMP. Specification of the threshold must come from the experience of personnel or trial and error. For CLT, subject matter expertise advised us that the typical threshold is 20 aircraft at a time.

Specification of DMP start and end times is the first and most significant decision the DRC must make. Multiple occurrences of demand-capacity imbalances may be addressed with one DMP or multiple DMPs, and specification of DMP start and times can factor into this fundamental design question. The operational realities of initiating and concluding a DMP, and the desire to minimize taxi and airborne delays while not overly constraining airport departure throughput , represent a complex set of considerations that factor into this initial design component.

While it may not be possible to precisely control the departure queue length during a DMP, the TDQL provides an effective means to tune the DMP to avoid runway starvation while maintaining the number of departures to a reasonable level. In tuning this variable, the average departure queue length can be balanced with taxi delay to achieve throughput and flight efficiency.

The unscheduled demand buffer did not appear to have a significant impact on the airport surface traffic performance under the DMP. This parameter may not have any positive effect without estimate of when unscheduled flights might appear. This parameter is likely of greater importance to airports with a significant portion of unscheduled traffic.

The DMP using the ATD-2 scheduling tools produced a significant reduction in the average total delay, and the average departure delay during the taxi and airborne phases of flight. The reduced total delay benefits the schedule integrity of the aircraft operators and travellers, and the reduced taxi delay and associated fuel burn and emissions reductions that can be beneficial to the aircraft operators and the airport operators.

Transit time uncertainties introduce some variability in the surface traffic levels and flight delays realized with a DMP. They could have an impact in the design of the DMP, thus could be modeled explicitly in the what-if analysis and accounted for in the DMP design.

9 Summary and Future Work

The NASA ATD-2 traffic management concept fits well within the FAA Surface CDM Concept of Operations. The what-if analysis is a core capability of the Surface CDM ConOps that enables the DRC to explore and collaborate with stakeholders in the design of DMPs to manage and mitigate airport departure traffic demand-capacity imbalances. This work was successful in serving as a proof of concept for the what-if analysis capability: developing a what-if analysis prototype comprising an airport traffic simulation and an emulation of the ATD-2 scheduling tools, identifying primary DMP parameters, creating use cases for the DRC to use the what-if analysis capability to explore and specify DMP parameter values, and initial evaluation of the what-if analysis use cases and the impact of DMP parameters on the performance of ATD-2 scheduling of departure traffic.

Work remains to explore the design of DMP parameters under different traffic and airport conditions; to evaluate the impact of traffic uncertainty on the effectiveness of a DMP; to explore the minimum necessary modeling fidelity for the what-if analysis capability to still be useful; performance metrics and interfaces useful for DMP specification; incorporation of stakeholder considerations in DMP design; policies for managing traffic if DMP thresholds, such as target departure queue length upper and lower bounds, are violated; operational considerations for instituting a DMP; and others.

10 References

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