Queue Buffer Sizing for Efficient and Robust Integrated Departure Scheduling

Husni Idris[1] and Ni Shen[2]

TASC an Engility Company, Billerica, MA

Aditya Saraf[3], Jason Bertino[4], and Natasha Luch[5]

ATAC Corporation, Santa Clara, California, 95050

Integrated schedules of arrival, departure and surface operations need to maintain a certain level of robustness in order to accommodate uncertainties stemming from the operations and the environment. This robustness is needed to maintain high throughput and conformance to the schedule. One method to achieve such robustness is for the schedule to allow for queue and delay buffers, particularly at the main choke resources of the system, such as runways. In this paper, a method based on identifying throughput saturation using analysis of historical data is used for determining the appropriate size of the buffers. The analyses are applied to departure operations of Charlotte International Airport and insights are drawn on the existence historically of throughput saturation of runways and the sensitivity of the buffer sizes to a number of modeling parameters and airport conditions.

I. Introduction

Delays originate mostly at major airports, and particularly at ones that constitute complex metroplexes of multiple interacting airports [1]. Major causes of delay at these metroplex systems are constrained resources on the airport surface particularly the runways and in the surrounding terminal airspace. These complex systems are characterized by high levels of interaction between flows of multiple adjacent airports sharing arrival and departure fixes and competing for gaps in the overhead traffic streams. Solutions to mitigate these choke points have consisted mostly of isolated concepts and capabilities that are applied to components of the system. For example, concepts focused on either arrival flow management for arrival metering, sequencing and spacing [2, 3] or on departure flow management such as departure metering at gates [4-6], precision departure release control [7, 8], or runway scheduling [9, 10]. Integrated solutions are needed in order to reap the benefits of the isolated capabilities [11]. Research has been conducted to demonstrate integrating arrival operations from the en route phase of flight to the landing [12]. Initial research into integrating runway arrival and departure operations has also been conducted generating preliminary concepts and algorithms [13-15]. In this paper, we describe a research activity in support of a concept developed by NASA (ATD-2) which attempts to integrate departure and arrival operations in a metroplex, with an emphasis on integrating departure operations [16-17]. The operations are integrated from the release from the gate on the airport surface, to the takeoff from the runway, to the crossing of departure fixes and the merging into the overhead traffic stream.

The integration of airspace and surface operations in a metroplex system aims to maintain high throughput of the system, efficient operations through expedited, uninterrupted travel, and minimum fuel burn and emission. This integration attempts to achieve these objectives through in part the generation of a coordinated schedule of departures at key resources or control points such as the release from the gates, the exit from the ramp area into the airport movement area, the takeoff from the runways and the crossing of departure fixes, as depicted in Figure 1. While it may be possible to simultaneously achieve these objectives under deterministic conditions, uncertainty in the operations and the environment brings about tradeoffs among them:

1. In order to maintain high throughput under uncertainty, delay or queue buffers are needed in order to keep pressure on the choked resources of the system and take advantage of any service opportunities that may

---

[1] Principal Research Engineer, TASC an Engility Company, AIAA Senior Member.
[2] Research Analyst, TASC an Engility Company, AIAA Member.
[3] Aviation System Engineer, ATAC Corporation, AIAA Senior Member.
[4] Director, ATAC Corporation, AIAA Member.
[5] Aviation System Engineer, ATAC Corporation, AIAA Member.

arise. Queues provide controllers the ability to sequence departures optimally and the controllability needed for conformance to prescribed schedules such as flow management restrictions. If the schedule assumed the fastest travel between resources with zero delay or queue buffers it would be violated due to any disturbance that results in longer travel time. This requires absorbing some delay near downstream resources, such as in the airspace near departure fixes and on the airport surface near the runways, as shown in Figure 1.

2. On the other hand, delay is absorbed more efficiently and cleanly on the airport surface (movement area) rather than in the airspace, and in turn, on the gate while the engines are off rather than on the airport surface.
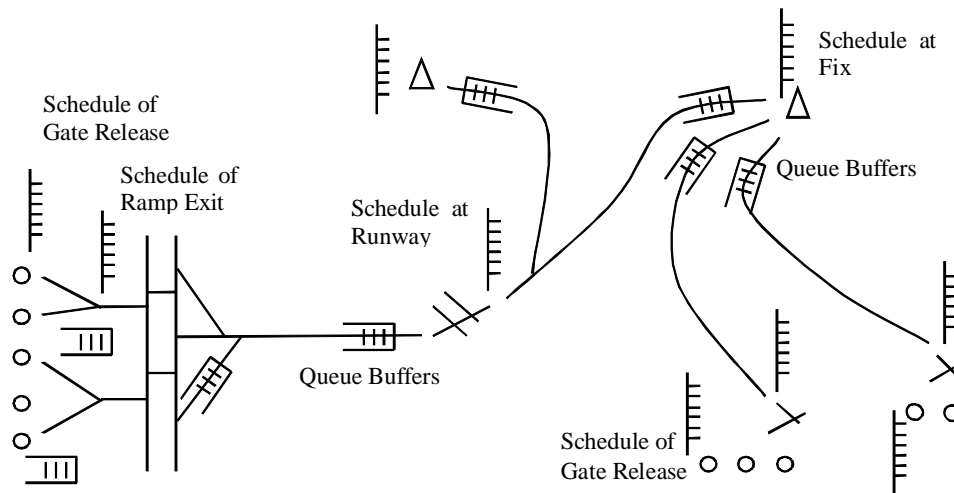

Figure 1. Integrated scheduling with target queue buffers

Therefore, the integrated scheduler needs to decide on the distribution and allocation of delay between the interconnected resources. NASA's ATD-2 concept includes a strategic surface scheduler which schedules the release of flights from the gates and/or the ramp in order to balance the throughput robustness with operations efficiency. Key parameters used in this decision are the desired queue or delay buffer sizes that the scheduler should target to achieve an appropriate balance between the throughput and efficiency objectives. Only sufficient buffers for throughput and conformance should be maintained by the scheduler, while additional delay should be absorbed at the gate more efficiently and with less workload.

An approach for identifying the desired size of the queue buffers based on historical data analysis is described in this paper. The queue buffer is determined as the size of the queue that resulted in throughput saturation on average as observed in historical data. Using a combination of two FAA databases, the Aviation System Performance Metrics (ASPM) and Airport Surface Detection Equipment (ASDE-X), it was possible to improve on previous models [1,18,19] by constructing higher fidelity models and identify queue buffers for each runway and under each runway configuration. The analysis reports on the desired buffer sizes for four different queue definitions that are being considered for the ATD-2 strategic scheduling applied at Charlotte International Airport (CLT):

1. The number of flights that left the gate but did not take off
2. The number of flights that left the gate and spent their unimpeded transit time from the gate to the runway but did not take off
3. The number of flights that left the ramp area but did not take off
4. The number of flights that left the ramp area and spent their unimpeded transit time from the ramp to the runway but did not take off

The paper also investigates the sensitivity of these buffers to a number of modeling parameters and airport conditions. A follow on paper will build on the findings of this analysis to conduct a simulation-based comparison of applying strategic departure metering using these four queue definitions. The statistical models used for identifying the queue buffers are described in the next section followed by the analysis results.

II. Statistical Modeling

Analysis of historical data was used in order to identify the size of the queue buffers that may be targeted in strategic departure metering and scheduling. This target queue buffer was identified as the queue size hat was historically sufficient to maintain throughput saturation of the runway. The analysis was applied to four queue parameters that are being considered in this metering process:

1. The number of flights that left the gate but did not take off
2. The number of flights that left the gate and spent their unimpeded transit time from the gate to the runway but did not take off
3. The number of flights that left the ramp area but did not take off
4. The number of flights that left the ramp area and spent their unimpeded transit time from the ramp to the runway but did not take off

The first and third definitions are system queues; they measure the number of flights in a particular system: between the gate and the runway and between the ramp and the runway, respectively. Some of these flights may be queued physically at the runway end while some may be transiting towards the runway using other airport surface resources. The second and forth definitions attempt to better approximate the physical queue at the runway end by assuming that a flight reaches the runway after its unimpeded transit time. This assumption is not always true as a flight may be delayed while transiting; however, it is a better approximation of the runway physical queue than the other two system parameters. The term queue is used for all the parameters for simplicity.

The main model used in this analysis is a throughput saturation model that relates the runway throughput to the queue size, defined as any of the four definitions above. The desired queue buffer size is detected at the queue size that was observed historically to be just enough for saturating the throughput. For measuring the size of the runway queues defined in numbers 2 and 4 above, models of the unimpeded transit time, between the gate and the runway for definition 2 and between the ramp and the runway for definition 4, are needed. These models are described in the next two subsections starting with the throughput saturation model and followed by the unimpeded transit time models.

A. Throughput Saturation Model

The throughput saturation models used in this analysis are based on ones previously reported in the literature [1, 18-24]. The historically reported throughput is plotted against the historically reported queue as shown in Figure 2 for one CLT runway (18L) using one year of data (10-1-2011 to 9-30-2012). In this plot the first system queue definition was used to demonstrate the model: the number of flights that left the gate but did not take off. (The model is applied to all the four queue definitions and compared in the analysis section of the paper.) The runway throughput (spelled thruput in the figure) is plotted on the vertical axis and the number of flights in the system queue, N(t), is plotted on the horizontal axis. The two variables are measured as follows:

1. The queue plotted on the horizontal axis was measured at every minute (t) as the number of flights that were in the queue at that minute – this is the number of departures that have entered the system (left the gate in this case) but have not exited from the system (taken off) by that minute. The entry time to the queue was set differently for each of the definitions of the queues. For the second definition, the entry to the queue was defined as the time a flight left the gate plus an unimpeded transit time from the gate to the runway assigned to the flight. For the third definition the entry was defined as the time the flight exited the ramp area into the taxiways and for the forth definition the entry was defined as the time a flight left the ramp plus an unimpeded transit time from the ramp to the runway that was assigned to the flight.
2. The throughput plotted on the vertical axis was measured at every minute (t) as the number of flights that took off in a time window symmetrically centered around the minute. The time window was set to twenty minutes in this analysis (the variable n in the plot). The throughput measurement was plotted at a time offset (the variable delta in the plot) from the queue measurement. The offset was selected for each plot as zero, five, or ten minutes. The offset that resulted in the highest correlation between the queue and the throughput was selected. In the example in Figure 2 the offset (delta) is shown in the title of the plot as five minutes. The throughput is reported per hour in all the plots in the paper.
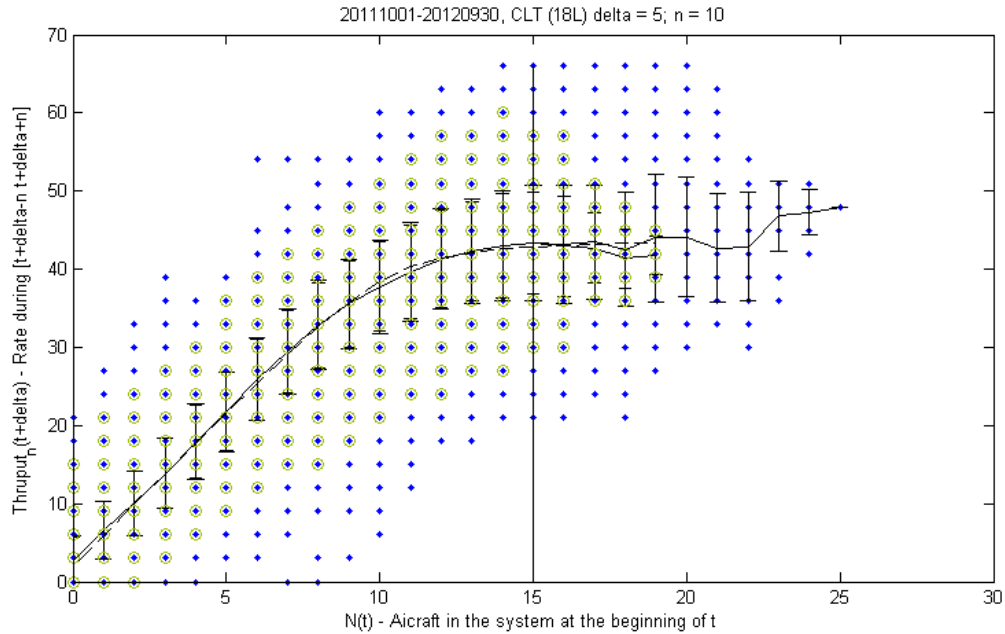
Figure 2. Throughput saturation analysis (CLT, Runway 18L departures)

The average throughput is computed at each queue value and connected with a solid line in the plot. Error bars show the variation in throughput at each queue value. As shown in Figure 2, the average throughput increases as the queue increases then saturates as the queue grows. In order to identify and quantify the saturation of the throughput at high queue values, a hyperbolic curve was fitted to the average throughput versus queue data (Dashed line in Figure 2). The curve asymptotes towards a constant throughput value as the queue tends to infinity. A second asymptote that passes through the initial point at zero queue was used for the curve fit. The values of the horizontal asymptote throughput and the angle of the second asymptote at the initial point were parameters that were varied for a best fit. The resulting horizontal asymptote approximates the average throughput capacity of the runway. Before performing the curve fit, the least frequent queue-throughput pairs were eliminated as outliers representing rare and off-nominal conditions. The removed pairs are the blue dots that are not encircled in Figure 2 and constituted in this case one percent of all pairs. The remaining pairs (green circles in the figure) were the only ones used in the curve fitting. As seen in the plot, the filtering excluded pairs of low throughput at high queue values. These pairs represent off-nominal conditions, such as airport closure or bad weather events, where high queues accumulated due to lack of throughput. The filtering also excluded pairs of high throughput at all queue values. These pairs represent rare reports of runway over-utilization. A sensitivity analysis to the percentage of outliers removed is discussed in the analysis section of the paper.

In this paper, the queue buffer that is sufficient for throughput saturation was considered at the point where the slope of the hyperbolic fit curve is 0.005. In the plot a vertical line is drawn at this point to indicate the value of the queue on the horizontal axis that corresponds to throughput saturation. In this case fifteen flights between the gate and the runway were considered sufficient to saturate the runway throughput. The values of these queue buffers are reported and compared in the next section of the four queue definitions considered.

B. Unimpeded Transit Time Model

The unimpeded transit time model was derived from the historical transit times of flights that travelled freely from the gate or ramp to the runway. The main factors that impede the travel of a flight include queuing interactions with other flights and flow management restrictions that may cause the flight to be suspended on the ramp or movement areas. In order to identify these flights, queuing analysis was conducted to correlate the transit time of a flight with the queue of the flights that it encountered during its transit. Figure 3 shows an example of this correlation for the transit from the gates to runway 18C at CLT. Previous research found that the taxi-out time for each flight i correlates well with the number of exits (in this case takeoffs) that occurred between its entry (in this case pushback) time and its exit (in this case takeoff) time, referred to in Figure 3 as Nac(i) [25]. As can be seen in

American Institute of Aeronautics and Astronautics

the plot, the average transit time (solid line) starts relatively constant at low Nac values, but as Nac becomes larger it starts to increase because the number of flights in the queue is large enough to induce interaction and impedance. It can also be seen that some flights spent a considerably large time (relative to the average solid line) to transit to the runway beyond the marginal time needed to account for the size of the queue Nac ahead of the flight. Many of these flights were likely restricted by flow management programs and were suspended for a period of time during their transit despite the lack of queues. In order to isolate these effects and identify a set of flights that were not significantly impeded by either flow restrictions or queuing, the following two techniques were used:
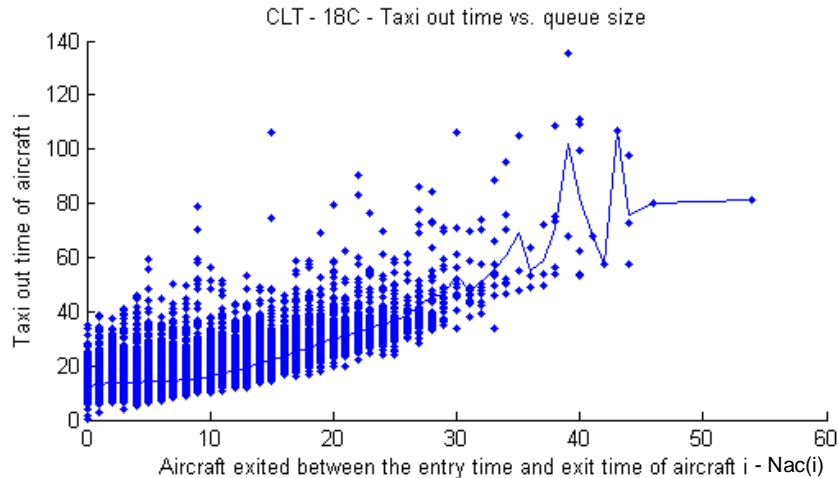

Figure 3. Queuing model for taxi-out time between gate and runway 18C at CLT

1. *Isolating restrictions effect*

In order to identify the effect of restrictions, each queue Nac(i) was divided into two components: the number of flights that have entered the system ahead of flight i and the number of flights that entered the system after flight i. The latter ones passed flight i along their transit and exited the system ahead of it. The first component is called the First Come First Serve (FCFS) part of the queue and the second component is called the passing component of the queue. Previous research found that the number of flights in the passing component reflects the level of restriction that a flight encountered: while a nominal amount of passing occurs due to sequencing activities, a restricted flight typically encounters excessive passing by other flights while it is suspended due to the restriction [25]. Figure 4 shows the decomposition of the queuing data of Figure 3 into the two components:
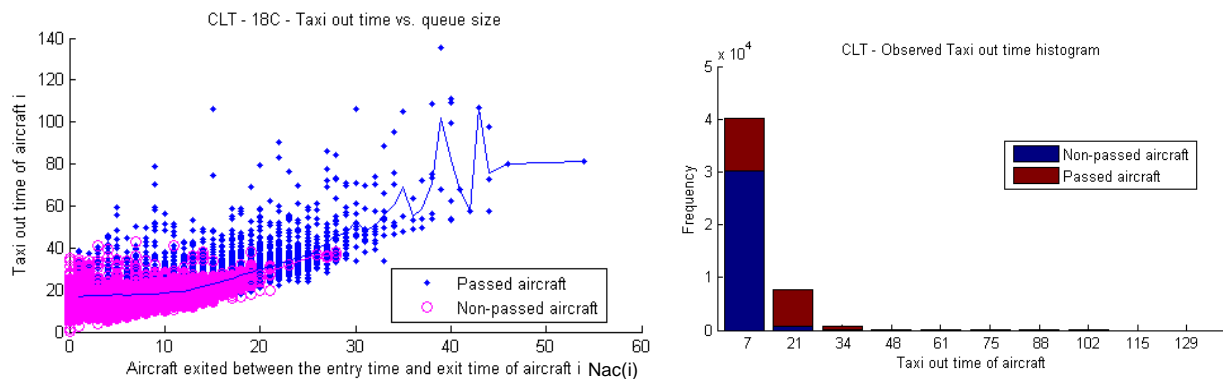

Figure 4. Unimpeded Taxi-Out Time Model

The left plot of Figure 4 shows the queuing correlation for the non-passed flights (magenta circles) that did not encounter any passing (all the flights ahead in the queue had entered earlier resulting in a zero passing component) and the queuing correlation for the passed flights (blue dots) that were passed by one or more flights. It is evident that the passed flights incurred more delay and larger queues during their transit time than the non-passed flights.

5
American Institute of Aeronautics and Astronautics

Most high delays and high queues are explained by some degree of passing. The plot on the right side of Figure 4 shows the distribution of the transit time (between the gate and the runway in this case) for the passed and non-passed flights. It demonstrates again that the higher values of the transit time are attributed to the passed flights. In order to identify and isolate flights that were not impeded by restrictions (to be used for the unimpeded transit time modeling), only flights that were passed by less than a threshold number of flights were considered. The threshold was set to three flights in this analysis, considering that a flight may be passed by two or less flights due to nominal sequencing activities that are not related to restrictions.

2. Isolating queuing effects

In order to filter out the queuing impedance effect, the distribution of the unimpeded transit time was obtained from the flights whose Nac is less than a value at which the correlation between the transit time and Nac becomes statistically significant. For this analysis only the flights passed by less than the threshold of three flights were used to identify the queuing correlation threshold. For example, in Figure 4, the queue cutoff value at the correlation threshold was identified as one flight for the runway shown. Using the subset of flights with queue Nac less than this correlation cutoff value, a distribution was generated for the unimpeded transit times between leaving the gate and the runway for the second queue definition and between leaving the ramp and the runway for the forth queue definition. Figure 5 shows an example of the unimpeded transit time distribution from the gates to runway 18C.
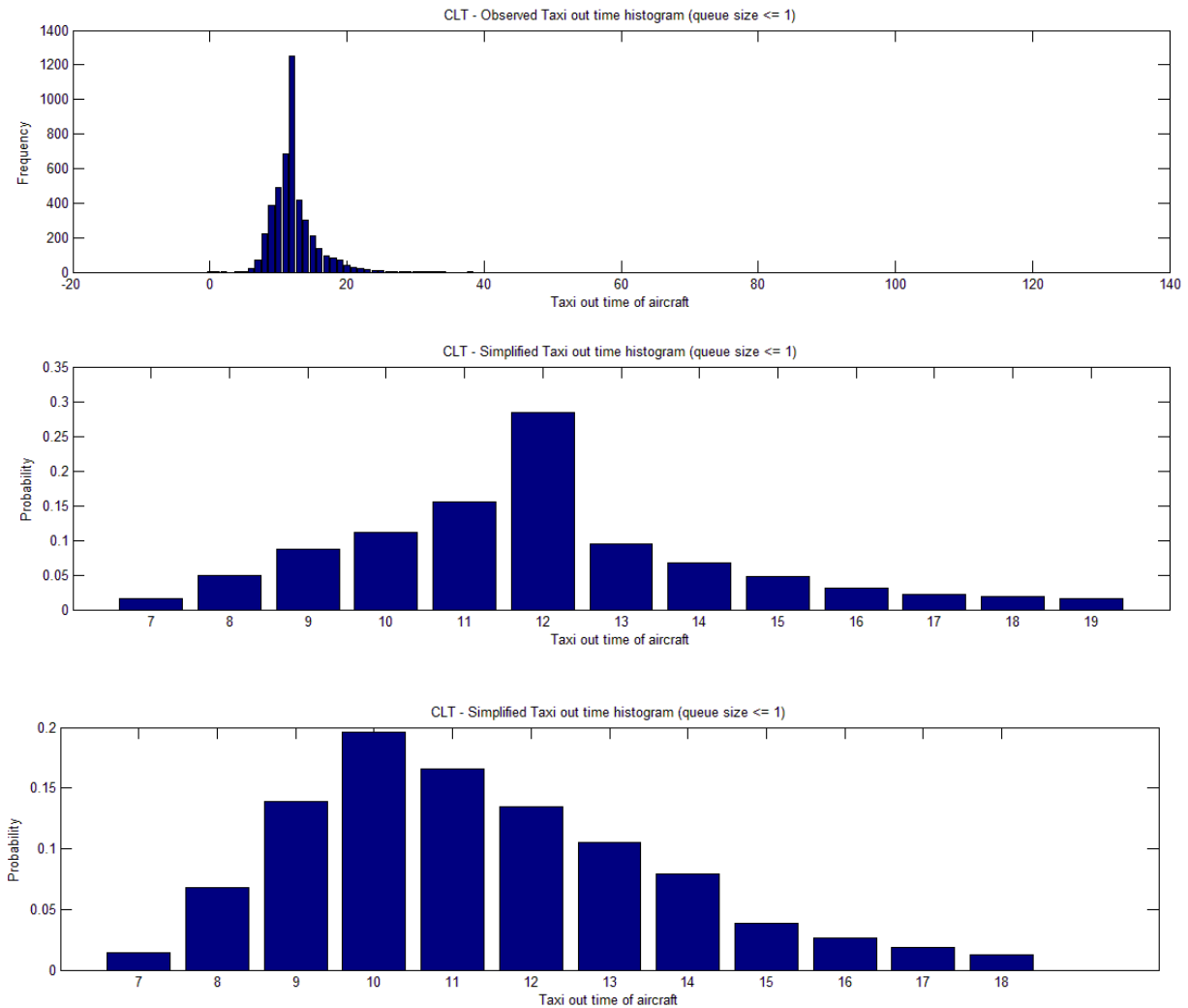

Figure 5. Model of unimpeded transit time from gate to runway 18C at CLT (Top: all unimpeded flights without truncation, middle: all unimpeded flights with truncation, bottom: unimpeded flights of one dominant carrier with truncation)

American Institute of Aeronautics and Astronautics

Using the subset of flights identified as described above, a distribution was generated for the unimpeded transit times between leaving the gate and the runway and between leaving the ramp and the runway for each pair of runway and carrier. The air carrier was used to approximate the ramp area from which the flight originates. To reduce the model bias by outliers, five percent of the data points were truncated off from the distribution while keeping all values with at least one percent of the sample size. In the example in Figure 5, the distribution of the unimpeded taxi-out time is truncated by excluding all the taxi-out times greater than nineteen minutes. The distributions of unimpeded taxi-out time for all flights with Nac(i) values less than or equal to one is shown in the top plot and its truncated version is shown in the middle plot of Figure 5, respectively. The corresponding truncated distribution for one carrier is shown in the lower plot of Figure 5. The distributions were generated only for the top carriers that constituted more than one percent of the operations. All the other carriers were grouped into one distribution.

C. Data Sources

Two FAA databases were used for the modeling and analysis conducted in this paper: The Aviation System Performance Metrics (ASPM) database and the Airport Surface Detection Equipment (ASDE-X) database. ASPM provides several information about each flight including the pushback, takeoff, touchdown and parking at the gate times with one minute resolution. It also provides information about the conditions of the airport such as the runway configuration and meteorological conditions in fifteen minute periods. The ASDE-X database contains the surveillance tracks of the airport traffic. Processed ASDE-X data was used to provide the time each flight exited the ramp into the airport movement area, the takeoff and landing times with one second resolution, and the specific runway that each flight used for takeoff or landing. By matching the flights in the two databases, it was possible to obtain the times of leaving the gate, leaving the ramp and takeoff for each flight, which were used in this analysis. It was also possible to construct a model and hence determine the queue buffer sizes for each runway under each runway configuration and meteorological condition. The two databases were matched using several identifiers for each flight that were available in both databases such as the call sign, aircraft type, origin, destination, and takeoff time. Over ninety percent of the flights were matched to within a ten minute difference in takeoff time.

III. Throughput Saturation and Queue Buffers Analysis

The throughout saturation analysis described in the previous section was applied to determine the buffer values of each of the four queue parameters considered for strategic scheduling and metering:
1. The number of flights that left the gate but did not take off.
2. The number of flights that left the gate and spent their unimpeded transit time from the gate to the runway but did not take off.
3. The number of flights that left the ramp area but did not take off.
4. The number of flights that left the ramp area and spent their unimpeded transit time from the ramp to the runway but did not take off.

This section describes the results of the analysis first in terms of their queuing buffer values needed to maintain throughput saturation and followed by the sensitivity of these values to a number of modeling parameters and conditions. All the results in this section were derived for one year of data (October 2011 through September 2012) at CLT, in the south runway configuration, landing runways 18R, 18C and 23 and departing runways 18C and 18L. The total number of departure operations during this year (that was reported in ASPM and analyzed) was 259,205 operations. Similar analyses can be produced for any runway in any airport for which similar data exist.

A. Queue Buffer Sizes

Figure 6 shows the throughput saturation curves for the first two queue parameters: the number of flights between the gate and the runway and the number of flights between the gate plus unimpeded transit time and the runway. Figure 7 shows the throughput saturation curves for the two parameters: the number of flights between the ramp and the runway and the number of flights between the ramp plus unimpeded transit time and the runway. All the plots shown are for runway 18C. Throughput saturation is evident in the plots where the throughout flattens as the queue parameters increase in value. For comparison of the queue buffers needed for throughput saturation, the onset of throughput saturation was considered at the point where the slope of the fitted hyperbolic curve is 0.005. In each plot a vertical line is drawn at this point to indicate the value of the parameter on the horizontal axis that corresponds to throughput saturation.
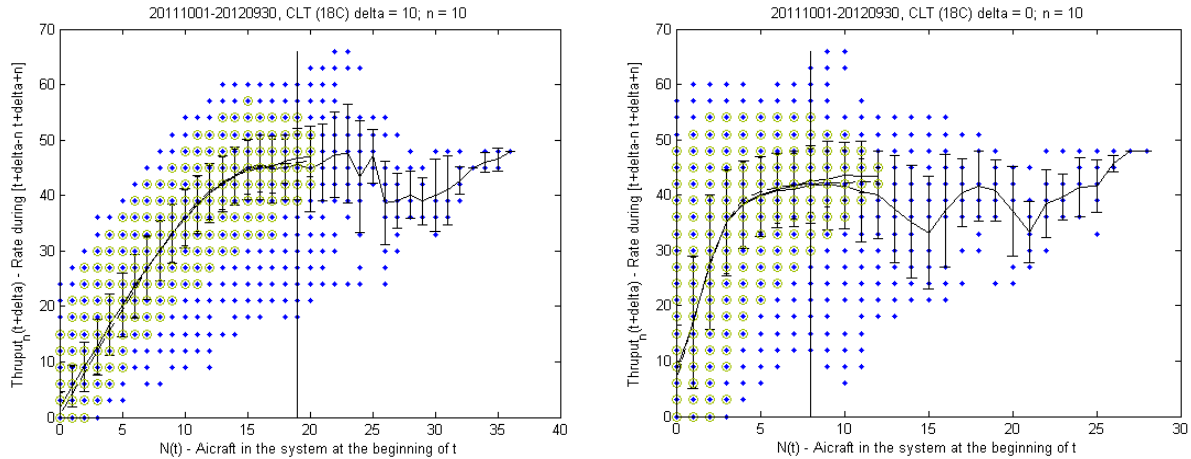
Figure 6. Throughput saturation analysis for CLT 18C (left: N is number of flights that left the gate but did not takeoff at t, right: N is number of flights that left the gate and spent unimpeded transit time from the gate to the runway but did not takeoff at t)
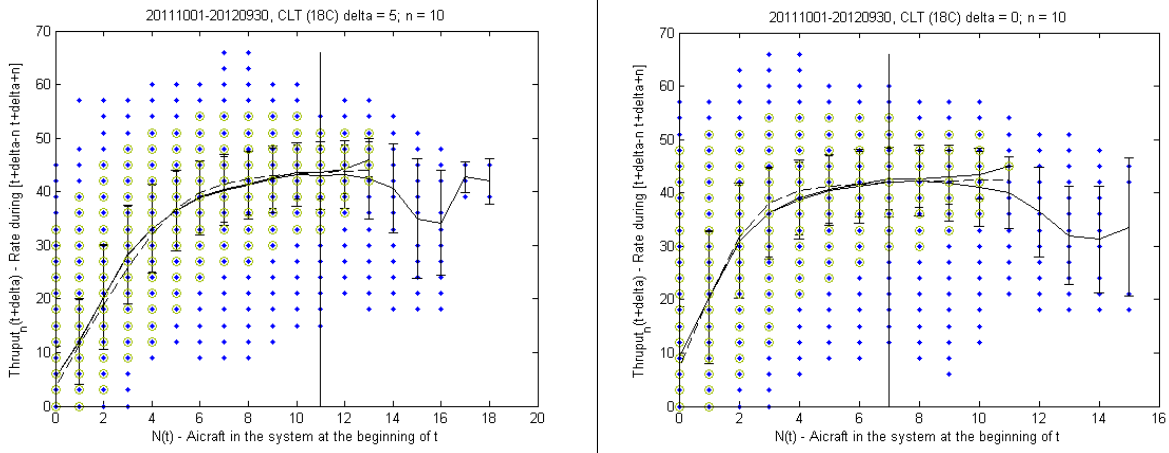

Figure 7. Throughput saturation analysis for CLT 18C (left: N is number of flights that left the ramp but did not takeoff at t, right: N is number of flights that left the ramp and spent unimpeded transit time from the ramp to the runway but did not takeoff at t)

The values of the queue buffers needed for throughput saturation (using the 0.005 slope point as a reference for comparison) are larger for the larger queues. This is expected since the throughput saturation is caused by the bottleneck resource which is the runway. As mentioned in the modeling section, measuring the number of flights that have waited their transit time (from the gate or from the ramp to the runway) but have not taken off attempts to approximate the physical queue at the runway. For these queues eight and seven flights, respectively, are sufficient to effect saturation. On the other hand a larger number of flights between the gate or the ramp and the runway (nineteen and eleven, respectively) is needed to guarantee the same number of flights physically queued at the runway to effect throughput saturation.

One observation from Figures 6 and 7 is that the asymptote saturation throughput is different for the different curves, despite the fact that it is a measure of the throughput capacity of the bottleneck resource, which is the same runway in all the cases. In order to understand this difference, note that the throughput numbers along the vertical axes are the same for all the plots, but they are plotted against different queue values on the horizontal axis in each of the plots. For example, in the left side plot of Figure 6, the throughput of a queue-throughput pair is plotted against the number of flights that have pushed back from the gate but not taken off at the same time instant. In the plot on the right side of the figure, the same throughput value is plotted against the number of flights that have

pushed back from the gate plus waited the unimpeded transit time and have not taken off at the same time instant. Therefore the horizontal queue value that corresponds to each throughput value is always smaller is the second plot relative to the first plot. This results in shifting the throughput data to the left along the horizontal axis leading to lower average throughput at each queue value in the second plot relative to the first plot. To reduce this effect one may remove some of the lull (low throughput, low queue) data points that do not contribute to the throughput saturation. (For example, the analysis can be conducted excluding night times.) However, removing this effect completely may be difficult to achieve and remains a question for further research. The sensitivity of the queue buffers and throughput saturation to the data filtering rate is discussed further in the next subsection.

Note: The throughput saturation point was selected at a slope of 0.005 of the throughput saturation curve. In a previous publication [19], Idris presented an analysis whereby iteration was performed on the throughput saturation point and a simulation of the metering process was conducted at each corresponding queue buffer value. The throughput that resulted in each iteration was measured and compared to the throughput from a baseline simulation without metering. The queue buffer that was just enough to maintain the throughput equal to the simulated baseline was selected as the desired buffer size for metering. This simulation approach will be performed in a follow on paper for the queue parameters analyzed in this paper.

B. Sensitivity to Data Filtering

The throughput saturation was detected by observing the trend in the throughput average at each queue value. This average encompasses a wide range of throughput values as evident in Figures 6 and 7. The wide range results from the variation in the airport and flight conditions surrounding each data point such as the weather condition, the rate of arrivals that occurred in each time window on which the rate of departures may depend, and the air traffic controller performance. In order to remove the rare off-nominal effects, the lowest frequency throughput-queue pairs were removed before the averaging and curve fitting were performed. The percent of data points removed becomes an important parameter that may affect the resulting throughput asymptote and the buffer values at throughput saturation.

Figure 8 shows the sensitivity of the saturation throughput and saturation buffer size to the percent of outlier data removed for the two gate-based queue parameters analyzed in the plots in Figure 6 for runway 18C. Figure 9 shows the same sensitivity analysis for the two ramp-based queue parameters analyzed in Figure 7 for runway 18C. The filtering percentage was increased (corresponding to decreasing the percentage of data included in the analysis shown in the plots) until the values of the saturation throughput asymptote and saturation buffer size stabilized as shown in Figure 8. The system and runway queues between the gate and the runway in Figure 8 showed less sensitivity to the filtering rate than the system and runway queues between the ramp and the runway in Figure 9.
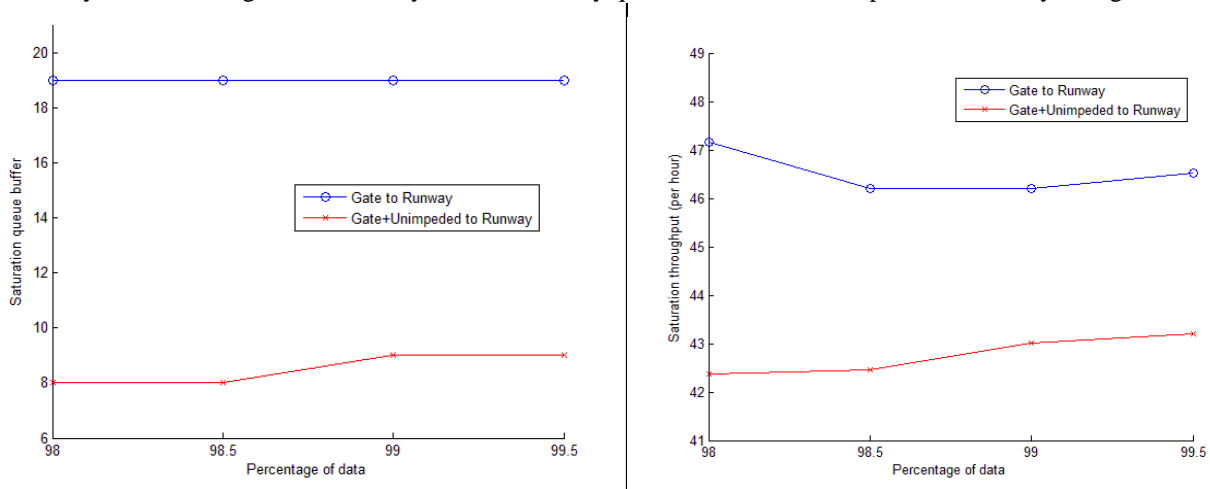

Figure 8. Throughput saturation sensitivity to outlier filtering for gate-to-runway queues for CLT 18C
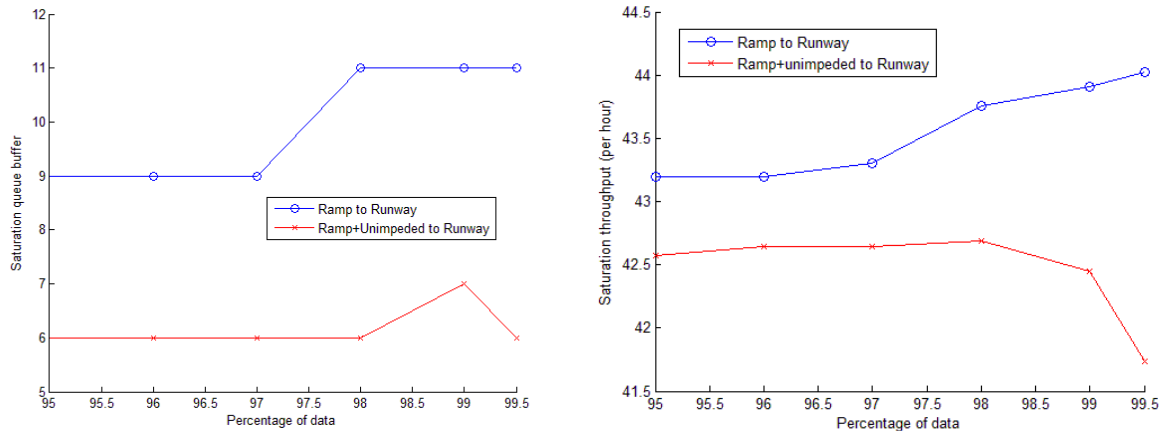
American Institute of Aeronautics and Astronautics

Figure 9. Throughput saturation sensitivity to outlier filtering for ramp-to-runway queues for CLT 18C

One interesting observation looking at the right side plot in Figure 9, is that as more outliers were removed (moving to the left along the horizontal axis), the saturation throughput decreased for the ramp to runway case (using the number of flights between leaving the ramp and takeoff). On the other hand, as more outliers were removed, the saturation throughput increased for the ramp-plus-unimpeded to runway case (using the number of flights that left the ramp plus waited the unimpeded transit time but did not takeoff). This indicates that the asymptote saturation throughput is over-estimated in the first case while under-estimated in the latter case. As mentioned above the asymptote throughput in both cases is for the same runway and they should approach each other as the estimate becomes more accurate. However, while they approached each other, this filtering was not sufficient to completely close the gap between them and further filtering may be investigated in future research. One may select the buffer sizes at filtering points where the two saturation throughputs are closer to each other, such as at ninety six percent (four percent removed). The plots in Figures 6 and 7 were generated with ninety nine percent of the data (i.e., one percent removed).

C. Sensitivity to Configuration

Figures 10 and 11 show the queue buffer and throughput saturation results for the gate-to-runway and ramp-to-runway queues for runway 18L as a function of the filtering percentage for comparison with the ones of runway 18C in Figures 8 and 9. The queue buffer sizes are different for the two runways: for example, runway 18C required nine flights between the ramp and the runway and six flights between the ramp plus unimpeded transit to the runway and the runway to effect saturation. On the other hand, runway 18L required less queues to saturate: only six to eight flights between the ramp and runway and only four to six flights between the ramp plus unimpeded transit and the runway, depending on the filtering rate used. One of the differences between the two runways is their proximity to the gates where runway 18L is closer than runway 18C. Another difference between the two runways under this runway configuration is their dependence on arrivals: runway 18C is used for both arrivals and departures while runway 18L intersects runway 23 which is used for arrivals. (Sensitivity to the arrival rate is discussed in the next subsection.) Therefore, in general, one should not assume that the queue buffers are the same for all runways; rather different queue buffers should be derived and used for the different runways under different configurations.
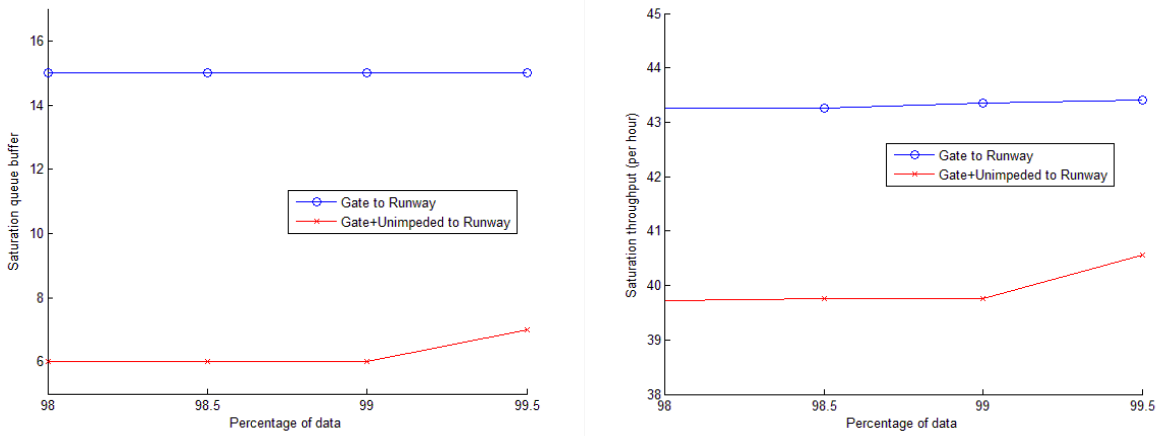
Figure 10. Throughput saturation sensitivity to outlier filtering for gate-to-runway queues for CLT 18L
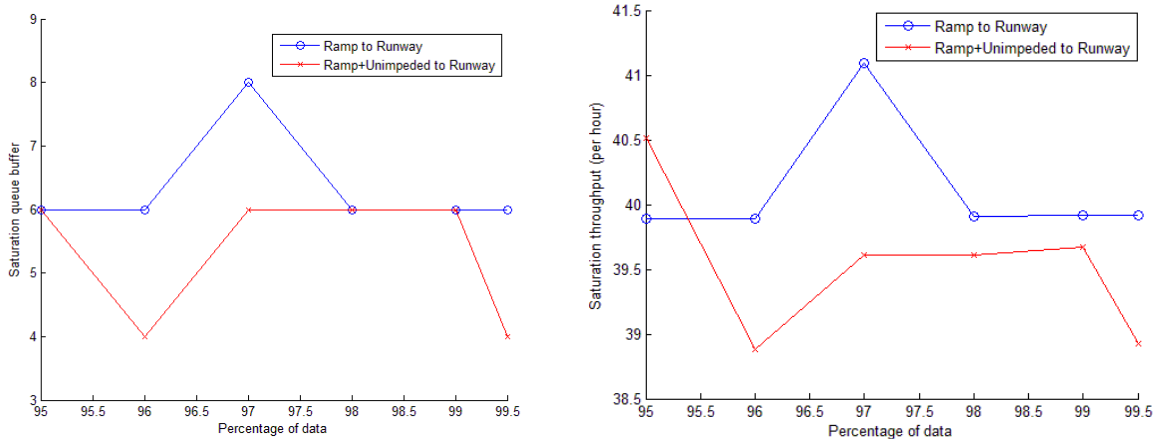

Figure 11. Throughput saturation sensitivity to outlier filtering for ramp-to-runway queues for CLT 18L

D. Sensitivity to Arrival Rate

A preliminary investigation of the sensitivity of the throughput saturation and queue buffer sizes to the arrival rate on the same or dependent runways was performed. In the year analyzed, the number of arrivals on runway 18C was 22882 flights compared to a number of departures of 80926 flights on the same runway. In the same year, the number of arrivals on runway 23 which crosses runway 18L was 92756 flights compared to a number of departures on runway 18L of 99171 flights. The analysis was conducted for runway 18L which showed more impact than 18C because of a wider range of arrival rates on it. The throughput saturation analysis was repeated for different arrival rates, ranging between 5 and 50 arrivals an hour as shown in Figure 12. The figure shows the queue buffers for the queues between leaving the gate and takeoff and between leaving the gate plus waiting the unimpeded transit time to the runway and takeoff. Clearly the departure throughput decreases as the arrival rate increases due to the interdependence between them. There was a slight indication that a smaller queue buffer may be sufficient to saturate the departure throughput when the arrival rate is higher as can be seen from the buffer of the queue between leaving the gate and takeoff. However, the trend is not as clear for the queue buffer for the queue between leaving the gate plus waiting the unimpeded transit time to the runway and takeoff. While further investigation is needed, it remains not completely conclusive that the queue buffers should be set differently depending on the expected arrival rate.
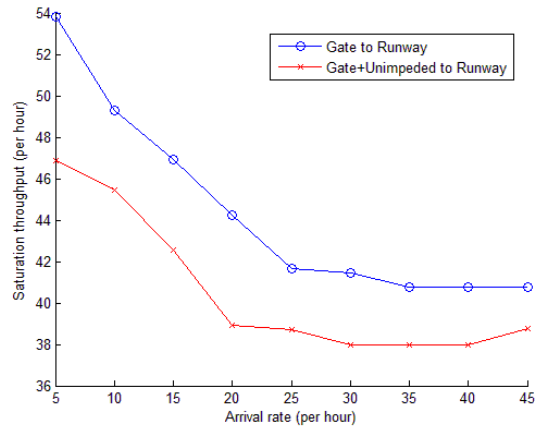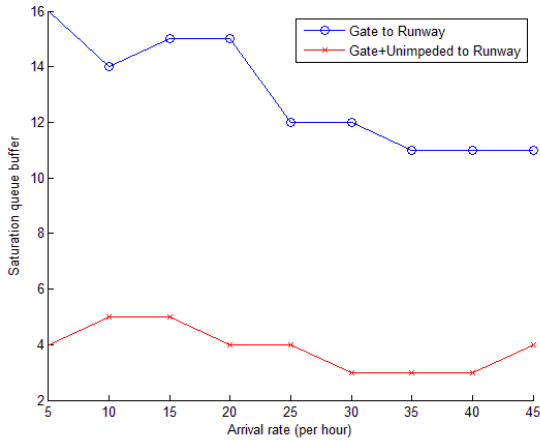
American Institute of Aeronautics and Astronautics

Figure 12. Throughput saturation sensitivity to arrival rate for gate-to-runway queues for CLT 18L

E. Sensitivity to Unimpeded Transit Time Model

The unimpeded transit time is an important parameter when estimating the buffer size of the runway queues: the number of flights that spent the unimpeded transit time from the gate/ramp to the runway after leaving the gate/ramp (respectively) and did not takeoff. The unimpeded transit time was modeled statistically as described in the modeling section III.B. Hence this model may affect the resulting throughput asymptote and buffer sizes at throughput saturation. In this analysis the unimpeded transit time was modeled as distributions for each carrier-runway combination under each runway configuration. Using these distributions, the following parameters where used as estimates of the unimpeded transit time: (1) sampling from the distribution randomly (2) the distribution mean (3) the distribution mode (4) the distribution median and (5) the tenth percentile of the distribution. The sensitivity of the throughput asymptote and the buffer size at throughput saturation to these methods was analyzed for each of the runway queue parameters; the results are shown in Figure 13 for runway 18C and Figure 14 for runway 18L.
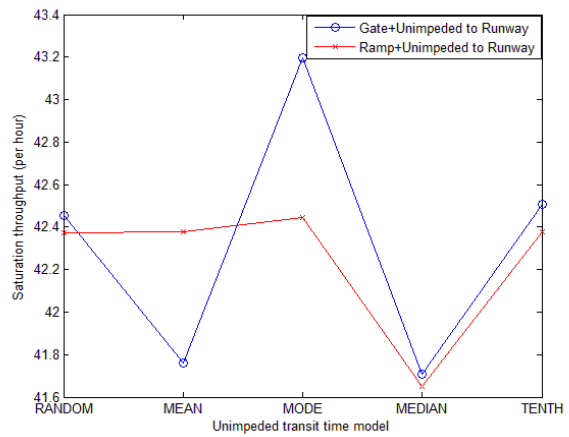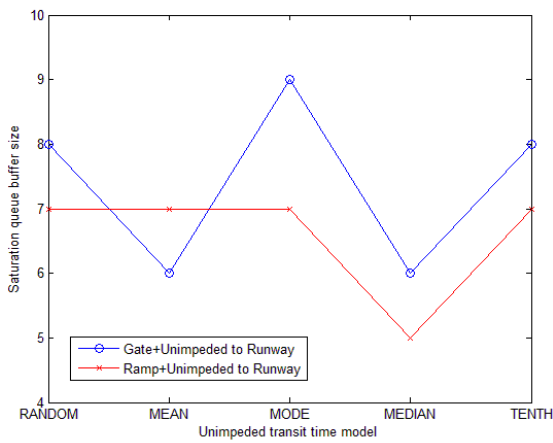

Figure 13. Throughput saturation sensitivity to unimpeded transit time model for CLT 18C
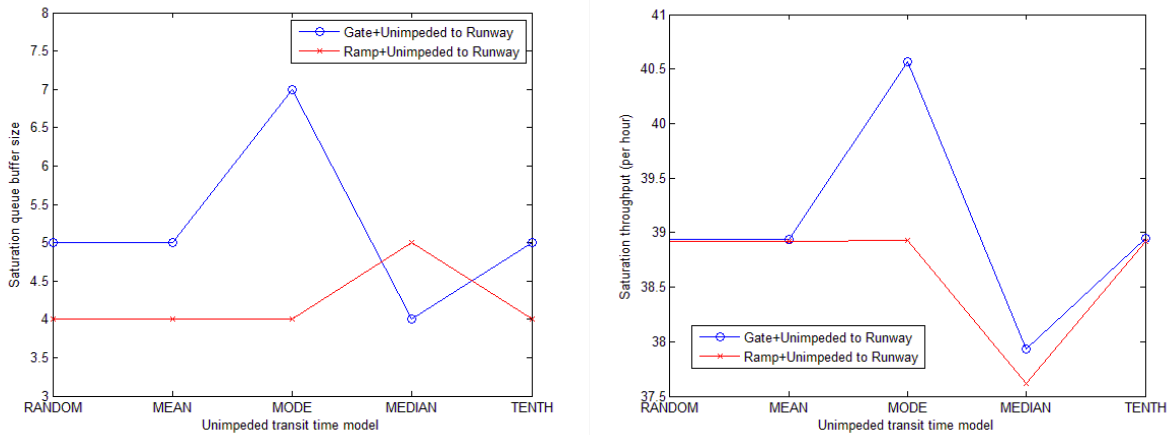
American Institute of Aeronautics and Astronautics

Figure 14. Throughput saturation sensitivity to unimpeded transit time model for CLT 18L

Figures 13 and 14 show that the queue buffers and saturation throughput have significant sensitivity to the unimpeded transit time. Generally, using the tenth percentile and the mode resulted in higher saturation throughput and correspondingly higher buffer sizes than the other estimates. The tenth percentile and the mode are lower estimates of the unimpeded transit time than the mean and the median and therefore result in larger saturation queue buffer values in general. Considering that the throughput capacity (throughput saturation) are under estimated when using the runway queues compared to using the system queues (as indicated in Figures 8-12), it is more conservative in terms of maintaining higher throughput to use the larger buffers sizes that are estimated from the lower unimpeded transit time estimates: the mode or the tenth percentile. The plots shown in Section IV.A and all the sensitivity analyses in the previous subsection were generated using the mode of the unimpeded transit time.

Note: The unimpeded transit time model is also important for estimating and predicting the demand for the runway and the resulting queues, which is needed in order to control the queues to the desired buffer sizes. Using the mode or tenth percentile will result in more conservative metering in terms of maintaining throughput using larger runway queue buffers.

IV. Conclusions

Historical data analysis was conducted to assess the size of the queue buffers needed for strategic departure metering and scheduling in support of NASA's integrated arrival and departure concept ATD-2. Using a throughput saturation analysis, the buffers sizes were determined at a level that is just sufficient to maintain maximum runway throughput. The statistical models used in the analysis were generated using the full fiscal year of 2012 at CLT airport. By combining ASPM and ASDE-X data bases it was possible to generate buffer sizes for each runway and for four different queue definitions that are considered for ATD-2 strategic scheduling: Two system queues defined as the number of flights between the gate and the runway and between the ramp and the runway, and two runway queues defined as the number of flights that have spent their unimpeded transit time since leaving the gate and leaving the ramp, respectively but have not taken off from the runway. Sensitivity analyses were conducted showing that the runway queue buffers are different for different runways, are sensitive to the unimpeded transit time model used and are to some extent sensitive to the arrival rate.

Acknowledgment

References

[1] Idris H., "Identification of Local and Propagated Queuing Effects at Major Airports," Presented at the AIAA Aviation Forum, Aviation Technology, Integration and Operations (ATIO) conference, Dallas, TX, July 2015.

American Institute of Aeronautics and Astronautics

[2] Swenson H., Thipphavong J., Sadovsky A., Chen L., Sullivan C., and Martin L., "Design and Evaluation of the Terminal Area Precision Scheduling and Spacing System." Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011), Berlin, Germany, 2011.

[3] Thipphavong J., Swenson H., Lin P., Seo A. and Bagasol A., "Efficiency Benefits Using the Terminal Area Precision Scheduling and Spacing System." AIAA Aviation Technology Integration and Operations (ATIO), Virginia Beach, VA. 2011.

[4] Hayashi M., Hoang T., Jung Y., Gupta G., Malik W., and Dulchinos V., "Usability Evaluation of the Spot and Runway Departure Advisor (SARDA) Concept in a Dallas/Fort Worth Airport Tower Simulation." Tenth USA/Europe Air Traffic Management Research and Development Seminar, Chicago, IL. 2013.

[5] Brinton C., Provan C., Lent S., Prevost T., and Passmore S., "Collaborative Departure Queue Management," Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011), Berlin, Germany. 2011.

[6] Simaiakis I., Khadilkar H., Balakrishnan H., Reynolds T., Hansman R.J., Reilly B., and Urlass S., "Demonstration of Reduced Airport Congestion Through Pushback Rate Control," Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011), Berlin, Germany. 2011.

[7] Engelland, S., Capps, A., Day, K., "Precision Departure Release Capability (PDRC) Concept of Operations," NASA/TM−2013-216534, June 2013.

[8] Engelland S. and Capps A., "Trajectory-Based Takeoff Time Predictions Applied to Tactical Departure Scheduling: Concept Description, System Design, and Initial Observations," 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, 2011.

[9] Gupta G., Malik W., and Jung Y., "Incorporating Active Runway Crossing in Airport Departure Scheduling." AIAA Guidance, Navigation, and Control Conference, Ontario, Canada, 2010.

[10] Capps A., Kistler M. and Engelland S., "Design Characteristics of a Terminal Departure Scheduler," 14th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, 2014.

[11] Zelinski S., "A Framework for Integrating Arrival, Departure and Surface Operations Scheduling," 33rd Digital Avionics Systems Conference (DASC), October 5-9, Colorado Springs, CO, 2014.

[12] Callantine T., Kupfer M., Martin L, Mercer J., and Prevot T, System-Level Performance Evaluation of ATD-1 Ground-Based Technologies. 14th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Atlanta, GA, 2014.

[13] Xue M. and Zelinski S., "Dynamic Stochastic Scheduler for Integrated Arrivals and Departures", 33rd Digital Avionics Systems Conference (DASC), October 5-9, Colorado Springs, CO, 2014.

[14] Bosson C., Xue M., and Zelinski S., "Optimizing Integrated Terminal Airspace Operations Under Uncertainty", 33rd Digital Avionics Systems Conference (DASC), October 5-9, Colorado Springs, CO, 2014.

[15] Bertsimas D., "Air Traffic Flow Management at Airports: A Unified Optimization Approach," Tenth USA/Europe Air Traffic Management Research and Development

[16] Aponso B., Coppenbarger R., Jung Y., Quon L., Lohr G., O'Conner N., and Engelland S., "Identifying Key Issues and Potential Solutions for Integrated Arrival, Departure, Surface Operations by Surveying Stakeholder Preferences," 15th AIAA Aviation Technology, Integration, and Operations (ATIO), Dallas, TX, 2015.

[17] Chevalley E., Parke B., Kraut J., Bienert N., Omar F., and Palmer E., "Scheduling and Delivering Aircraft to Departure Fixes in the NY Metroplex with Controller-Managed Spacing Tools," 15th AIAA Aviation Technology, Integration, and Operations (ATIO), Dallas, TX, 2015.

[18] Shen N., H. Idris, and V. Orlando, 2012, Estimation Of Departure Metering Benefits At Major Airports Using Queuing Analysis, 31st Digital Avionics Systems Conference, Williamsburg, VA, Oct.

[19] Idris H. and N. Shen, 2014, Impact of Gate Availability on Departure Metering Benefit, 14th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Atlanta, Georgia.

[20] Nakahara, A., and T. G. Reynolds, 2012, An Approach for Estimating Current and Future Benefits of Airport Surface Congestion Management Techniques, 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Indianapolis, Indiana.

[21] Simaiakis, I., and H. Balakrishnan, 2009, Queuing Models of Airport Departure Processes for Emissions Reduction Techniques, Proceedings of the AIAA Guidance, Navigation and Control Conference.

[22] Idris, H., A. Evans, S. Evans, and D. Kozarsky, 2004, Refined Benefits Assessment of Multi-Center Traffic Management Advisor for Philadelphia and New York, 4th AIAA Aviation Technology, Integration, and Operations (ATIO) conference, Chicago, IL.

[23] Evans A. and . Idris, Estimation of Arrival Capacity and Utilization at Major Airports, 6th USA/Europe Air Traffic Management Research and Development Seminar, Baltimore, Maryland, June 27 – 30.

[24] Pujet, N., 1999, Modeling and Control of the Departure Process of Congested Airports, PhD Thesis. Cambridge, Massachusetts Institute of Technology.

[25] Idris H., J-P Clarke, R. Bhuva, and L. Kang, 2002 Queuing Model for Taxi-Out Time Estimation, Air Traffic Control Quarterly Journal, Volume 10, Number 1.

[26] Saraf A., Timar S., Shen N., and Idris H., "Preliminary Queuing Analysis of Integrated departure operations in metroplex systems," 34th Digital Avionics Systems Conference, Prague, Czech Republic, September 13-17, 2015.