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14. ABSTRACT

AS A PART OF THE DEVELOPMENT OF THE TOWER FLIGHT DATA MANAGER, IT IS NECESSARY FOR THE WEATHER SENSING GROUP AT MIT LINCOLN LABORATORY TO DEVELOP DECISION SUPPORT TOOLS TO GIVE AIRPORT GROUND AND DEPARTURE CONTROLLERS ACCESS TO INCREASED AMOUNTS OF INTUITIVELY-DISPLAYED REAL-TIME DATA, WITH THE GOAL OF MAKING ROUTING DECISIONS FOR AIRCRAFT MORE EFFICIENT. THE QUESTION OF CONFIGURATION CHANGE (THE DIRECTION, NORTH OR SOUTH AT DALLAS-FORT WORTH INTERNATIONAL AIRPORT, TOWARD WHICH AIRCRAFT LAND AND TAKE OFF) IS AN ELEMENT OF THIS PROCESS. WITHIN A DATA SET CONSISTING OF 20 DAYS WITH 28 CONFIGURATION CHANGES, IT WAS CALCULATED THAT THE DECISION TO CHANGE THE CONFIGURATION OF DFW COST PLANES WAITING IN QUEUE APPROXIMATELY 1 MINUTE ON THE GROUND ON AVERAGE, AND A CONFIGURATION CHANGE DOUBLES THE CHANCE THAT AIRCRAFT WAIT MORE THAN 5 MINUTES IN QUEUE. FURTHER, IT CAN BE REASONABLY SUGGESTED THAT A PROPORTIONAL RELATIONSHIP EXISTS BETWEEN QUEUE TIME AND TIME OF DAY, AS WELL AS BETWEEN QUEUE TIME AND OVERALL DELAY.

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Configuration Changes at DFW

Analysis of Existing Conditions

FAA Contract Approved
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9/1/2010

ABSTRACT

As a part of the development of the Tower Flight Data Manager, it is necessary for the Weather Sensing Group at MIT Lincoln Laboratory to develop Decision Support Tools to give airport ground and departure controllers access to increased amounts of intuitively-displayed real-time data, with the goal of making routing decisions for aircraft more efficient. The question of configuration change (the direction, North or South at Dallas-Fort Worth International Airport, toward which aircraft land and take off) is an element of this process. Within a data set consisting of 20 days with 28 configuration changes, it was calculated that the decision to change the configuration of DFW **cost planes waiting in queue approximately 1 minute on the ground on average**, and a configuration change **doubles the chance that aircraft wait more than 5 minutes in queue**. Further, it can be reasonably suggested that **a proportional relationship exists between queue time and time of day, as well as between queue time and overall delay.**

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Acknowledgements

This report would not have been possible without the constant support and guidance of the MIT Lincoln Laboratory Weather Sensing Group. Significant thanks are due to Mariya Ishutkina, Richard Jordan, Tom Reynolds, Robert Hallowell, David Clark, Lionel Sotomayor, Bhrett Parrish, Tanya Kortz, Jessica Montana and Dr. James Kuchar of Group 43, as well as Gary Hackett, Kristy Wood, Asher McGuffin, Casey Hanson, Adam Heskitt, Catherine Lee and Garrett Bernstein of MIT Lincoln Laboratory.

Introduction

Tower Flight Data Manager and Decision Support Tools

The Tower Flight Data Manager (TFDM) is a set of Decision Support Tools (DSTs) and displays intended to replace the existing system of paper flight strips currently in use in the vast majority of major US control towers. At the core of the system is a new system of information touch-screens utilizing electronic flight strips, significantly easier to edit and more efficient to transfer. For the first time, controllers will be able to access information on any aircraft on the airfield (shown in its close geographical position) with a touch screen.

The development process for this new system has also been undertaken by the Weather Sensing Group as an opportunity to conceive and construct additional DSTs for a number of operational issues which commonly effect airport safety and efficiency, airport configuration being one such issue.

Ideally, a DST provides condensed, filtered, relevant information to controllers, allowing them to make more informed decisions. In the case of configuration changes, the DST could be pictured in several forms. In one vision, a controller will be able to set the time of a desired configuration change and the DST will display an anticipated delay profile. This report represents the first step in developing such a tool: the analysis of existing conditions.

Dallas-Fort Worth International Airport – Conditions and Procedures

DFW Airport is the test site for the TFDM system and the target of this study. The airfield consists of 7 non-intersecting runways, with 4 central north-south runways carrying most of the operations:

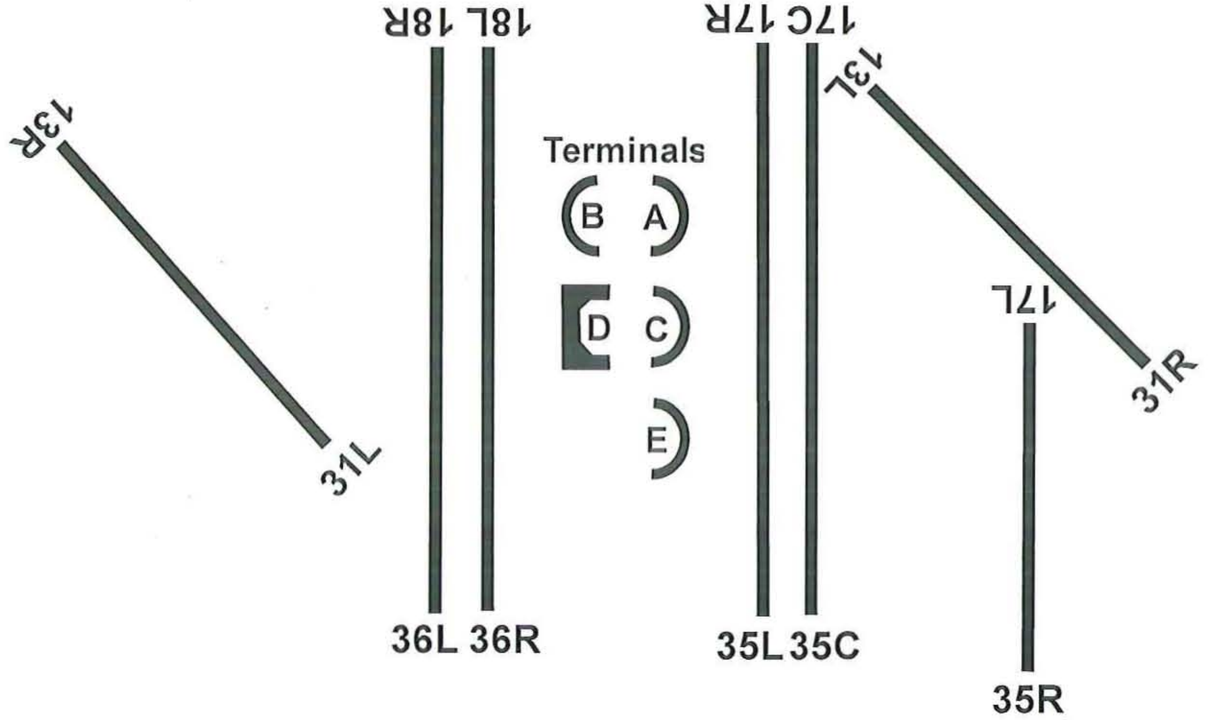

Figure 1 - Layout of DFW Airport (Credit: Richard Jordan)

DFW airport operates under FAA configuration selection procedures. As at all airports, the direction of take-offs and landings is chiefly determined by wind direction and intensity, defined as follows:

- **Tailwind (TW)** - measured in knots: Refers to the component of the wind vector (direction and magnitude) which has the same heading as the aircraft, which is equivalent to that of the runway during take-offs and landings. Roughly, it is calculated as velocity multiplied by the sine of the difference between the headings of the runway and the wind. Negative tailwind is synonymous with positive **Headwind (HW)**.

$$TW = Vel_{wind} \times \cos(h_{wind} - h_{RW})$$

- **Crosswind (CW)** - measured in knots: Refers to the component of the wind vector perpendicular to the runway/aircraft heading.

$$CW = Vel_{wind} \times \sin(h_{wind} - h_{RW})$$

At major commercial airports in the United States, the following wind limits apply to aircraft operations[i]:

- **TW/HW**: The FAA recommends a configuration change when tailwind exceeds 7 Kn (HW < -7Kn). Most commercial airliners can operate in tailwind up to 10 Kn, which is the standard most often used at DFW. When tailwind exceeds 10 Kn, a change will likely be initiated.
- **CW**: Under ideal surface conditions, the FAA mandates a configuration change when crosswind exceeds 20 Kn. At DFW, these changes shift all traffic to the diagonal "crosswind" runways.

In addition to the general standards, DFW maintains its own standard for configuration during the warmer months:

> *Between April 1st and November 1st, when the centerfield wind at DFW is 5 knots or less, the landing and departure direction is south flow. North flow is not normally preferred on "high temperature days" due to poor aircraft climb performance in conjunction with potential satellite departure conflicts.*[ii]

In summary, it should be expected that a major directional change will occur at DFW when one of the following happens (or is expected to happen):

- Tailwind exceeds 10 Kn (though one may occur at 7 Kn)
- Crosswind exceeds 20 Kn and would be lower in a new configuration
- Tailwind drops below 5 Kn when airport is in northbound configuration

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[i] As per "National Safety and Operational Criteria for Runway Use Programs," FAAO 8400.9

[ii] "DFW ATCT Air Traffic Control: DFW 7110.65", Ch. 9, Sec. 1, Sub-Sec. 6

Methodology and Data Selection

An analysis of the operational impact of ATC decisions can be reduced to 3 simple questions:

1. **What happened**: What patterns can be identified in the data?
2. **Why did it happen**: What are major influences (i.e. weather or behavior) on decision-making?
3. **What was the impact?**

For an analysis of existing conditions for configuration changes at DFW, these questions translate to:

1. How often did configuration changes occur?
2. Why do controllers at DFW initiate configuration changes?
3. What effect does a configuration change have on delays (specifically departure queues)?

Ideally, the study will eventually answer an additional question:

4. How is the queue effect of a certain configuration change related to the timing, demand/weather conditions, or reason for the configuration change? Can we predict longer or shorter delays based on any of these factors?

Data Acquisition and Selection of Analysis Days

Data on weather and airport operations were acquired from the following sources:

- Data on all departures and arrivals were acquired from post-processed Runway Status Lights (RWSL) data. Included for departures were Unique ID (usually flight number), runway, queue enter and leave times, time spent in queue, and wheels-off time. "Queue" in this context refers to a box defined on the taxiway covering the between 1 and 3 queue lanes for each runway:

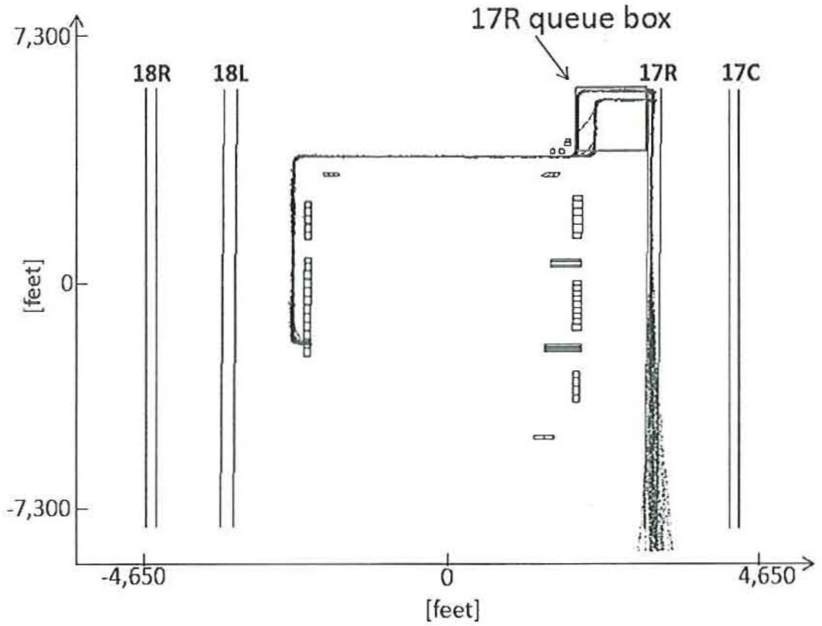
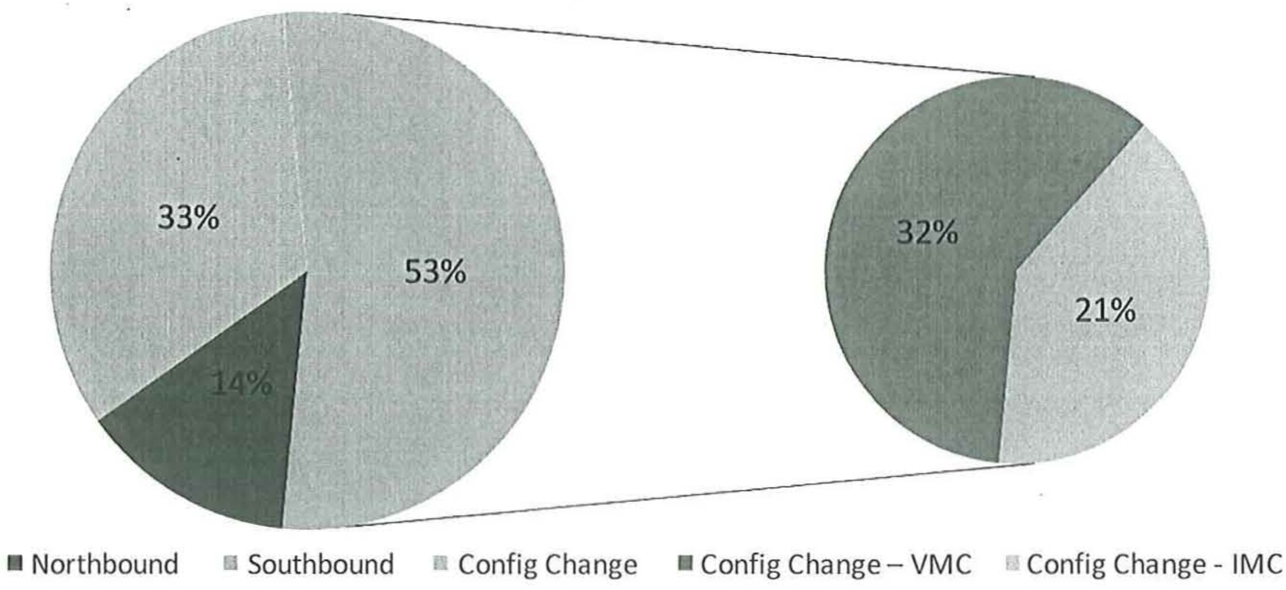


Figure 2 - Diagram Showing Queue Box Location (Credit: Mariya Ishutkina)

- Data on runway configuration were acquired from the FAA Airport Performance Metrics (APM) online archive[iii]. The APM provided change times accurate to the hour, which were then refined using the departure data. "Change time" is generally defined as the wheels-off time for the first aircraft to depart in the new configuration.
- Data on wind conditions were acquired from the National Weather Service/FAA Automated Surface Observation System at DFW (ASOS)[iv]. Wind velocity and direction used in tailwind and crosswind calculations were taken over 5 seconds every minute. Ideally, data were available for all 24 hours of a given day, but many days had sizable gaps.

The set of available days was first established by the days for which Lincoln could archive RWSL data and store it for use with TFDM (see **Appendix B-1**). This set, spread over approximately 30 months from Fall 2008 to Summer 2010, contained 198 days. The first step to condensing the data set from 198 days to 20 was to isolate only the days when a configuration during uninterrupted high visibility (VMC, as opposed to IMC) to eliminate the variability of visibility in the analysis. To accomplish this, the days were broken down by configuration and those with changes further divided according to visibility:

Figure 3 - Distribution of Sample Days by Configuration and Visibility Conditions



Within the 27% of the set (54 days) where configuration changes occurred on VMC days, days were further eliminated by several factors:

- **Data Availability**: Some days in the sample either weren't available for analysis or were missing crucial data. These days were eliminated.
- **Data Disagreement**: Many configuration changes recorded by APM were not evident in the RWSL data. This could be because a single flight or a very few flights used a different configuration for reasons other than a full change, and APM recorded a change in error.
- **Early Morning Changes**: There is a significant trend at DFW to change airport configuration between 5-7 AM (almost 50% of days with changes experienced one in that period), perhaps because that is when traffic begins to increase, or because the configuration cannot be changed before that time by airport policy/procedure. Because there was little traffic that early, and because those changes often did not correspond to significant wind shifts, days with *only* an early morning change were excluded.

Once these criteria were applied, the set was reduced from 54 VMC days to a final set of 20 (one of the days, 2/3/10, is not VMC – it was included for comparison purposes). For detail on these changes, see **Appendix B-2**:

Table 1 - List of Days in Data Set

10/1/2008	12/5/2008	2/1/2009	2/2/2009	2/3/2009
2/4/2009	2/11/2009	2/16/2009	8/5/2009	8/27/2009
11/3/2009	11/26/2009	1/12/2010	1/26/2010	2/3/2010
2/24/2010	5/3/2010	5/5/2010	5/17/2010	5/27/2010

[iii] http://aspm.faa.gov/apm/sys/default.asp

[iv] ftp://ftp.ncdc.noaa.gov/pub/data/asos-onemin/

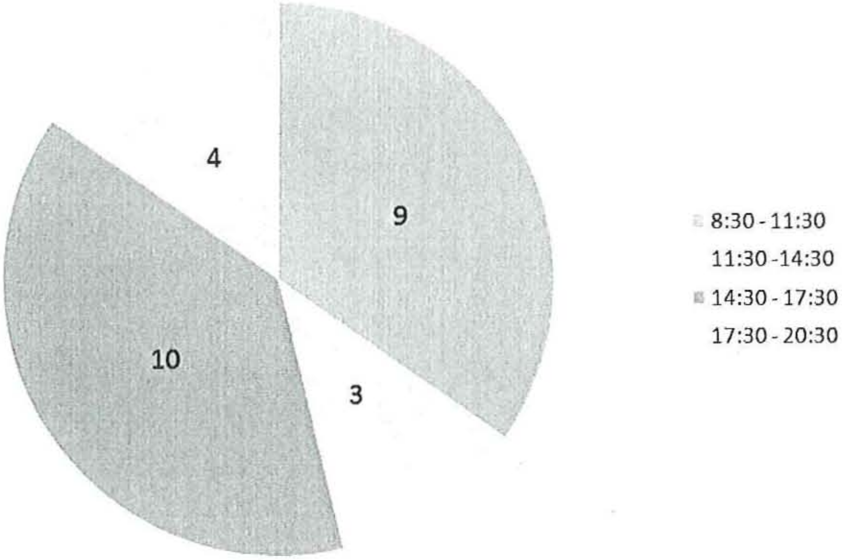
Analysis and Interpretation of Results

Patterns in Configuration Changes

Time of Day

Among the 20 query days, there exist 29 configuration changes (the greatest number on any one day is 4, on 8/27/9). Of the 26 changes which did not occur between 5:00 and 7:00, the changes were roughly clustered in a pair of 3-hour periods in the late morning and afternoon:

Figure 4 - Distribution of Configuration Changes by Time of Day



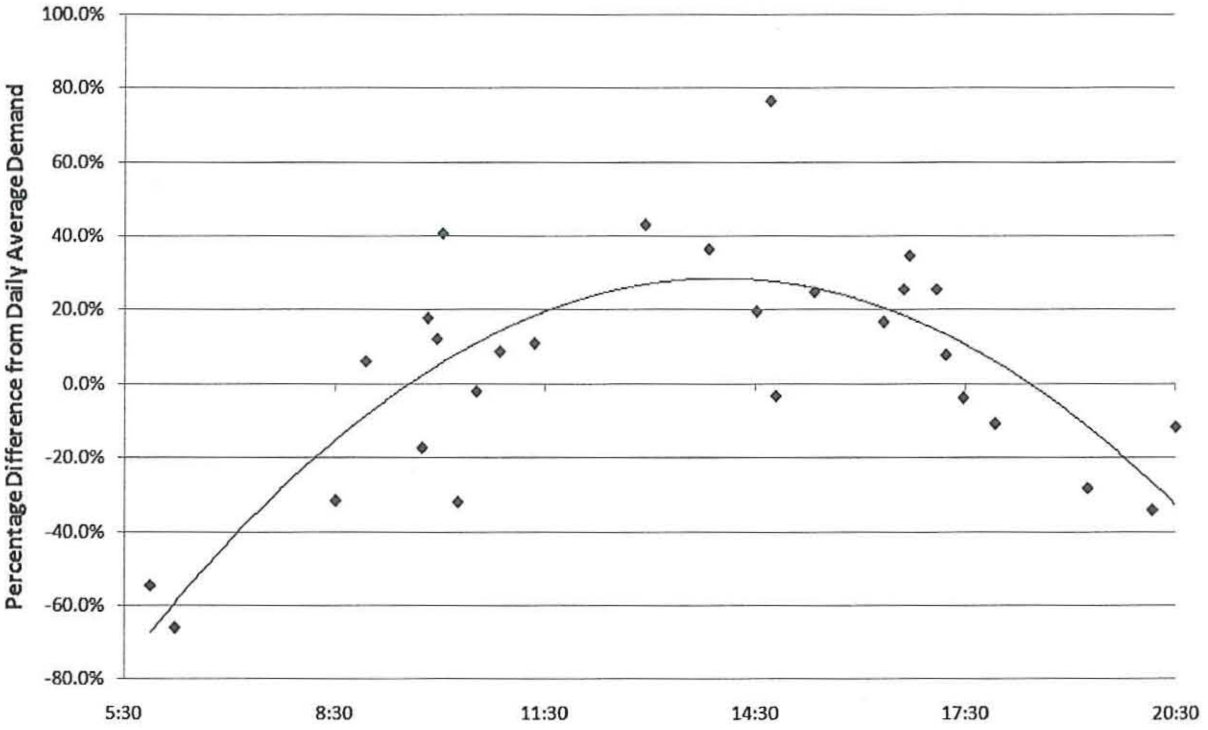
Demand

Because the configuration changes clustered at times when high utilization would be expected at any airport, and certainly at a major international airport such as DFW, the hypothesis was made that changes were being conducted at periods of high demand. The demand data were obtained from the APM in the form of scheduled wheels-off times.

Scheduled times were used as opposed to actual times to eliminate the effects of any convective weather or the configuration change itself on the activity profile. If the actual times were used, delays caused by these unique daily factors would appear in the data. Since these departure times would then be disconnected from what was intended, the scheduled times were used to make the results applicable to any day as opposed to the particular days in question.

The demand average was taken over the period between 5:00 and 22:00 to limit the range to the airport's active period. The percentage difference was taken between the demand within 40 minutes of the configuration change (the number of flights scheduled to take off during that period) and the overall average for that day. The plot resembles the demand curve for any single day (see **Appendix A-1/C-4**):

Figure 5 - Profile of Demand at Moment of Configuration Changes vs. Time of Day

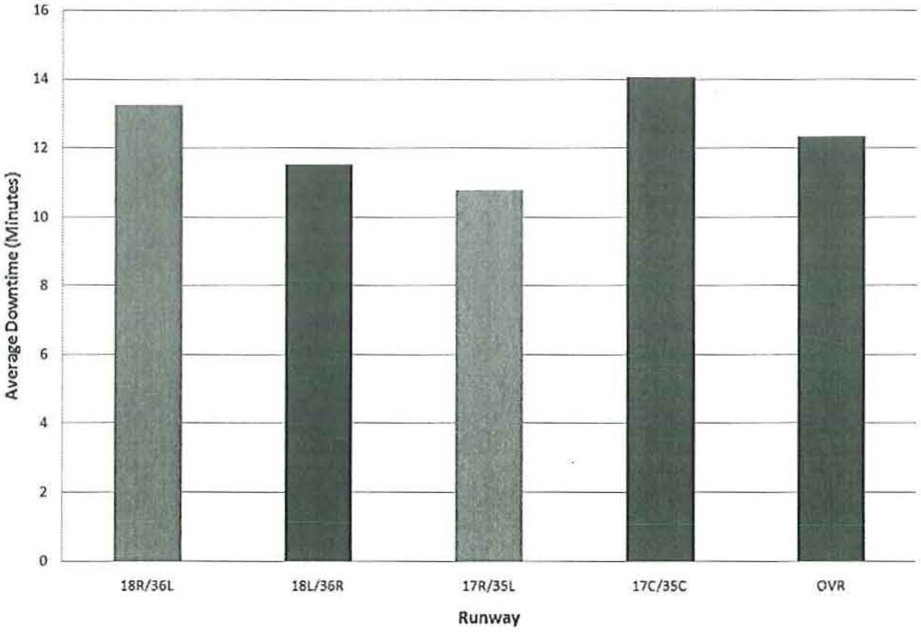


Downtime

A third attribute identified for the configuration changes was downtime, the period when the runway is cleared and shut down between changes. If the downtime is excessive, flights build up in queue behind the change, as well as potentially accumulating in gates, on ramp areas, or on the shoulders of taxiways.

A runway at DFW is shut down for an average of between 12 and 13 minutes during a configuration change. The airport as a whole shuts down for an average of 4 minutes (runways shut down and reopen at different times).

Figure 6 - Average Runway Downtime by Runway



Explanations for Configuration Changes

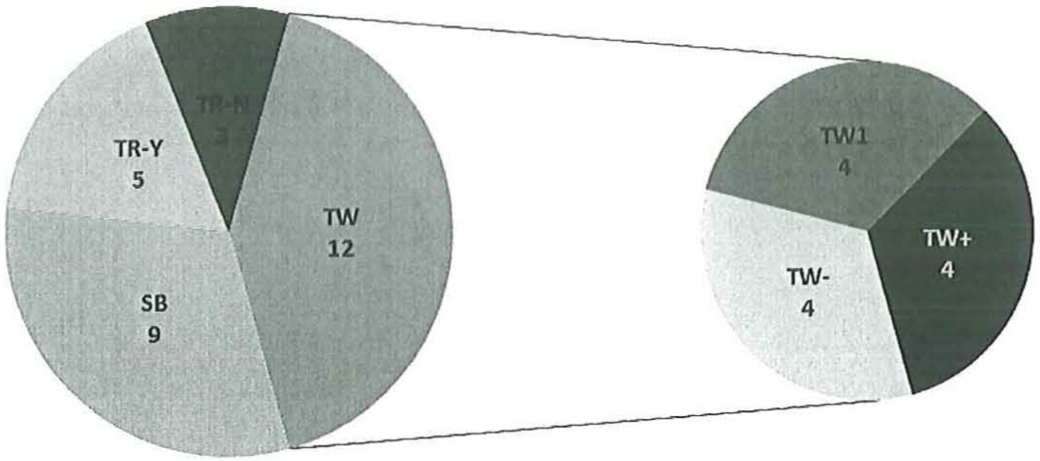
To give explanations for configuration changes based on wind conditions, the tailwind and crosswind were plotted for all of the days on which configuration changes occurred (for examples, see **Appendix A-3**). Based on these plots, the following categories of configuration changes were identified:

- **Tailwind-Induced Changes (TW)**: Changes which directly followed instances of 10 Knot tailwind violations (within 2 hours) were marked as TW. These changes were required by regulation and were further divided by the amount of time that elapsed between the initial violation (the first time tailwind dropped below 10 Knots in the 2-hour window) and the time of the change:
    - **TW-**: Less than 1 hour elapsed (this was the most efficient type of change)
    - **TW1**: Approximately 1 hour elapsed between violation and change.
    - **TW+**: More than 1 hour elapsed between violation and change.

  The average duration between violation and change was almost exactly 1 hour. This time can be accounted for by the procedures to ask supervisors for permission to change, as well as informing stakeholders (Dallas Center, other airports) that change was imminent.
- **Southbound Preference Changes (SB)**: These changes resulted from airport procedures, as outlined earlier, that the direction should be reversed when headwinds in northbound configuration drop below 5 knots. Because these changes were not crucial to the functioning of the airport, a major question for queue analysis and correlation is whether they had a greater or lesser impact than other changes.
- **Trend Extrapolation Changes (TR)**: These changes occurred simultaneously with a trend which could be extrapolated to a tailwind violation in the near future. It could be conjectured that controllers initiated the change in response to the trend. They are further divided based on the success or failure of the trend to indeed cause a violation had the airport remained in its original configuration (**TR-Y** or **TR-N**).

All 29 configuration changes in the data set fell into one of the three categories (for a wind plot example of each, see **Appendix A-2**):

Figure 7 - Distribution of Configuration Changes by Explanation



Effects of Configuration Changes

The effect of configuration changes on air traffic can be measured by several metrics. In addition to departure queue times, which will form the heart of this analysis, it is also possible to analyze the number of flights which waited excessively or the length of the queue.

Departure Queue Times

As previously mentioned, the queue data used here comes from the record of all flights picked up by DFW's RWSL system. Before the data were used for analysis, it was filtered to eliminate flights which either had faulty reports or were statistical outliers for reasons unrelated to configuration changes. Among the types of reports eliminated:

- Multiples (as indicated by multiples of a single unique ID)
- Reports which did not include a key piece of data (usually a "0" for queue enter or leave time, or for the queue duration itself).
- Reports which included excessively long queue times: As a rule, any flight which queued for over 1000 seconds (approximately 30 minutes) was considered to have a unique situation which demanded that it wait in queue. Possible explanations include weather along route or mechanical trouble. Exceptions were made for instances where queue times rose above 1000 seconds for all flights at the airport, but typically any flight above 800 seconds not surrounded by similar queue times and almost all flights above 1000 seconds were discarded for analysis.

At the conclusion of these steps, the average day had approximately 850 records of departures, although some had significantly less. The records eliminated represented a very small fraction of the total set.

Three average queue times were calculated for each configuration change. The first "overall" average was over a period beginning 1 hour prior to the change and ending 1 hour after (referred to hereafter as the "2-hour period"). When changes happened in close succession, these periods sometimes overlapped. The other two averages were for 20-minute and 40-minute periods, both also centered on the change time.

The length of the three periods was chosen to maximize specificity (the 2-hour period, for instance, was meant to minimize fluctuations in full-day averages caused by convective (or non-local) weather or excessive crosswind occurring at a different time of day. Twenty minutes was the smallest period which could be selected around a change due to downtime (12 minutes per runway). Forty minutes, besides being twice the 20-minute period, also caught flights held in queue during long delays leading up to TW changes, as well as changes which had no flights in the 20-minute period.

The three averages for each change are provided in the table below:

Table 2 - Average Queue Time Increases by Configuration Change

Date	Time of Change	2-Hour Avg. (sec)	20-Min. Avg. (sec)	40-Min. Avg. (sec)
10/1/08	9:50	213	263	185
12/5/08	10:32	297	495	465
2/1/09	16:21	147	165	165
2/2/09	17:29	187	170	183
2/3/09	9:58	200	221	209
2/4/09	10:03	156	129	165
2/11/09	8:31	161	146	159
2/16/09	8:57	169	126	111
8/5/09	17:56	320	692	842
8/5/09	20:10	320	334	283
8/27/09	9:45	243	297	278
8/27/09	14:44	240	190	224
8/27/09	20:30	438	495	359
11/3/09	5:53	132	131	143
11/3/09	10:16	182	295	244
11/26/09	14:48	117	167	132
1/12/10	12:57	201	244	239
1/26/10	10:52	208	289	234
2/3/10	6:14	161	NF	116
2/3/10	15:21	217	276	243
2/3/10	17:14	296	515	383
2/24/10	16:43	233	246	259
5/3/10	14:32	211	151	176
5/3/10	19:15	469	673	640
5/5/10	12:22	300	307	306
5/17/10	17:06	380	633	446
5/27/10	13:51	241	239	216
5/27/10	16:38	274	537	424
OVR		**237**	**297**	**255**

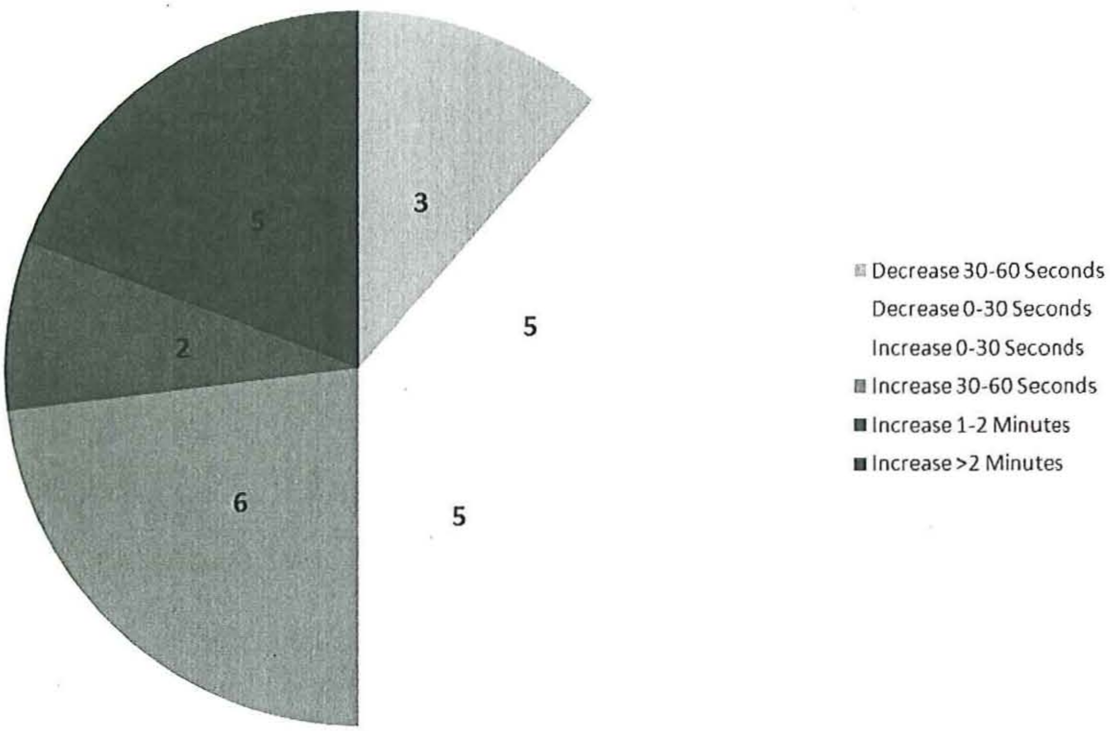
It is evident from the data above that the average configuration change added 1 minute to the queue times of departures taking place within 20 minutes of the change.

This may not appear to be a massive increase, but since each change during the active period sees approximately 15 departures within the 20-minute window, 15 flights will be delayed by approximately 25% (the percentage increase overall during changes) by each change.

Categorizing Queue Time Differences

Additionally, the impact of configuration change on queue time was measured two other ways besides simple averaging. The first was to categorize the average queue times for each change (as displayed in the table above) in terms of the difference between the average queue time during the change (20-min. period) vs. overall local average (2-hr. period):

Figure 8 - Distribution of Configuration Changes by Queue Time Increase



It is important to note that 5 of the changes, representing 18% of the total, had average increases of more than 2 minutes.

Percentage of Flights to Wait Excessively

The final method of displaying the impact of configuration change on queue times is to find the percentage of individual flights to queue for a "long" period of time, defined as being greater than 5 minutes (300 seconds). The totals and percentages for the 20-minute period and the entire day are displayed below (totaled over the entire set):

Table 3 - Comparison of Number of Flights which Queue Excessively

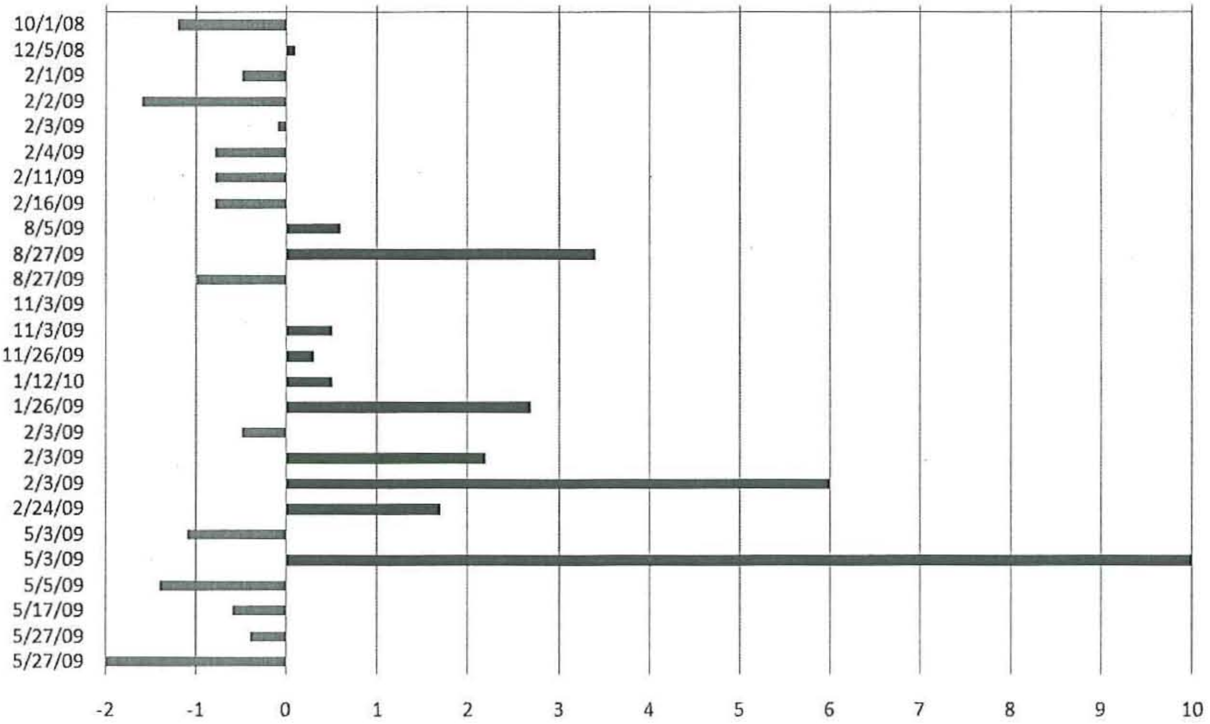
	20-Minute Period at Change	All Day
Total Flights	279	15,290
5-Minute Queues	93	2,408
Percentage Over 5 Minutes	33.3%	15.7%

Thus, there is slightly more than twice the chance that an aircraft departing during a configuration change will queue for more than 5 minutes as an aircraft departing at an arbitrary time under the same conditions.

Length of Queue

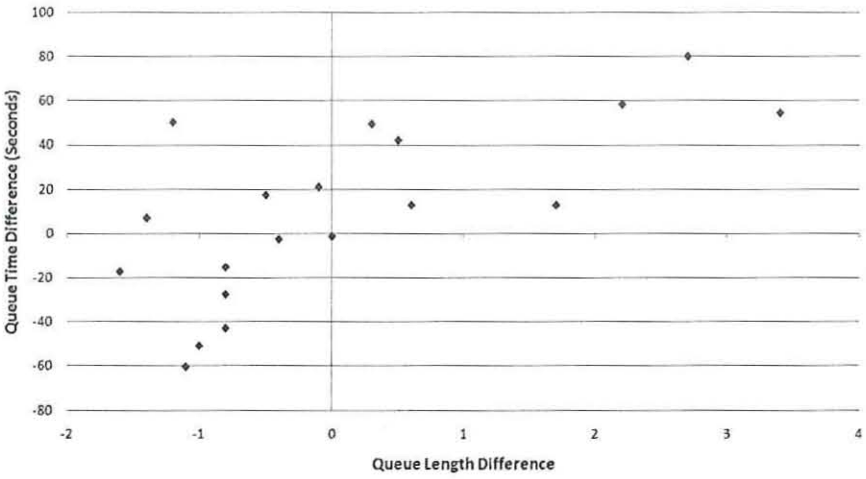
Unlike the other metrics, which showed a strong correlation between configuration changes and lower efficiency, the length of queue showed almost no connection. For each configuration change, the number of flights in queue was counted every minute between the first tailwind violation (1 hour before the change if none occurred) and 1 hour after the change. This period often corresponded to the 2-hour period used above (see **Appendix C-2**). The chart below compares the average of the minute counts within the 20-minute period with the average from within the 2-hour period (local average):

Figure 9 - Average Queue Length Increases by Change



Red lines signify longer queues during the 20-minute period, green lines signify shorter queues. Note that although no trend can truly be indentified in the sign of the difference, when queues are longer the difference is significantly larger than when they are shorter. There is a reasonable correlation between queue length (excluding the outliers, see below) and queue time difference ($R^2 = 0.48$):

Figure 10 - Queue Time Difference vs. Queue Length Difference



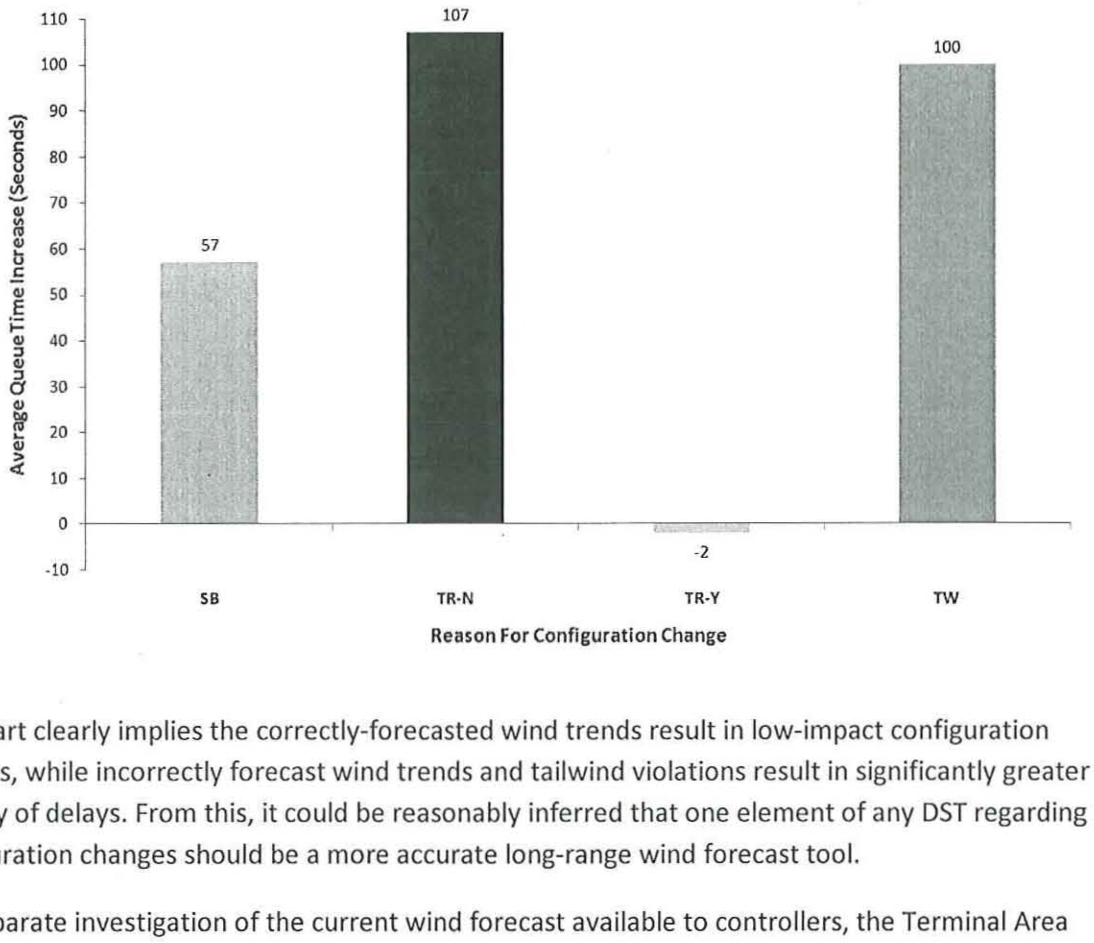
Correlation and Implication of Results

The final stage of the existing conditions analysis was to attempt to build connections between severity of queue delays caused by configuration changes and airport conditions at the time of the change. At this stage of the analysis, it can be reasonably suggested that a wind-related variable (the reason for the change – TW, TR, SB), time of day, and a performance variable (2-hour average queue time) are to some degree proportionally related to delay severity.

Reason for Change

As stated above, configuration changes were divided into categories based on the wind-related reason for the change: southbound preference (SB), correct and incorrect predictions (TR-Y and TR-N), and violation of tailwind regulations (TW). All levels of change delay in the tailwind violations were combined for the correlation analysis due to the lack of enough data for any one of them to provide a meaningful average queue time. The delay severity for each is provided below:

Figure 11 - Average Queue Time Increase by Explanation



The chart clearly implies the correctly-forecasted wind trends result in low-impact configuration changes, while incorrectly forecast wind trends and tailwind violations result in significantly greater severity of delays. From this, it could be reasonably inferred that one element of any DST regarding configuration changes should be a more accurate long-range wind forecast tool.

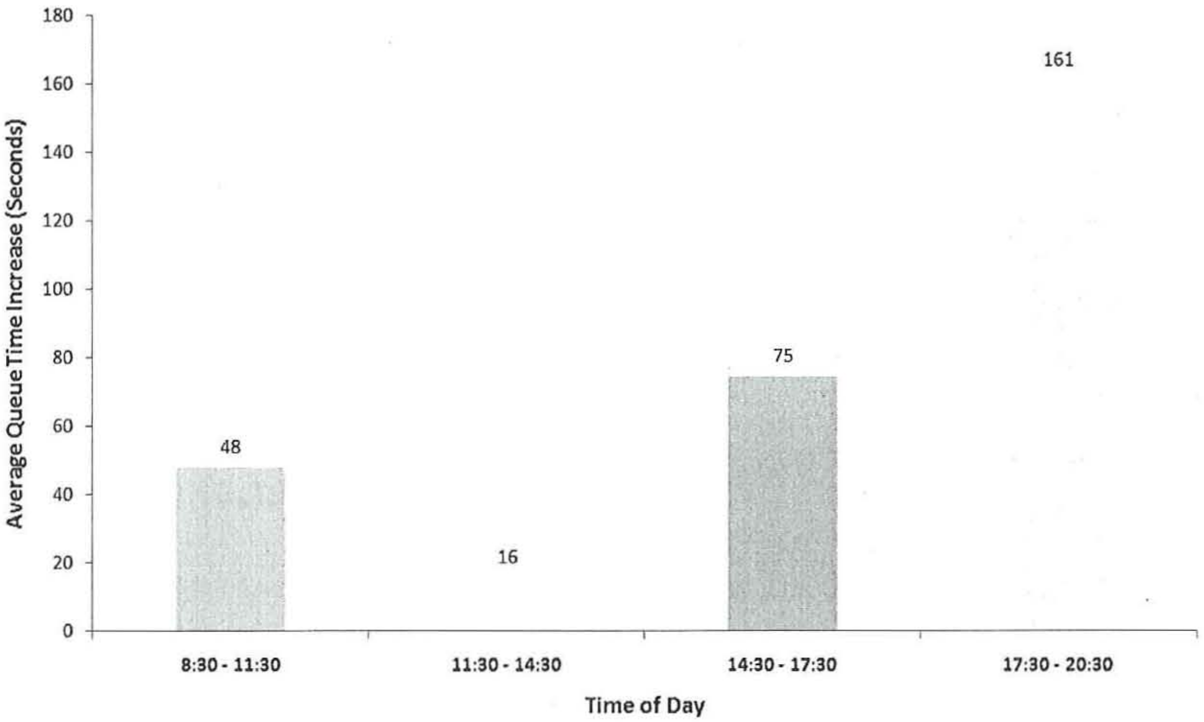
In a separate investigation of the current wind forecast available to controllers, the Terminal Area Forecast (TAF), the predictions of the TAF were found to be very low resolution and highly unreliable.

Controllers interviewed at DFW consider the TAF to be at most 50% accurate and rely more on observations relayed from pilots than on official forecasts.

Time of Day

As shown in a prior section, configuration changes clustered in 3-hour periods roughly corresponding to the mid-morning and mid-afternoon. Averaging the queue time increase over these periods produced a clear trend toward more severe delays as the day progressed:

Figure 12 - Average Queue Time Increase by Time of Day

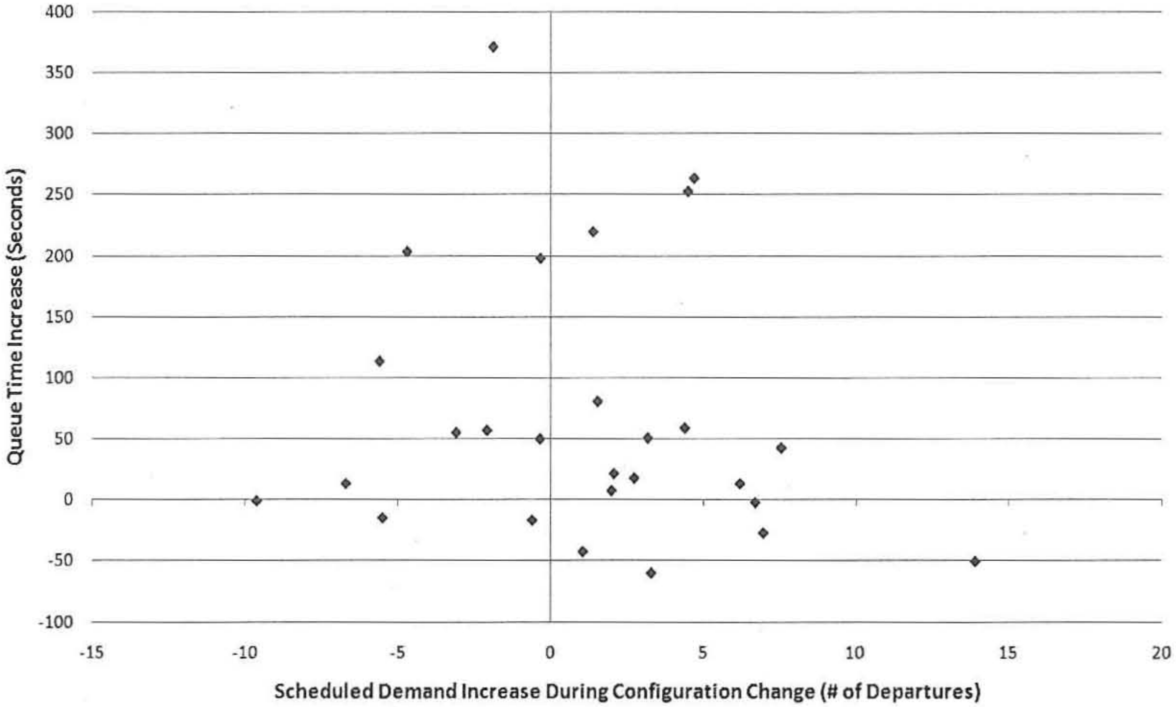


It could be proposed that to maximize efficiency, controllers should avoid the evening rush period. Indeed, queue times were significantly worse afternoon, although this could also be attributed to changing weather conditions as the delay progressed. Again, access to improved wind forecasts could allow controllers could allow controllers to change the configuration well in advance of afternoon wind shifts, especially considering that the late evening changes which are so severe above are all due to theoretically predictable tailwind violations.

Demand and 2-Hour Averages

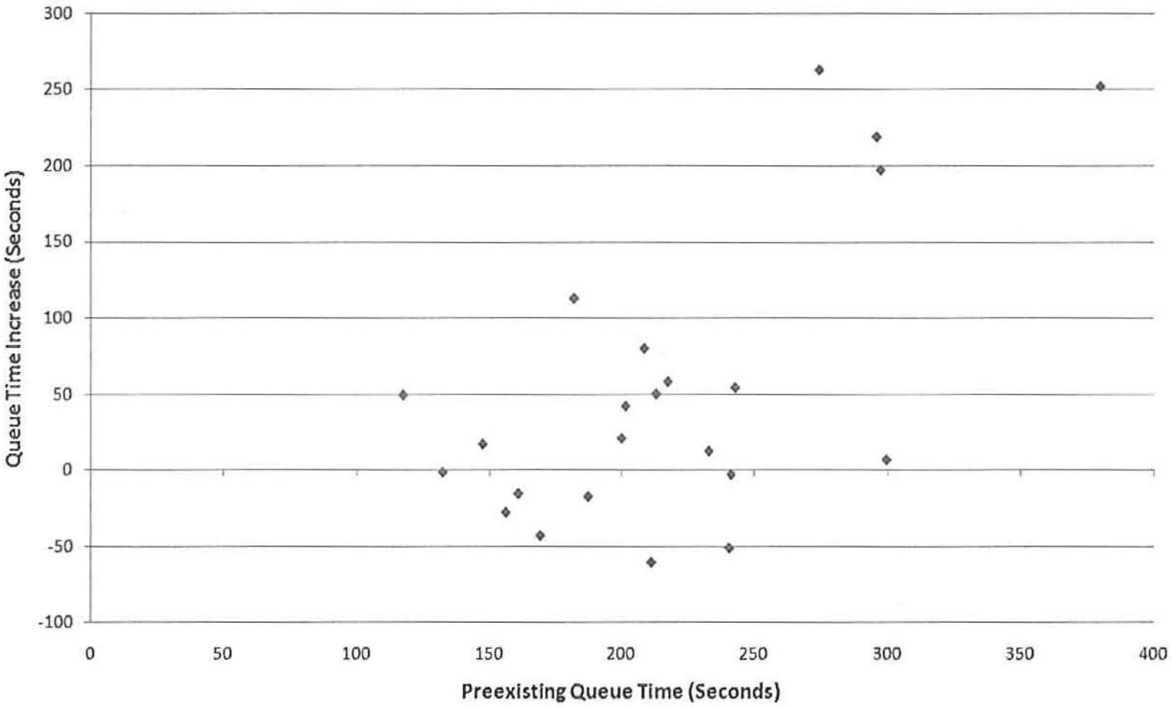
Two different independent variables were available to measure the queue impact against performance. The first was the difference between the 20-minute and 2-hour demand averages, using the scheduled wheels-off time as done previously. As is clear below, there is no correlation discernable:

Figure 14 - Average Queue Time Increase vs. Demand Increase



The other variable available was the 2-hour average queue time for the change, which represents the preexisting conditions. The hypothesis was that when the existing delays were severe, the impact would increase. Because extremely poor efficiency days (average queue above 6 minutes) were likely to be connected to other variables besides configuration changes and were wildly unpredictable, these days were removed from the sample for analysis. Among the remaining data, a clear trend appeared:

Figure 13 - Average Queue Time Increase vs. Preexisting Queue Time



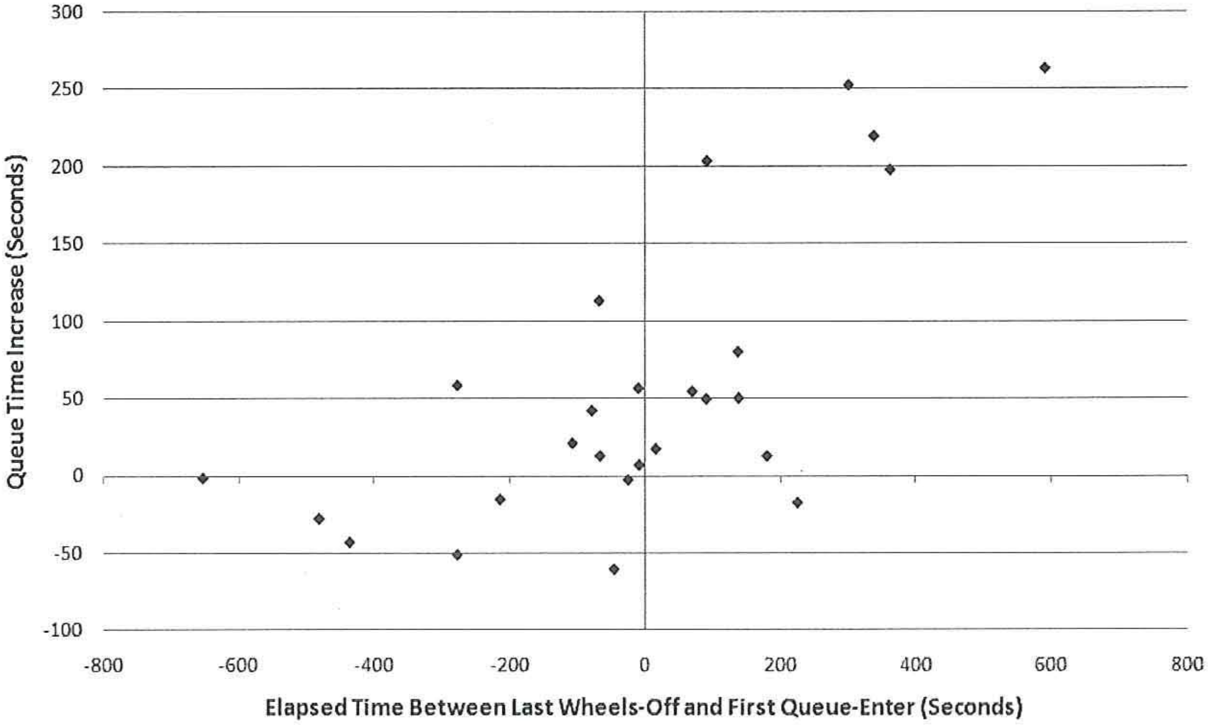
It should be noted that for any preexisting delay longer than approximately 4 minutes, there was no change that did not result in some increase in queue times. It can therefore be reasonably suggested that configuration changes exacerbate existing delays.

Preemptive Queuing

Preemptive Queuing is one possible method for measuring the duration and efficiency of a configuration change. The metric is produced by noting the time the first plane entered queue in the new configuration, and the elapsed time (positive or negative) between that event and the time the final plane left the runway in the old configuration (see **Appendix B-3**).

The value is called "delta" here for simplicity:

Figure 15 - Average Queue Time Increase vs. Delta



Negative values of delta represent instances where the last plane left in the old configuration before the first plane entered queue in the new. Positive values represent the opposite – planes queuing for the new configuration before the change actually occurs, which can also represent a preexisting queue in the old configuration that must be cleared (planes were rarely observed to change ends while queuing). Queue times tended to be longer for aircraft which enter queue for a new configuration prior to a change, while aircraft held at the gate or on the taxiways saw queue times which were roughly proportionally shorter ($R^2 = 0.49$). This follows from average downtime, which indicates that a plane placed preemptive queue will have to wait for the runway to reopen. It also must be balanced with a future correlation analysis for downtime as well as the fact that aircraft placed in queue after the change may have waited outside the queue box (the "spot" or the gate) for an extended period.

Next Steps

The next steps in the existing conditions analysis either change or add independent variables for correlation or change the method by which queue data are processed. Some are already planned or in progress in the weather-sensing group.

Demand

As noted in the section above, demand was measured using scheduled wheels-off times. It is possible that the use of another value to place departures in time might change the demand profiles or the results of the correlation analysis. Work is currently planned to re-do the analysis in those section using actual push-back times to remove variability in taxi time and gate location, as well as to tie the profile even more closely to airline schedules. In addition, consideration should be paid to absolute demand as opposed to demand increase.

Efficiency

Delta is not the only way to measure efficiency. The full analysis of the downtime for each change is more than half-complete at the time of writing, and once it is finished, correlation will be possible between the average runway downtimes and queue time increases for all changes.

Because the recommendation from the Preemptive Queuing analysis is to wait to begin queuing in the new direction as long as possible, this analysis will provide a balance for the DST – ideally producing a "sweet spot" between the two.

In addition, to eliminate the uncertainty over where aircraft were held (taxiway or queue box), the analysis could be modified to use total delay as opposed to queue time.

Database

Two of the major issues with all the analysis in this report are a relatively small data set and the difficulty and complexity of adding data to the analyses. It is possible, through the use of a database program such as Matlab, Microsoft Access, or Oracle Database to simplify and even automate this process.

Any DST would need the ability to renew its data, particularly if it is offering any sort of recommendation (as opposed to simply displaying predictions). Because the data used in these analyses are relatively simple and do not require a huge amount of storage space, years worth of changes could theoretically be analyzed and the results stored, with each day entered as the next day begins.

Further, changes could be analyzed in categories for wind conditions, convective weather, time of day, or whatever researchers and controllers deemed relevant.

The results and conclusions in this report were conducted with the largest data set realistically available, and have a relatively high confidence level. However, it is conceivable that when far more days enter the set (and changes are analyzed based on conditions and characteristics) that some of these conclusions may require some reassessment.

Conclusions

Summary of Findings – Effects of Configuration Changes

Metric	Conclusion – During a Change...
Average Queue Time	...flights queue 1 minute longer on average.
Excessive Queue Time	...flights have twice the chance of queuing excessively.
Queue Length	...no clear proportionality, but when it rains it pours.

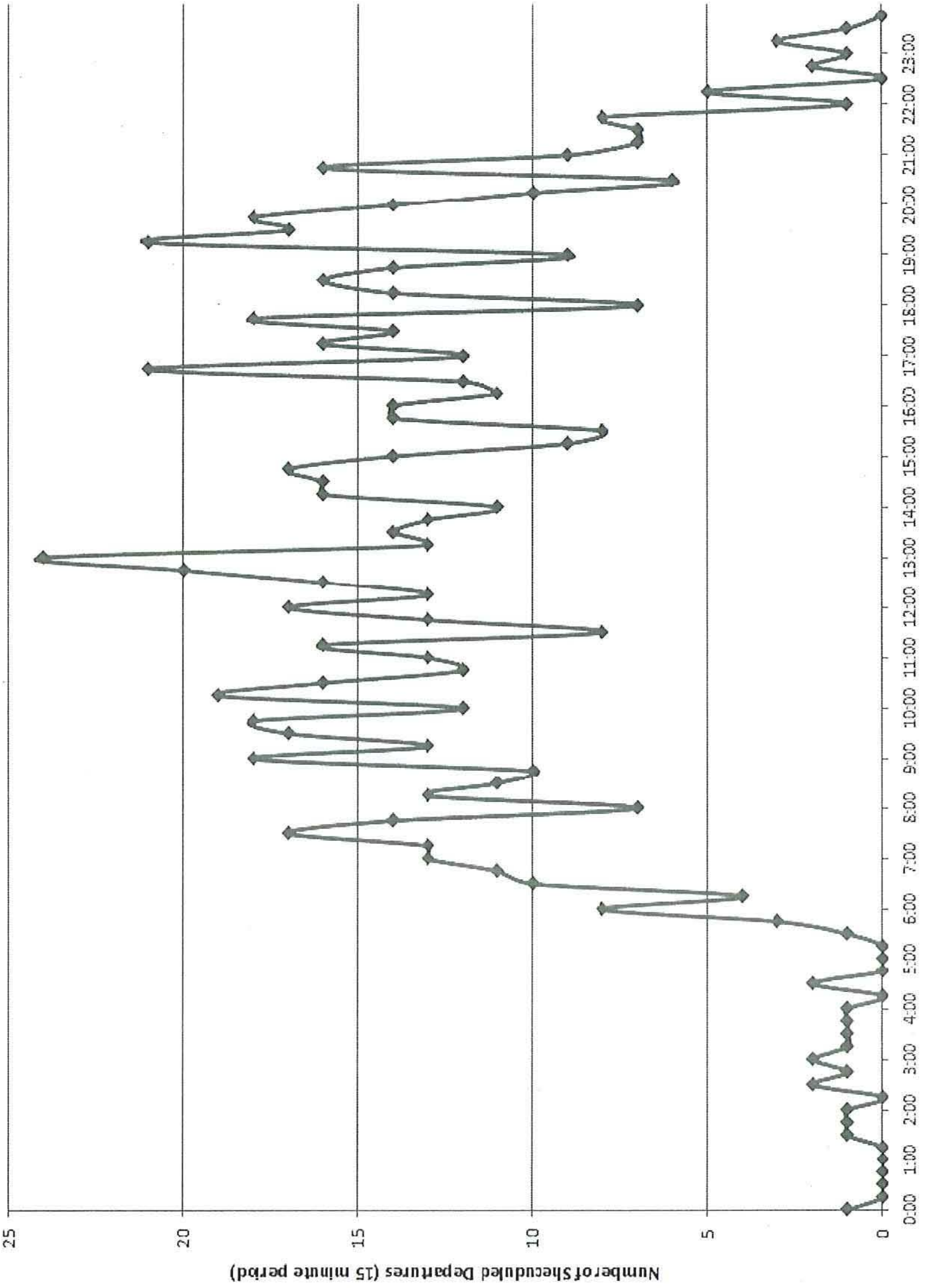
Summary of Findings – Conditions and Recommended DST Features

The conclusions below apply varyingly to elective changes (southbound preference) and required changes (tailwind violations). Ideally, improved wind forecasting will improve the delay impact of all types of changes by allowing controllers to preemptively change configuration at the lowest-impact times (as demonstrated by low delays during TR-Y changes).

Condition	Correlation	Proposed Remedy (DST Features)
Reason for Delay	Incorrect trend forecasts and tailwind violations produce more harmful configuration changes	Improved wind forecasts
Time of Day	Impact increases as day progresses	Avoid changes late in day, improved wind forecasts
Demand	No correlation observed using scheduled wheels-off times	Re-attempt forecast using actual push-back times
Preexisting Delays	Clear trend toward higher impact during more congested periods	Avoid changes during high-delay periods
Preemptive Queuing	Roughly proportional, $R^2 = 0.49$	Do not queue planes in new configuration before change, balance with future downtime analysis

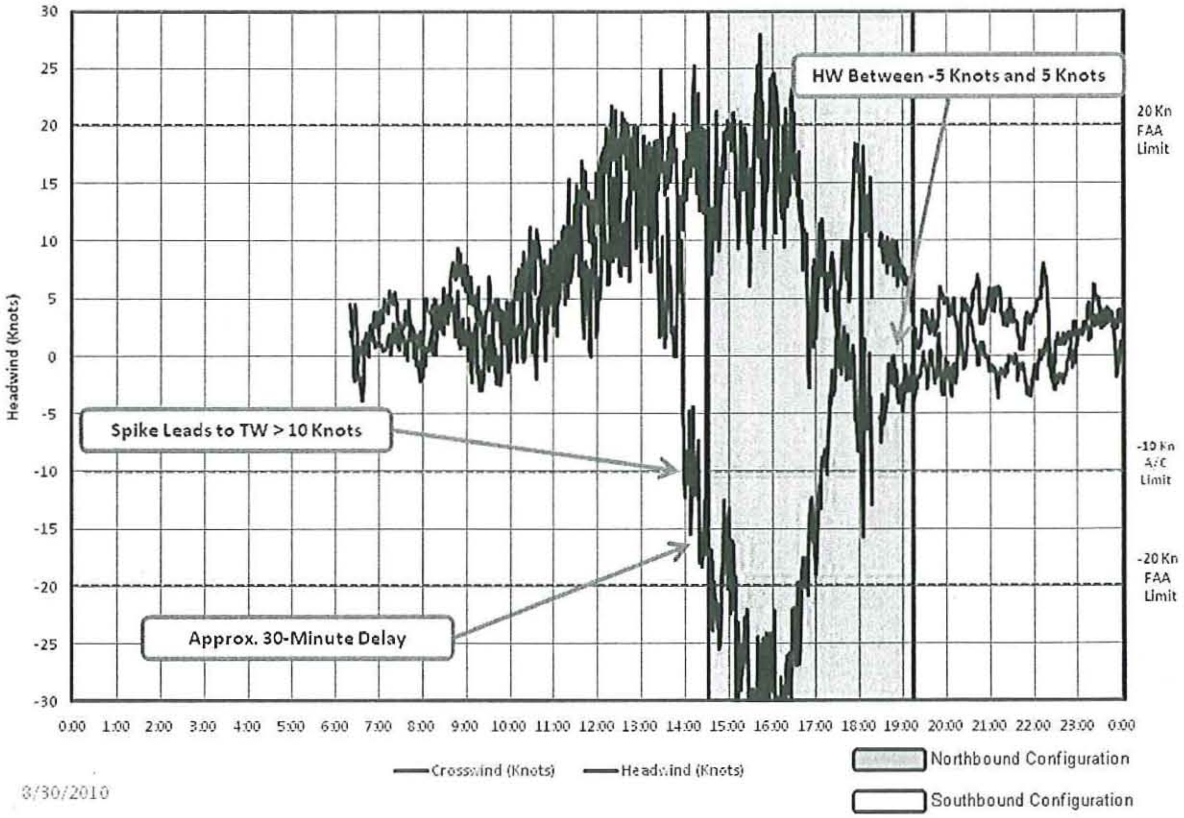
Appendix A: Charts

Appendix A-1: Demand Curve



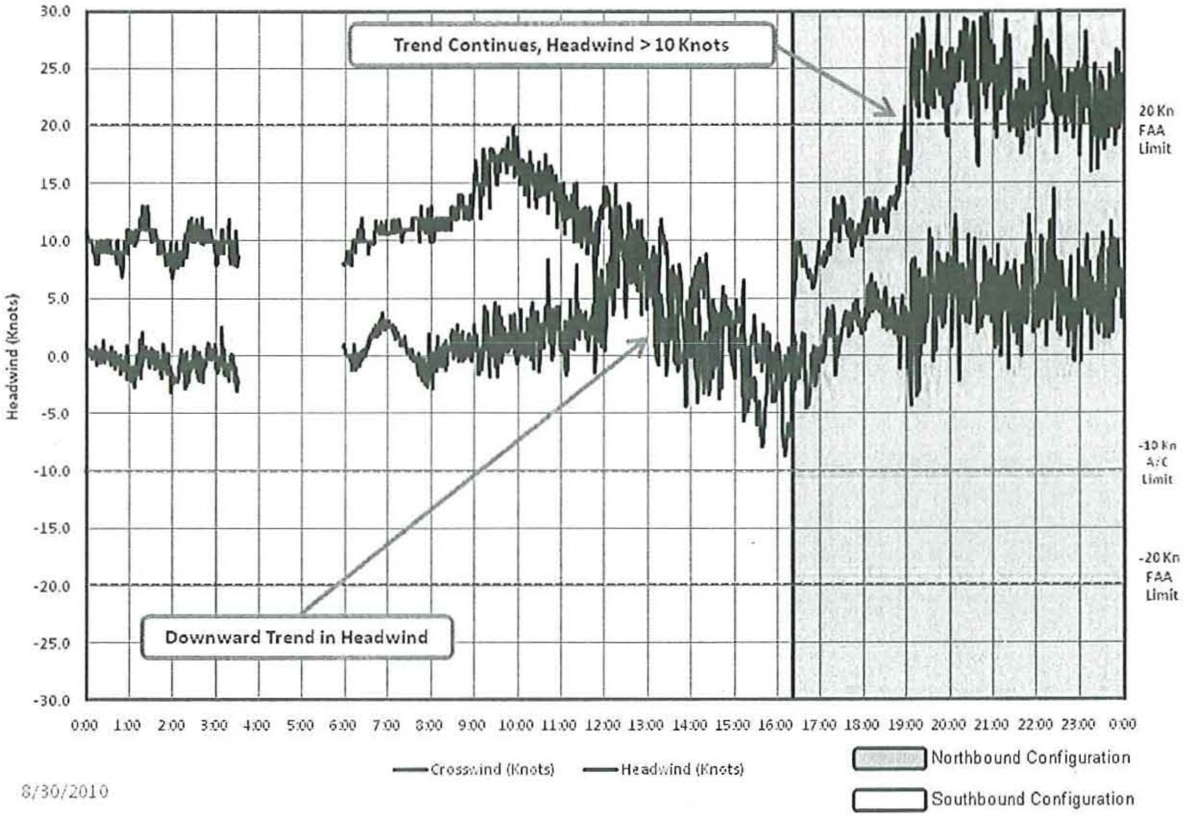
Appendix A-2: Headwind/Crosswind Plots by Type

Wind Plot for 5/3/10: Changes Induced by Tailwind, Southbound Preference

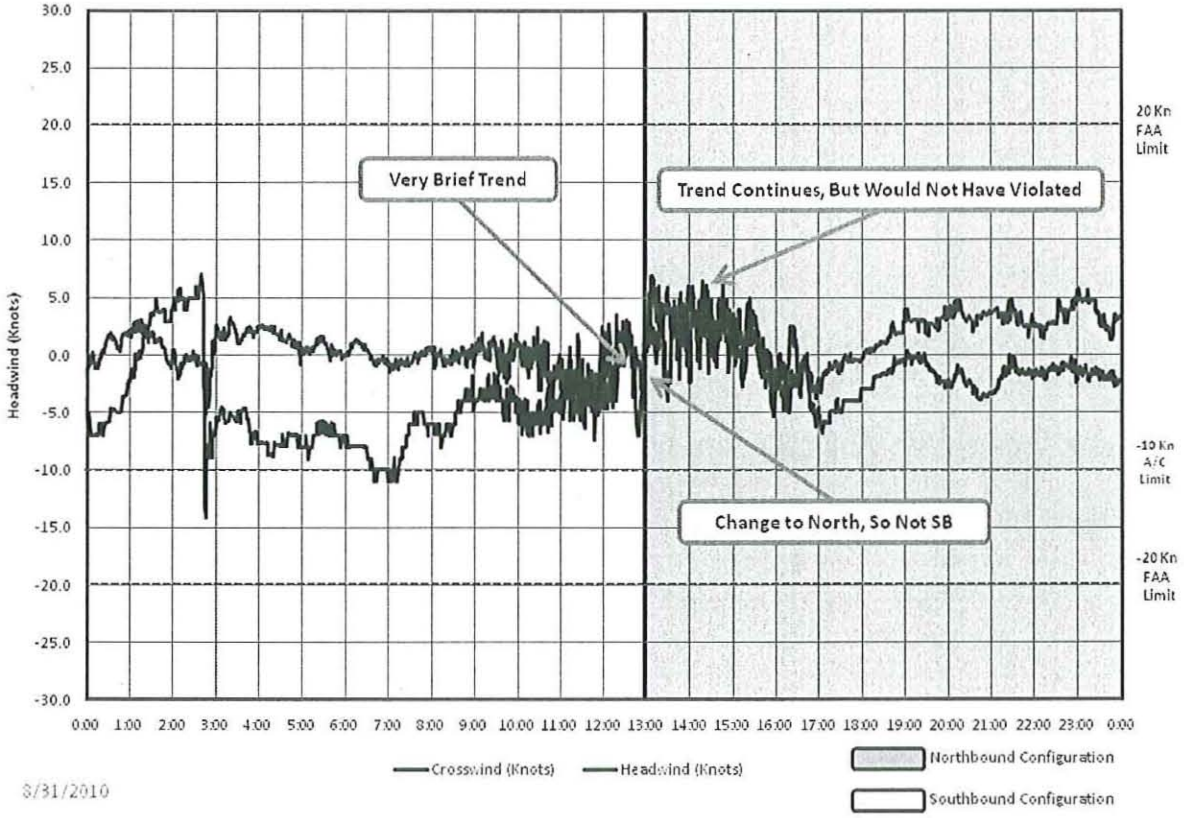


8/30/2010

Wind Plot for 2/1/09: Correctly-Predicted Trend



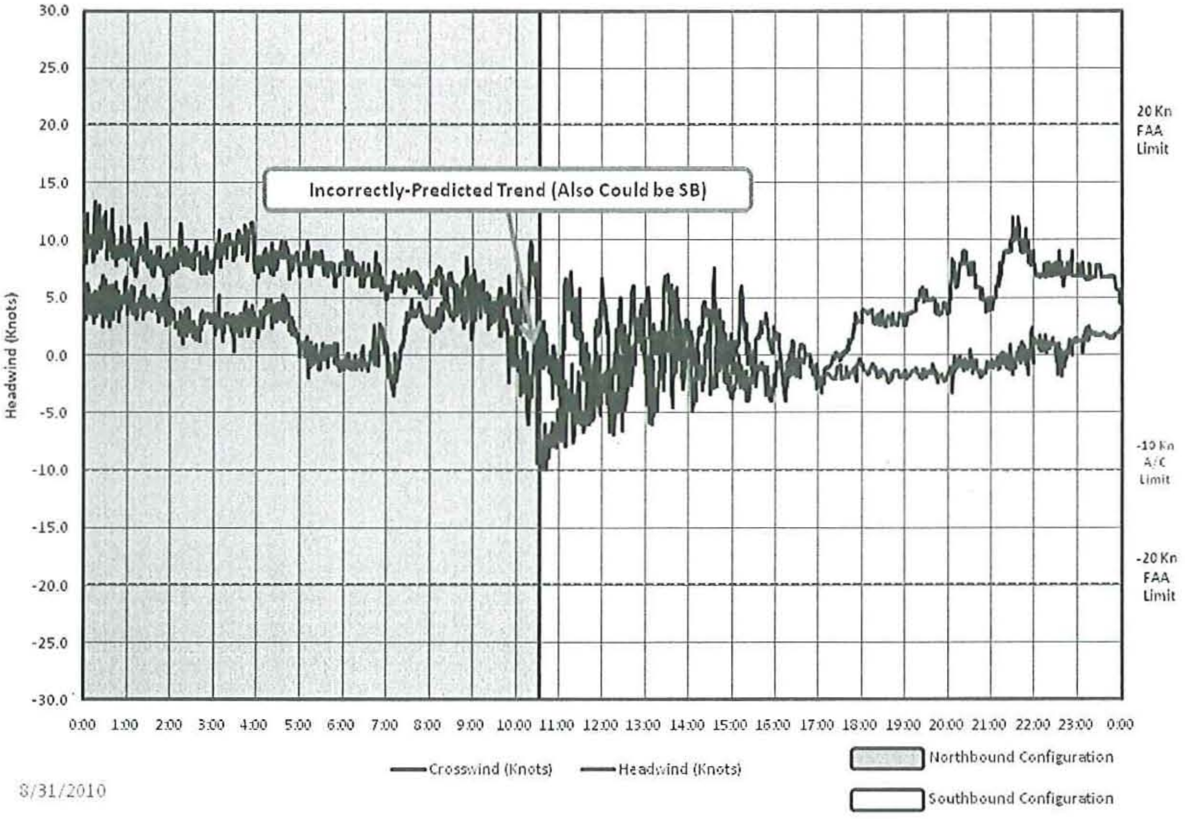
8/30/2010



Wind Plot for 1/12/2010: Incorrectly-Predicted Trend

8/31/2010

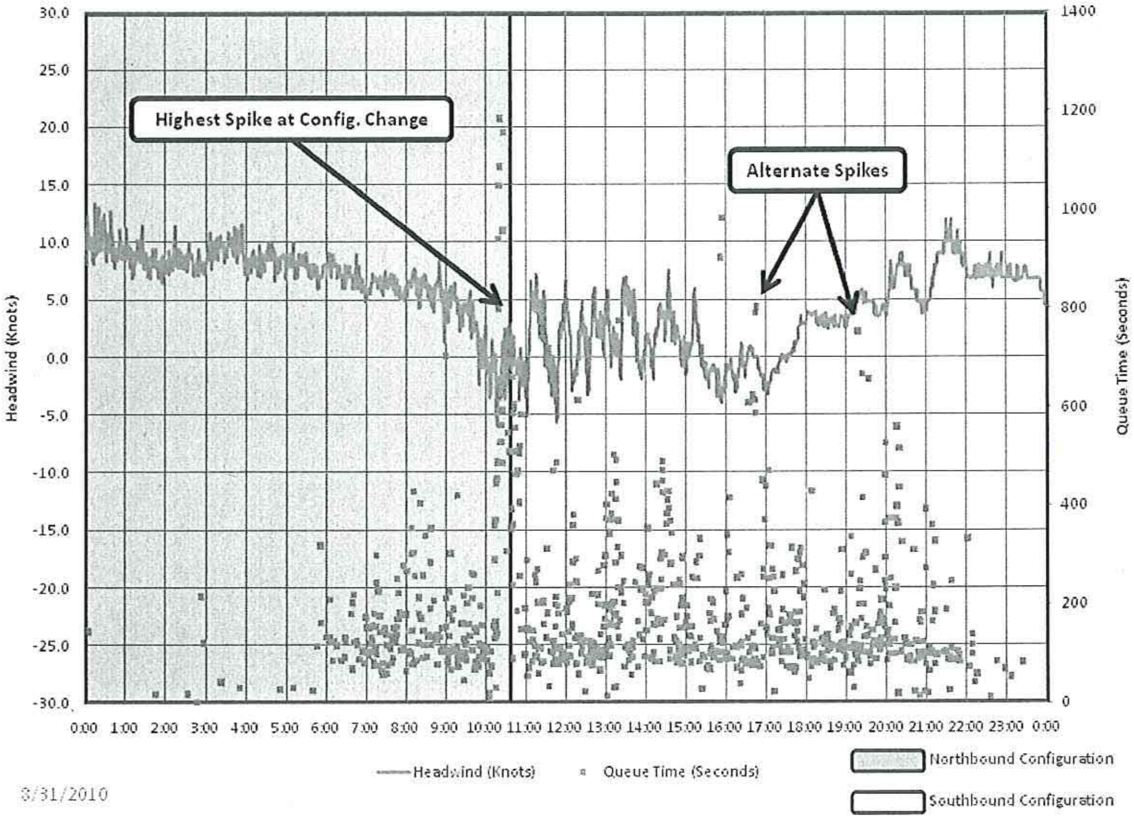
Appendix A-3: Sample Plots for December 5, 2008



Headwind and Crosswind: 12/5/2008

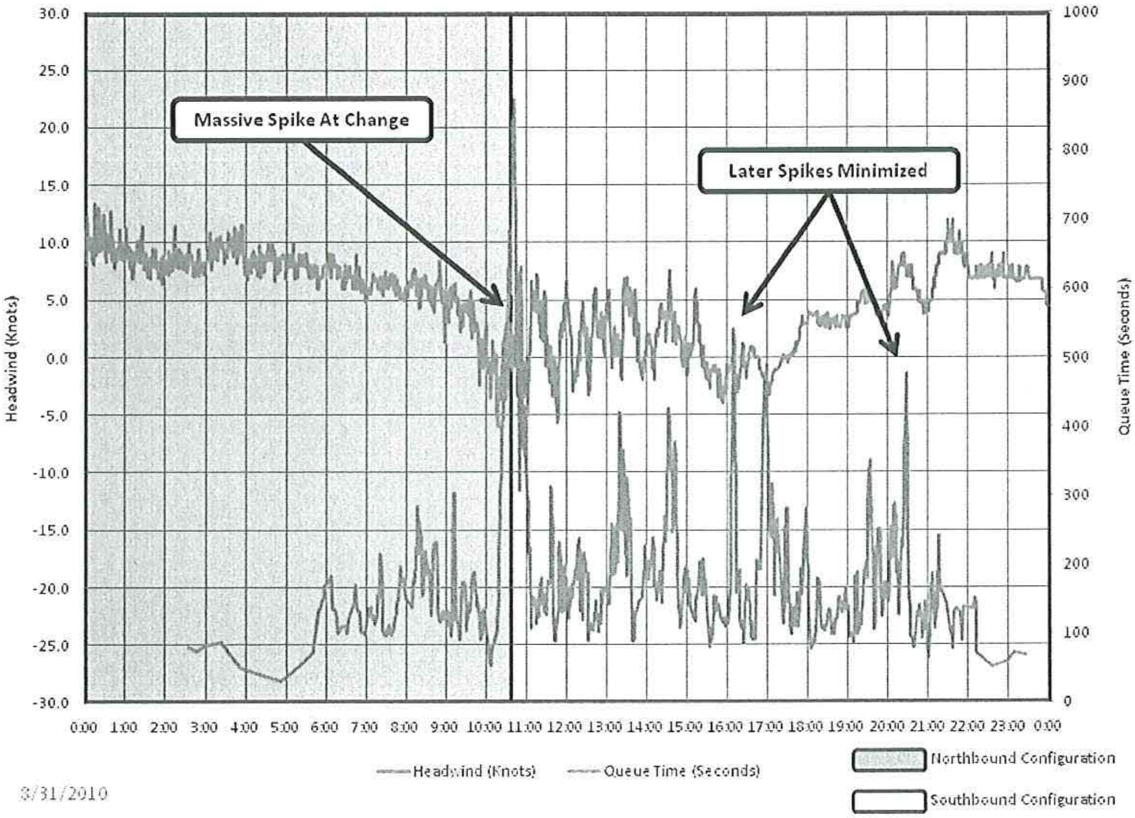
8/31/2010

N-S Wind Orientation and Individual Queue Time by Entry: 12/5/2008



3/31/2010

N-S Wind Orientation and Rolling Avg. Queue Time: 12/5/2008



3/31/2010

Appendix B: Wind and Queue Tables

Appendix B-1: Configuration and Weather Conditions on Full Set

DATE	CONFIG	WX	DATE	CONFIG	WX	DATE	CONFIG	WX
10/1/08	N/S	V	1/1/09	S	V	1/1/10	N/S	V
10/8/08	N/S	V	1/2/09	S	V/I	1/2/10	S/N/S	V
11/3/08	S	V	1/3/09	S	I/V	1/3/10	S/N	V/I
12/2/08	N/S	V	1/4/09	S/N	V/I	1/4/10	S/N	V
12/5/08	N/S	V	1/5/09	N	I	1/5/10	N/S	V
6/10/09	S/N/S	V/I	1/6/09	N/S/N	V	1/6/10	S	V/I
6/11/09	S	V/I	1/7/09	N/S	V	1/7/10	S/N	I/V
6/23/09	S	V	1/8/09	S/N/S	V	1/8/10	N	V
6/24/09	S/N/S	V	1/9/09	S	V/I	1/9/10	S	V
6/27/09	S	V	1/10/09	S/N	V/I	1/10/10	N/S	V
7/8/09	S	V	1/11/09	N/S	V	1/11/10	N/S	V
7/13/09	S	V	1/12/09	S/N	V	1/12/10	S/N/S	V
7/19/09	S	V	1/13/09	N/S	V	1/13/10	N/S	V
7/20/09	S	V/I	1/14/09	S	V	1/14/10	S	V/I
7/26/09	S	V	1/15/09	S/N	V	1/15/10	S/N	I/V
7/27/09	S/N/S	V/I	1/16/09	N/S	V/I	1/16/10	N/S	V/I
7/28/09	S	V/I	1/17/09	S/N	I/V	1/17/10	N/S	V/I
8/1/09	S/N/S	V/I	1/18/09	N	V	1/18/10	S	V/I
8/5/09	S/N/S	V	1/19/09	N	V	1/19/10	S	V/I
8/21/09	S/N/S	V/I	1/20/09	N	V	1/20/10	S	V/I
8/27/09	S/N/S/N/S	V	1/21/09	N/S	V	1/21/10	S/N	V
9/1/09	S	V	1/22/09	S	V	1/22/10	N/S	V/I
9/10/09	S	V	1/23/09	S/N	V	1/23/10	S/N/S	V/I
9/11/09	S/N/S	V/I	1/24/09	N	I	1/24/10	S/N	V
9/12/09	S/N/S/N	I	1/25/09	N/S	I/V	1/25/10	N	V
9/14/09	N	I	1/26/09	S/N	I	1/26/10	N/S	V
9/16/09	N	V/I	1/27/09	N	I	1/27/10	S	V
9/17/09	N	I	1/28/09	N/S/N/S	I/V	1/28/10	S/N	V/I
9/21/09	S	I/V	1/29/09	S/N	V/I	1/29/10	N	I
9/22/09	S/N	I/V	1/30/09	N/S/N	V	1/30/10	N	I
10/1/09	S/N	V/I	1/31/09	N/S	V	1/31/10	N/S	I/V
10/5/09	N/S	I	2/1/09	S/N	V	2/1/10	S	V/I
10/6/09	S/N	I	2/2/09	N/S	V	2/2/10	S/N	I
10/7/09	N/S	I	2/3/09	S/N	V	2/3/10	N/S/N/S	V/I
10/11/09	N/S	I	2/4/09	N/S	V	2/4/10	S/N	I
10/13/09	S	I	2/5/09	S	V/I	2/5/10	N	I/V
10/21/09	S	I	2/6/09	S	I/V	2/6/10	N	V/I
10/26/09	S/N	I	2/7/09	S	I/V	2/7/10	N/S	I
10/29/09	S/N	I/V	2/8/09	S	I/V	2/8/10	S/N	I
11/2/09	S	V	2/9/09	S	V/I	2/9/10	N	I/V
11/3/09	S/N/S	V	2/10/09	S	V/I	2/10/10	N/S	V
11/4/09	S	V	2/11/09	S/N	V	2/11/10	S/N	V/I
11/5/09	S	V	2/12/09	N/S	V	2/12/10	N	I

11/10/09	N	V	2/13/09	S/N	V/I	2/13/10	N/S	V/I
11/11/09	N	V/I	2/14/09	N	V/I	2/14/10	S/N	V/I
11/18/09	N/S	V	2/15/09	N	V	2/15/10	N	V
11/23/09	S	V/I	2/16/09	N/S	V	2/16/10	N	V
11/26/09	N/S	V	2/17/09	S	V/I	2/17/10	N/S	V
11/27/09	S	V	2/18/09	S/N	V	2/18/10	S	V
1/17/10	N/S	V/I	2/19/09	N	V	2/19/10	S	V/I
2/4/10	S/N	I	2/20/09	N/S	V	2/20/10	S	I/V
2/10/10	N/S	V	2/21/09	S/N	V/I	2/21/10	S/N	V/I
2/11/10	S/N	V/I	2/22/09	N/S	V	2/22/10	N/S	I
2/12/10	N	I	2/23/09	S	V	2/23/10	S/N	V/I
2/13/10	N/S	V/I	2/24/09	S	V/I	2/24/10	N/S	V
3/1/10	S/N	V/I	2/25/09	S	V/I	2/25/10	S	V
3/8/10	S	I/V	2/26/09	S	I/V	2/26/10	S/N	V/I
5/1/10	N	V	2/27/09	S/N	I	2/27/10	N	V
5/2/10	N/S	V	2/28/09	N	I/V	2/28/10	N/S	V
5/3/10	S/N/S	V						
5/4/10	S	V						
5/5/10	S/N	V						
5/6/10	N/S	V						
5/7/10	S/N	V/I						
5/8/10	N/S	V						
5/9/10	S	V/I						
5/10/10	S	I/V						
5/11/10	S	I/V						
5/12/10	S	V/I						
5/13/10	S/N	V/I						
5/14/10	N/S/N/S	V/I						
5/15/10	S	I/V						
5/16/10	S/N	V						
5/17/10	N/S	V						
5/27/10	S/N/S	V						
6/14/10	S	V/I						
6/15/10	S	V						
6/16/10	S	V						
6/17/10	S	V						
6/18/10	S	V						

Appendix B-2: Time, Wind, and Queue Time Peak of Configuration Changes

Date	Time of Change	Initial Direction	Final Direction	Type	Peak?
10/1/08	9:50	N	S	SB	Y
12/5/08	10:32	N	S	TR-N	Y
2/1/09	16:21	S	N	TR-Y	Y
2/2/09	17:29	N	S	SB	Y
2/3/09	9:58	S	N	TR-Y	Y
2/4/09	10:03	N	S	SB	Y
2/11/09	8:31	S	N	TR-Y	N
2/16/09	8:57	N	S	TR-Y	N
8/5/09	17:56	S	N	TW1	Y
8/5/09	20:10	N	S	TW1	Y
8/27/09	5:00	S	N	TW1	▨
8/27/09	9:45	N	S	SB	Y
8/27/09	14:44	S	N	TW+	Y
8/27/09	20:30	N	S	TW+	Y
11/3/09	5:53	S	N	TW-	N
11/3/09	10:16	N	S	SB	Y
11/26/09	14:48	N	S	SB	N
1/12/10	12:57	S	N	TR-N	Y
1/26/10	10:52	N	S	TR-N	Y
2/3/10	6:14	N	S	SB	N
2/3/10	15:21	S	N	TW-	Y
2/3/10	17:14	N	S	SB	Y
2/24/10	16:43	N	S	SB	Y
5/3/10	14:32	S	N	TW-	N
5/3/10	19:15	N	S	TW+	Y
5/5/10	12:22	S	N	TR-Y	Y
5/17/10	17:06	N	S	TW-	Y
5/27/10	13:51	S	N	TW1	Y
5/27/10	16:38	N	S	TW+	Y

Appendix B-3: Preemptive Queuing and Downtime of Configuration Changes

Date	Time of Change	Last Wheels-Off	First Queue-In	Δ (Sec)	RW Avg. Downtime (Min)
10/1/08	9:50	9:45	9:42	138	8.38
12/5/08	10:32	10:27	10:21	362	7.81
2/1/09	16:21	16:12	16:11	16	10.26
2/2/09	17:29	17:29	17:25	225	8.17
2/3/09	9:58	9:51	9:53	-108	8.62
2/4/09	10:03	9:53	10:01	-482	10.92
2/11/09	8:31	8:22	8:26	-215	8.59
2/16/09	8:57	8:49	8:57	-437	30.20
8/5/09	17:56	17:50	17:51	-67	19.02
8/5/09	20:10	19:58	20:01	-199	9.00
8/27/09	9:45	9:36	9:35	70	11.25
8/27/09	14:44	14:42	14:47	-278	12.77
8/27/09	20:30	20:24	20:24	-10	15.83
11/3/09	5:53	5:49	6:00	-654	13.28
11/3/09	10:16	10:09	10:10	-68	9.30
11/26/09	14:48	14:48	14:47	91	8.38
1/12/10	12:57	12:50	12:51	-79	
1/26/10	10:52	10:47	10:44	137	
2/3/10	6:14	6:01	6:12	-628	
2/3/10	15:21	15:12	15:17	-278	
2/3/10	17:14	17:06	17:01	338	
2/24/10	16:43	16:38	16:35	180	
5/3/10	14:32	14:28	14:29	-46	8.63
5/3/10	19:15	19:00	18:58	92	14.21
5/5/10	12:22	12:20	12:20	-9	8.79
5/17/10	17:06	16:55	16:50	300	12.73
5/27/10	13:51	13:47	13:48	-25	12.91
5/27/10	16:38	16:29	16:19	591	18.20
			OVR	Runway	12.32
				Airport	3.99

Appendix C: Code and Data for Demand and Length of Queue

Appendix C-1: Matlab Code for Queue Length

The **qlength_change** function takes in vectors of the runway configuration heading (180 or 360), tailwind intensity (knots) and enter and leave queue times for the entire day. It will output an array with a variable number of columns and 180 rows, which contains the time and length of queue for each minute in a roughly 3-hour range around each configuration change on that day.

```
function [qlength_out] = qlength_change(rw_config, twind , enter_queue, leave_queue)

change_time = [];
change_j = [];
rw_time = 60:60:86400;
```

This "for" loop defines the elements of the vector **change_time** as any minute at which the runway heading does not match that of the preceding minute.

```
J = length(rw_config);
rw_config(J+1) = rw_config(J);
twind = [twind;zeros(2,1)];

for j = 1:J

    if rw_config(j) ~= rw_config(j+1)
      change_time = [change_time rw_time(j+1)];
      change_j = [change_j (j+1)];
    end

  end
```

This "for" loop defines the vector **twind_time** as the minute within 2 hours of **change_time** at which the first tailwind violation occurred (HW < -10Kn). If there was no violation, **twind_time** is set to be 1 hours prior to the change.

```
C = length(change_j)
twind_time = ones(C,1);
twind_k = ones(C,1);


  for d = 1:C
    for k = 1:1440
      if twind(k) <= -10
        if (rw_time(k) - change_time(d) > -7200) && (rw_time(k) - change_time(d) < 0)
          twind_time(d) = twind(k+2);
          twind_k(d) = k+2;
          break
        end
      end
```

```
    end
    if twind_time(d) == 1
      twind_time(d) = change_time(d) - 3600;
      twind_k(d) = change_j(d) - 60
    end
  end
```

The variable **dst** is set to be equal to the number of seconds in either 5 or 6 hours depending on whether daylight savings time is in effect. This number will be subtracted from the initial zulu times to convert to local central time.

```
  if (enter_queue(1) < 21600)
    dst = 18000;
  elseif (enter_queue(1) > 36000) && (enter_queue(1) < 39600)
    dst = 18000;
  else
    dst = 21600;
  end
```

The final section of code creates a vector of minutes from **twind_time** as defined above and 1 hour past **change_time**, for each entry in these vectors (and thus each configuration change) it then searches the queue enter and leave vectors for instances in which each minute of the resulting time vector, **qlength_time**, falls between **enter_queue** and **leave_queue**, and increases by 1 the corresponding entry in **n_int**. Finally, the program enters both the **qlength_time** and **n_int** vectors into the next available columns in the output array.

```
M = length(enter_queue);
n_int = zeros(180,C);
qlength_time_out = zeros(180,C);

  for c=1:C
    qlength_time = rw_time(twind_k(c):(change_j(c)+60));
    N = length(qlength_time);
    for n=1:N
      for m=1:M
        if ((qlength_time(n)+dst) > enter_queue(m)) && ((qlength_time(n)+dst) < leave_queue(m))
          n_int(n,c) = n_int(n,c) + 1;
        end
        qlength_time_out(n,c) = qlength_time(n)/86400;
      end
    end
  end

qlength_out = [];
  for c = 1:C
    qlength_out = [qlength_out qlength_time_out(:,c) n_int(:,c)];
  end

end
```

Appendix C-2: Summary of Queue Length Values

Date	Time of Change	Avg. Queue Length in 20-Min Period	% Difference from Daily Avg.
10/1/08	9:50	1.5	-45.8%
12/5/08	10:32	5.9	2.3%
2/1/09	16:21	2.4	-14.7%
2/2/09	17:29	1.2	-56.8%
2/3/09	9:58	2.7	-3.9%
2/4/09	10:03	2.2	-26.5%
2/11/09	8:31	1.2	-38.7%
2/16/09	8:57	1.5	-33.4%
8/5/09	20:10	2.5	25.9%
8/27/09	9:45	6.3	120.3%
8/27/09	14:44	1.9	-36.4%
11/3/09	5:53	0.5	-7.1%
11/3/09	10:16	3.2	16.6%
11/26/09	14:48	1.5	23.6%
1/12/10	12:57	3.9	13.6%
1/26/10	10:52	5.7	88.3%
2/3/10	6:14	0.5	-52.7%
2/3/10	15:21	4.6	91.8%
2/3/10	17:14	10.8	135.0%
2/24/10	16:43	5.2	47.3
5/3/10	14:32	2.3	-34.3%
5/3/10	19:15	14.3	233.5%
5/5/10	12:22	2.8	-34.8%
5/17/10	17:06	7.2	-7.3%
5/27/10	13:51	3.7	-11.7%
5/27/10	16:38	1.3	8.9%
OVR		**3.7**	**18.3**

Appendix C-3: Matlab Code for Demand

The function **demand_15** takes in the scheduled wheels-off times (or any other time associated with departures) for every departure on a given day and returns the number of flights scheduled to depart in every 15-minute period throughout the day.

```
function [demand_output] = demand15(sched_sec)

per_ends = 0:900:86400;

J = (length(per_ends)-1);
demand_output = zeros(J,1);

for j = 1:J
  for k = 1:length(sched_sec)
    if sched_sec(k) >= per_ends(j) && sched_sec(k) < per_ends(j+1)
      demand_output(j) = demand_output(j)+1;
    end
  end
end

end
```

Appendix C-4: Summary of Demand

Date	Time of Change	Flights in 20-Min. Window	Daily Avg. Flights/20 Min.	Δ
10/1/08	9:50	21	17.8	3.2
12/5/08	10:32	17	17.3	-0.3
2/1/09	16:21	19	16.3	2.7
2/2/09	17:29	16	16.6	-0.6
2/3/09	9:58	19	16.9	2.1
2/4/09	10:03	24	17.0	7.0
2/11/09	8:31	12	17.5	-5.5
2/16/09	8:57	18	16.9	1.1
8/5/09	17:56	16	17.9	-1.9
8/5/09	20:10	13	19.7	-6.7
8/27/09	9:45	15	18.1	-3.1
8/27/09	14:44	32	18.1	13.9
8/27/09	20:30	16	18.1	-2.1
11/3/09	5:53	8	17.6	-9.6
11/3/09	10:16	12	17.6	-5.6
11/26/09	14:48	11	11.4	-0.4
1/12/10	12:57	25	17.5	7.5
1/26/10	10:52	19	17.5	1.5
2/3/10	6:14	6	17.6	-11.6
2/3/10	15:21	22	17.6	4.4
2/3/10	17:14	19	17.6	1.4
2/24/10	16:43	24	17.8	6.2
5/3/10	14:32	20	16.7	3.3
5/3/10	19:15	12	16.7	-4.7
5/5/10	12:22	20	18.0	2.0
5/17/10	17:06	22	17.5	4.5
5/27/10	13:51	25	18.3	6.7
5/27/10	16:38	23	18.3	4.7