12.2 **INVESTIGATING THE "TIME OF WIND RETURN" (TOWR) FOR TRANSIENT TERMINAL CONVECTIVE WEATHER EVENTS**

Jennifer L. Bewley,* Colleen Reiche, Michael Robinson, Chad Craun

AvMet Applications Inc., Reston, Virginia

1 INTRODUCTION

Air traffic operations are significantly disrupted when convective weather impacts an airport terminal. In addition to the immediate safety threats associated with thunderstorms (dangerous wind shear, lightning strikes, heavy rainfall, and reduced ceilings and visibility), convectively-induced outflow winds (typically referred to as "gust fronts") often result in drastic changes in wind speed and direction at the airport, which require runway reconfigurations. Over the years, much research and development has been devoted to identifying and predicting gust front passage through airport terminal airspace. As a result, traffic managers and airport tower controllers have made great strides in mitigating the impacts of these initial storm-driven wind shifts in terminal airspace.

However, significant challenges remain in managing terminal airspace and airport surface operations when the terminal wind field is perturbed by convection. One of the most vexing challenges for traffic managers and tower controllers is determining when the off-nominal wind conditions—and resultant changes and impacts to the air traffic operation—associated with transient convection will cease and the pre-impact wind regime will be re-established. Absent any decision support information or even any historical data analysis that may assist them in their attempts to anticipate the end of the storm-induced wind shift, tower personnel often resort to calling neighboring towers "upstream" of the convection (e.g., nearby airports where the weather in the area may have cleared their operational airspace) and asking if pre-impact wind conditions have returned, sometimes making repeated phone calls.

The conceptual example in Figure 1 illustrates the operational decisions that traffic managers must consider when dealing with transient convectively-induced wind shifts. In this example for Chicago O-Hare International Airport (ORD), pre-impact storm conditions include a southwesterly synoptic wind direction and subsequent 22L, 32L departure runway operations (Figure 1 A). Some time later, convective storm cells move through the ORD terminal airspace, producing a gust front (Figure 1 B, pink line) that causes the winds to shift sharply from a southwesterly to northwesterly direction and force tower traffic managers to reconfigure departure runways to 4L, 32R. Eventually, the thunderstorm moves out of the terminal, and the pre-impact wind direction is anticipated to return (e.g., by way of Central Weather Service Unit [CWSU] meteorologist input, tower controllers checking Meteorological Terminal Aviation Routine Weather Reports [METAR] at similarly-impact airports "upstream," etc.) (Figure 1 C). However, operational decision makers do not know *when* this second wind shift—the Time of Wind Return (TOWR)—will occur, which limits options for proactive runway configuration management and inhibits opportunities to effectively manage taxi queues.

* *Corresponding author address*: Jennifer L. Bewley, AvMet Applications Inc., 1800 Alexander Bell Dr., STE 130, Reston, VA 20191 email: bewley@avmet.com

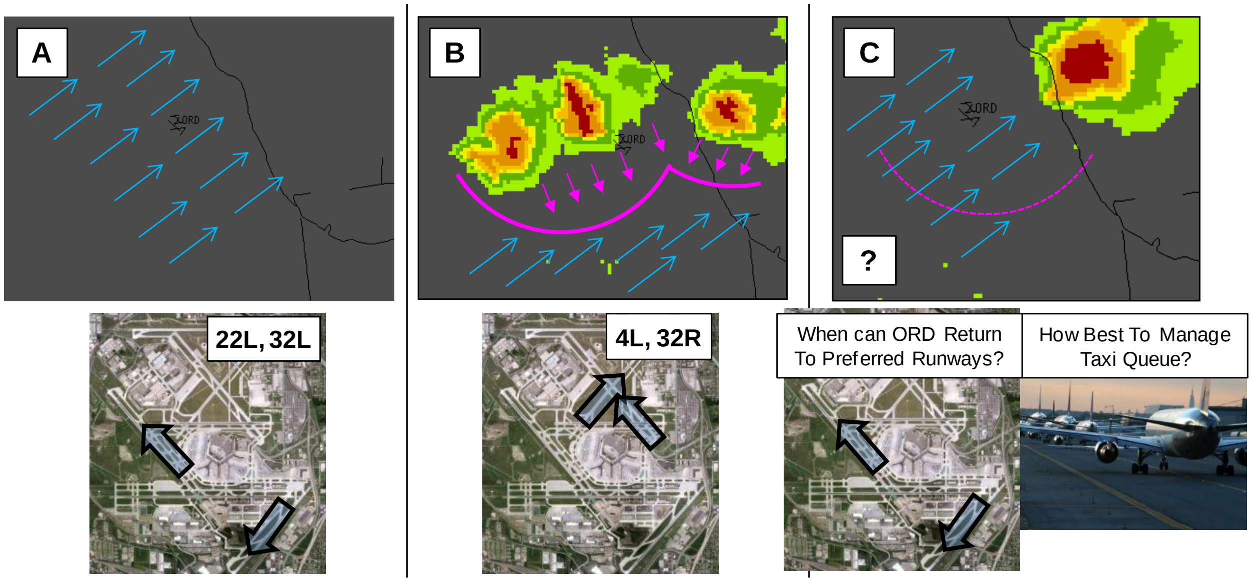


Figure 1: Conceptual Example of Transient Convective Weather Impact Event, with Storm-induced Terminal Wind Shifts, at Chicago O-Hare (ORD) Airport

Without the ability to anticipate these TOWR periods, tower operators, in an effort to continue claiming capacity, often must continue staging terminal operations and manage the airport surface as if a second wind shift (after the initial gust front) is not expected. Increased demand often presents during pending TOWR periods as operations that were temporarily suspended when thunderstorms impacted the airport are added to the post-impact scheduled demand. This effect only exacerbates the problem, causing taxi queues to build and increasing airport surface congestion. If the airport surface is in this posture, still serving the wind-shifted runway configuration, and the TOWR occurs (Figure 2), the result may be any or all of the following:

- Increased taxi and departure delay
- Increased fuel burn
- Increased emissions
- Increased Air Traffic Control (ATC) workload
- Increased airport surface congestion
- Increased safety risk (given increased surface traffic and higher probability of runway incursions)
- Increased risk of airport surface "gridlock"

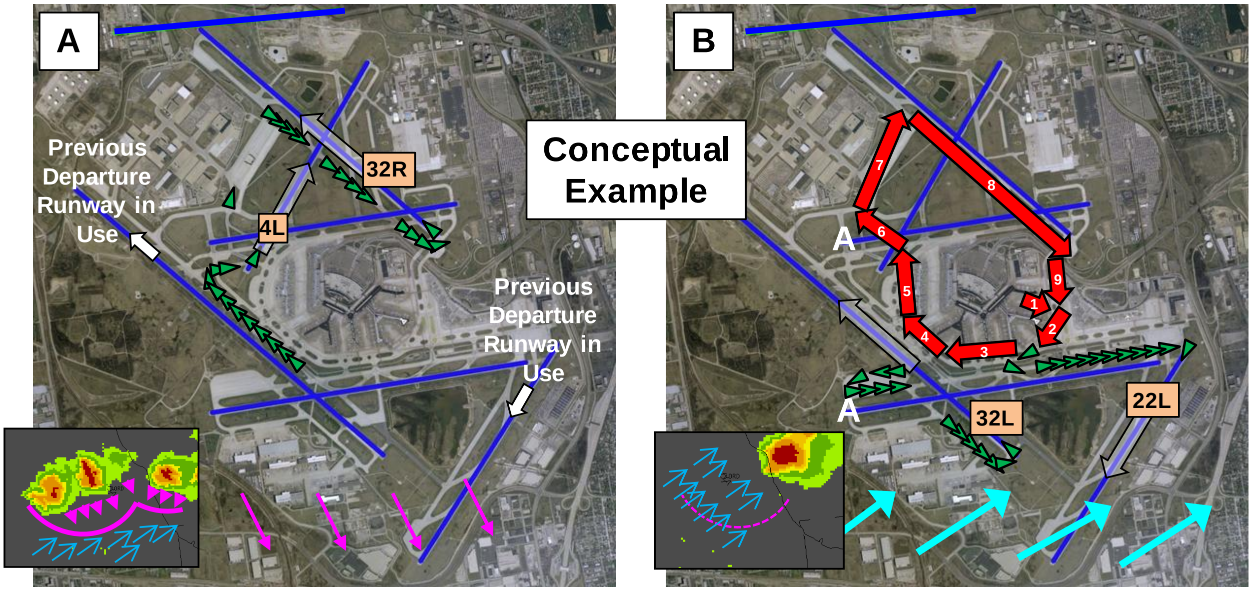


Figure 2: Conceptual example of potential consequences of an unanticipated terminal convective TOWR event. Departures in queue (green arrows) for off-nominal departure runways due to a thunderstorm wind shift (A) are forced into extended taxiing.

Beyond the current shortfalls and operational needs, the importance and applicability of TOWR predictions (and anticipation of "impact event cessation" in general) will only increase with the increase in automation, seamless operations, and focus on environmental impact mitigation that will accompany the Next Generation Air Transportation System (NextGen). In fact, without the ability to anticipate TOWR and proactively plan for changing terminal conditions and operations, most targeted Solution Sets for NextGen may fail to mitigate avoidable delay in these weather impact conditions.

This report quantifies the potential impacts of TOWR events on airport operations, and the potential applications and benefits of TOWR forecast decision support by employing a novel process to assess the technical feasibility of developing an operationally-relevant TOWR predictor.

2 TIME OF WIND RETURN OVERVIEW

To study the pervasiveness of convective events throughout the National Airspace System (NAS) and associated characteristics that generate operationally-significant wind shifts and wind returns in airport/terminal airspace, a comprehensive examination was conducted for the Core-29* airports (Figure 3). The analysis period for terminal convection and TOWR events at these airports was the convective weather season (April – September) during the ten-year period from 2002-2011.

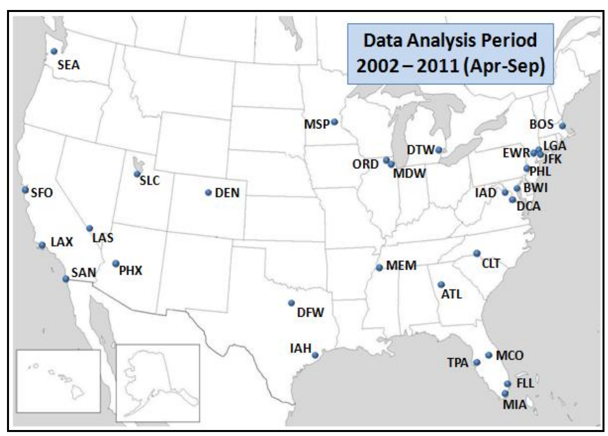


Figure 3: Core-29 Airports and Data Analysis Period for Investigating Terminal Transient Convective TOWR Events

---

* Honolulu International Airport (HNL) was not included in this analysis. See Appendix A for complete list of airports included in this study.

2.1 Time Of Wind Return Event Data-Mining and a Scalable Database

A step-by-step "layered" approach for identifying TOWR events in the context of terminal operations was employed for this project to ensure that the analysis of this phenomenon is considered from an air traffic management perspective. More specifically, this layered data-mining approach addresses the following points pertinent to this analysis:

- Airport TOWR events will be runway-specific, so the domain space (dominant runway configurations) must be defined. In this study, departure runway configurations and TOWR impacts on terminal departure operations were the primary focus.
- TOWR events will be specific to synoptic and "storm-shifted" wind conditions and therefore should be examined in this context.
- Examining thunderstorm event, TOWR frequency, and the distribution of TOWR lengths in the context of departure runway usage, taxi-out time, etc., better positions the problem identification results, and follow-on research into TOWR prediction/impact translation capabilities.

In this approach, each "layer" of data was examined across temporal periods that scaled down from 10 years (the entire data analysis period) to one hour, allowing examination of runway-specific thunderstorm impact and TOWR statistics, and how they vary for meteorologically and operationally meaningful time periods. The results from each phase of the data-mining analysis are presented in Section 3. The analysis of airport taxi-time statistics in conjunction with results derived from this data-mining and event identification effort are presented in Section 4.

The data utilized in the TOWR event and impact research included the following:

- Federal Aviation Administration (FAA) Aviation System Performance Metrics (ASPM) runway configurations
- ASPM taxi-time statistics (taxi-in and taxi-out times)[*]
- METAR Present Weather and Precipitation Codes (for objective analysis of thunderstorm impacts at the airport)
- METAR Winds (direction and speed)
- National Convective Weather Diagnostic (NCWD) precipitation
- National Oceanic and Atmospheric Administration (NOAA) Rapid Update Cycle (RUC) analysis fields, including diagnostic winds at various vertical levels and thermodynamic variables

2.2 TOWR Event Identification

Before investigating the frequency and characteristics of convective weather events at the Core-29 airports that are accompanied by a TOWR, the following TOWR event variables need to be defined:

- Terminal Thunderstorm Event
- Pre-Storm Wind Condition
- Operationally-Significant Wind Shift
- Post-Occurrence Winder Return (POWR)
- TOWR
- Time Elapsed Between End of Convection and TOWR (Delta+/-)

These variables are defined in the rest of this Section. As noted in Section 2.1, per airport statistical results for the amount, the frequency of occurrence, and/or the variability across different time periods for *each* of these variables are binned by the most frequently used departure runway configurations. In this manner, this meteorological analysis stays focused on the operational motivation of this research.

[*] Specifically, these taxi-time statistics are derived from Airline Service Quality Performance (ASQP) Out-Off-On-In (OOOI) data available via the ASPM database.

2.2.1 Terminal Thunderstorm Event

Using METAR data for an objective analysis, an airport thunderstorm impact was identified if any of the following precipitation codes were recorded in the present weather identifier for the five target airports:

- Thunderstorm, slight or moderate, with rain
- Thunderstorm, slight or moderate, with hail
- Thunderstorm, heavy, with rain
- Thunderstorm, heavy, with hail
- Lightning visible, no thunder heard
- Thunderstorm, but no precipitation at the time of observation

2.2.2 Pre-Storm Wind Condition

Once an airport thunderstorm event was identified, METAR-reported wind conditions at the airport were used to define the pre-impact synoptic wind direction: the "baseline" wind conditions to which thunderstorm wind-shift and wind-return occurrences would be compared. Specifically, the pre-storm impact synoptic wind condition is objectively defined as:

> *METAR wind observation nearest and exceeding two hours prior to the first "active" or "vicinity" airport thunderstorm observation (or first "rain" observation associated with the eventual storm occurrence) at the airport that defines the start of the terminal impact event.*

2.2.3 Operationally-Significant Wind Shift

In this analysis, an operationally-significant wind shift was defined as:

> *Time at which a wind shift, associated with terminal convective weather impact event first exceeds +/- 50 degrees compared to the pre-impact synoptic wind direction.*

For aircraft arrival and departure operations, a 50-degree crosswind is typically considered by pilots to be a threshold of significance in the context of aircraft rudder control and maintaining headwind orientation. If the runway crosswinds increase much beyond 50 degrees, it may become more difficult for pilots to maintain their optimal landing posture, and in more extreme situations (e.g., even larger crosswind angles) the arrival or departure may not be possible. When this occurs, an airport runway reconfiguration is typically required to lessen the degree of the crosswind.

In this initial study, it is assumed in the objective analysis that runway configurations are well-aligned with pre-impact synoptic winds and initial crosswind conditions are minimized. Thus, a 50 degree shift from the pre-impact winds is also assumed to match the departure runway-specific threshold for crosswinds condition. Figure 4 is a conceptual illustration of an operationally-significant wind shift for storms impacting Hartsfield-Jackson Atlanta International Airport (ATL) during 26L, 27R (and 28) departure runway operations.

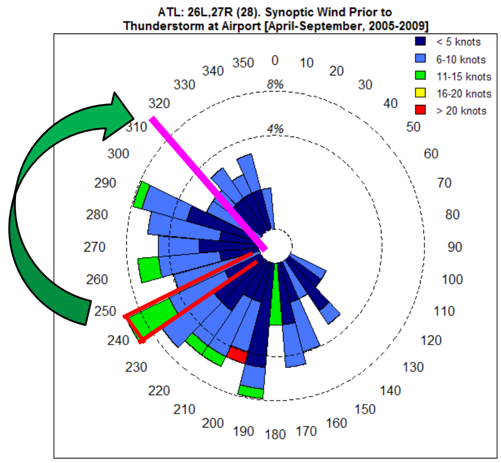


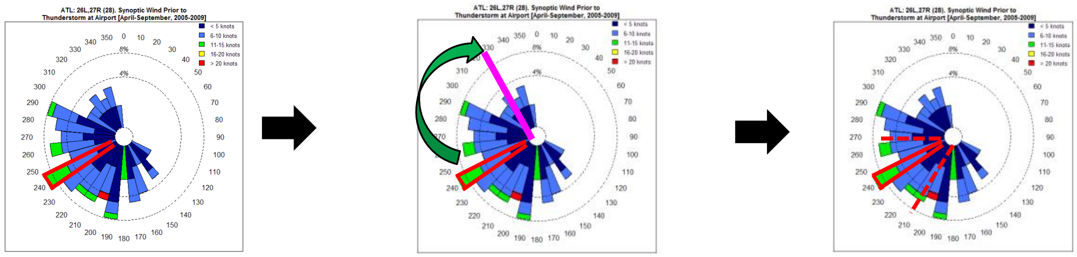
Figure 4: Wind-rose Statistics of Pre-impact Synoptic Wind Conditions Associated with Thunderstorm Impacts at ATL when the Departure Runway Configuration was 26L, 27R, (28)

2.2.4 Post-Occurrence Wind Return

A TOWR event does not occur unless the wind direction returns to the pre-impact synoptic wind direction, within a range, after the terminal thunderstorm-induced wind shift (Figure 5). In this analysis, this is identified as the Post-Occurrence Wind Return (POWR). Specifically, a POWR event is defined as:

> *An airport thunderstorm event that is accompanied by (a) a thunderstorm wind shift of at least 50 degrees from the pre-impact synoptic wind direction AND (b) a return to the pre-impact synoptic wind direction, within +/-30 degrees and within 6 hours of the initial wind shift.*

A range is provided for the wind return relative to the defined pre-impact wind direction based on the assumption that, if desired, airport departure operations could be returned to pre-storm runway configurations once winds conditions within acceptable crosswind limits had returned. In this analysis, 30 degrees from the pre-impact wind conditions was identified as this acceptable crosswind threshold.



Pre-Impact "Synoptic" Wind
(2-hours prior to start of thunderstorm event)

Storm-Induced Wind Shift Events
(At least 50 degrees from synoptic wind)

POWR Event
(Wind return to within +/- 30 degrees of synoptic wind)

Figure 5: Components of Terminal Convective POWR Event, Including the Pre-impact Synoptic Wind Direction, the Operationally-significant Storm-induced Wind Shift, and the Post-impact Wind Direction Returning to the Pre-impact Wind Direction, +/- 30 Degrees

In our research, POWR events were not considered if:

- Pre-impact synoptic winds were variable or calm, with no discernible wind direction (as discussed in Section 2.2.2).
- Back-to-back airport storm impacts (when a storm impacts the airport, METAR-identified thunderstorm conditions subside, and new METAR-identified thunderstorm conditions return after some period) are not separated by at least two hours, preventing the second storm event from being "anchored" to a pre-impact synoptic wind.
- The "wind return" does not occur within six hours of the initial storm-induced wind shift (to help ensure the POWR event is related to more "transient" convection, rather than storms associated with a frontal passage, for example, where the wind shifts are not driven by local, mesoscale processes).

Another type of POWR event has been defined based on the potential operational opportunities for surface management. When the pre-impact synoptic wind returns while convection is still ongoing at the airport, there are minimal surface management actions in response to the wind return, since operations would likely be diminished or halted due to the ongoing, direct storm impact. For this reason, a <u>POWR-T</u> event has been defined as:

> *A POWR event occurring in the presence of ongoing convection in the immediate vicinity of the terminal.*

2.2.5 Time Of Wind Return

The <u>TOWR</u> is defined as follows:

> *The time elapsed between the initial, operationally-significant storm-induced wind shift and the time of POWR/POWR-T (or wind return to the pre-impact wind direction).*

Figure 6 illustrates the period during terminal convective weather impact events that equates to TOWR.

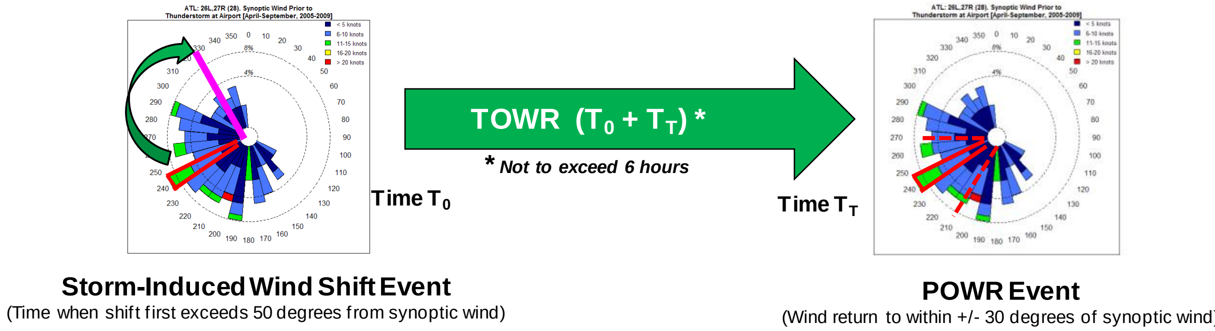


Figure 6: Calculating TOWR for Transient Terminal Convective Weather Events

2.2.6 Time Elapsed Between End of Convection and TOWR (Delta+/-)

The time elapsed between when convection moves off airport runways (or decays) and pre-impact synoptic wind direction returns is referred to as Delta+ and is only associated with POWR events (Figure 7, top). The Delta+ represents potential periods for proactive traffic management, given convection is no longer impacting the airport when pre-impact synoptic wind direction resumes.

The time elapsed between when pre-impact synoptic wind direction returns and convection moves off airport runways (or decays) is referred to as Delta- and is only associated with POWR-T events (Figure 7). The Delta- represents the amount of time it takes for convection to move off the airport or decay after the pre-impact synoptic wind direction returns. Delta- is the most operationally-relevant metric for POWR-T events (rather than TOWR itself) because at the time of wind return the airport is still being impacted by convection and thus there are minimal opportunities for proactive surface management. Delta- however, represents the amount of time it takes for convection to cease at the airport. Because the winds have already returned to the pre-storm condition, knowing when the convection will cease to impact the airport will allow for proactive surface and arrival management (e.g., planning for pulling aircraft from holding stacks, managing taxi queues, etc.).

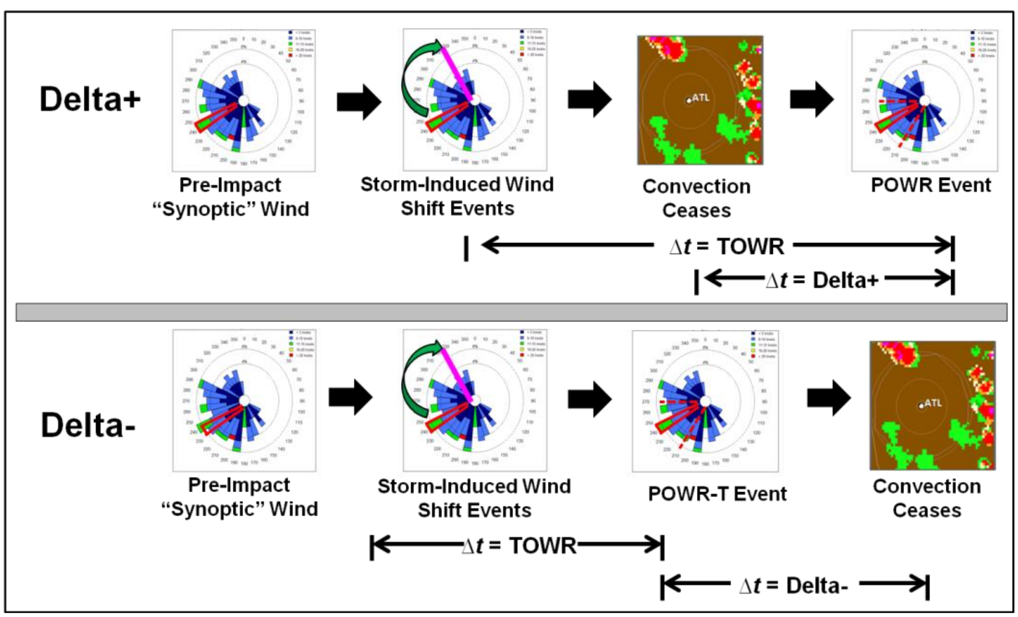


Figure 7: Schematic Diagram of the Components of Delta+ (top) and Delta- (bottom) for POWR and POWR-T Events, Respectively

3 TIME OF WIND RETURN EVENT ASSESSMENT AT CORE-29 AIRPORTS

This section will examine the frequency of TOWR events at Core-29 airports to elicit an understanding of how pervasive these events are throughout the NAS.

3.1 Historical Time Of Wind Return Frequency

From a pool of more than 10,000 terminal convective events that occurred during the analysis period across the Core-29 airports, the frequency of TOWR-specific events were identified, and are shown in Table 1. The frequency of TOWR events was computed relative to both the larger pool of terminal convective events (Table 1, column 1) and the total events with wind shifts of at least 50 degrees (Table 1, column 2). Storm events occurring while the airport was under its primary or secondary runway departure configuration, termed “Runway” storms, were also considered and the “runway” TOWR frequency was computed relative to the larger pool of “runway” terminal convective events (Table 1, column 3). Finally, to understand departure runway usage at each airport during TOWR events, “runway” TOWR event frequency was computed relative to all TOWR events at each airport (Table 1, column 4).

Table 1: Event Frequencies for All Core-29 Airports from 2002-2011

	All Convective Events with a TOWR	Wind Shift Events with TOWR	“Runway” Storms with TOWR	TOWR “Runway” Events
ATL	38%	69%	40%	98%
BOS	35%	66%	40%	88%
BWI	29%	70%	32%	94%
CLT	33%	74%	33%	93%
DCA	43%	70%	49%	93%
DEN	34%	57%	40%	60%
DFW	40%	68%	42%	87%
DTW	35%	69%	38%	97%
EWR	40%	71%	41%	97%
FLL	46%	78%	47%	94%
IAD	39%	78%	44%	74%
IAH	37%	70%	40%	49%
JFK	32%	60%	35%	86%
LGA	36%	69%	38%	87%
MCO	38%	73%	40%	79%
MDW	38%	75%	46%	66%
MEM	35%	66%	38%	62%
MIA	41%	74%	43%	80%
MSP	36%	66%	40%	89%
ORD	36%	72%	38%	52%
PHL	42%	70%	45%	87%
SLC	40%	64%	43%	93%
TPA	42%	75%	42%	20%
LAS	29%	57%	30%	90%
LAX	25%	50%	33%	100%
PHX	42%	62%	26%	59%
SAN	10%	33%	25%	100%
SEA	32%	73%	38%	91%
SFO	50%	100%	50%	100%

Across most airports, about 30-40% of all terminal convective events have a TOWR, even considering only convective events occurring while the airport is in its primary or secondary runway configuration. When a wind shift does occur, there is a high likelihood that there will be an associated wind return (60-80%). The fraction of TOWR events that occur while the airport is operating in its primary or secondary departure runway configuration (“runway”) varies greatly by airport and region. This is likely due to some airports having many available runway configurations, such as ORD, which has 16 departure runway configuration options, resulting in a relatively low frequency of TOWR “runway” storms. Others such as ATL and EWR have only five departure configuration options, resulting in a high frequency of TOWR "runway" storm events.

To further examine TOWR event frequency throughout the NAS, the annual average number of TOWR events was computed across the analysis period of 2002-2011 (Figure 8). The Florida airports, where convection is generally the most frequent, had the greatest annual average number of TOWR events, while the fewest occurred along the West coast and in the Southwest. Because a primary goal of this analysis is to characterize and classify TOWR events at airports where the frequency of occurrence warrants attention and analysis, a threshold of five TOWR events per year (red line in Figure 8) was chosen and only those airports with greater annual TOWR events were retained for more focused analysis. This threshold eliminated Phoenix Sky Harbor International Airport (PHX), Las Vegas McCarran International Airport (LAS), Seattle/Tacoma International Airport (SEA), San Francisco International Airport (SFO), Los Angeles International Airport (LAX), and San Diego International Airport (SAN) from further analysis and leaves 23 "focus" airports.

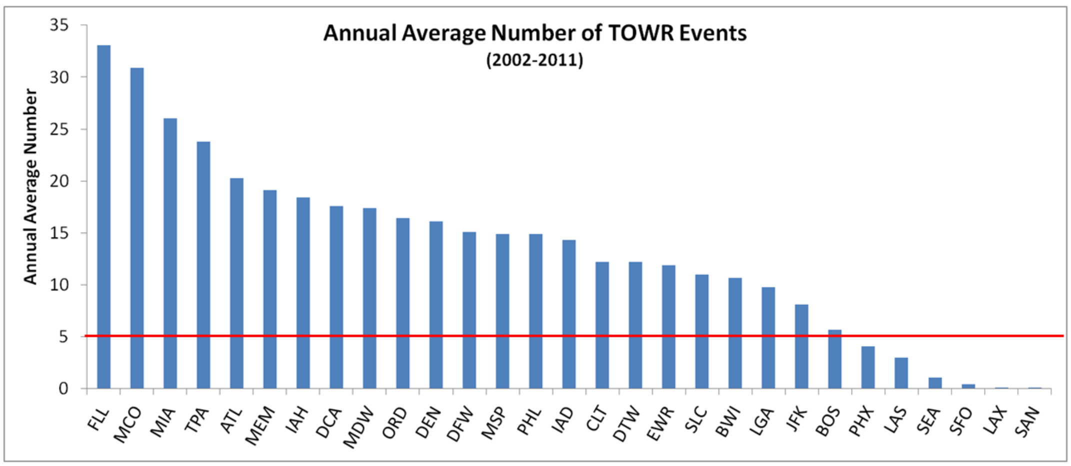


Figure 8: Annual Average Number of TOWR Events at Core-29 Airports from 2002-2011; Red Line Denotes Threshold of Five Events per Year

The annual average number of TOWR events was also examined by departure runway configuration to understand which configurations were in use during TOWR events at each airport (Figure 9). Airports were grouped by geographic region (shown in red text in Figure 9) and similar event frequencies were observed in each region, suggesting that it may be possible to "intelligently group" airports for TOWR classification and prediction. Departure runway configuration during TOWR events varied by airport and region, with Midwest airports tending to be in a secondary runway configuration most frequently during TOWR events and Florida airports tending to be in their primary runway configuration during TOWR events.

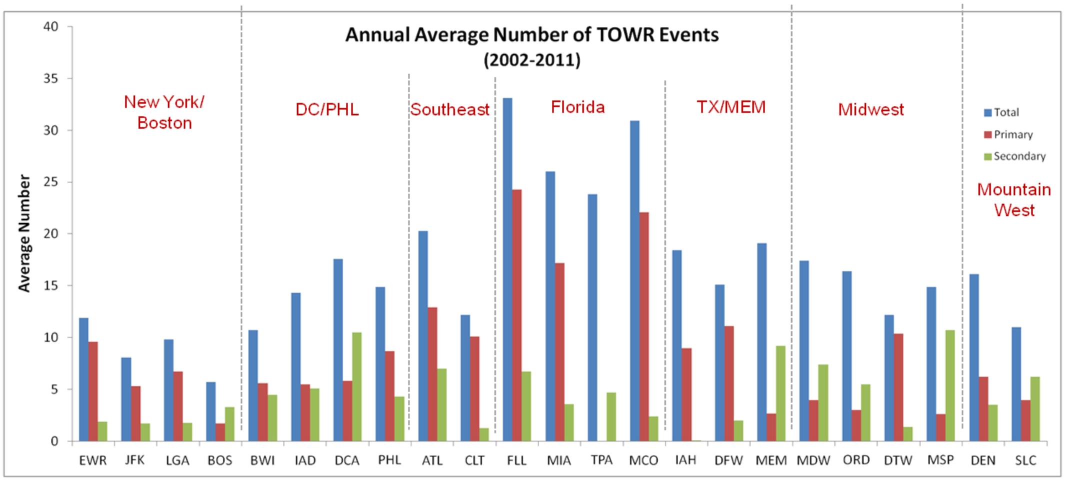


Figure 9: Figure 8 data Limited to the 23 Focus Airports Broken Down By Primary And Secondary Departure Runway Configuration; Regional Groupings of Airports Labeled in Red

To examine the relationship between time of day and TOWR event occurrences at focus airports in each region, event frequencies were computed in three-hour time windows across the analysis period (2002-2011) by departure runway configuration, two samples of which are shown in Figure 10.

Washington DC/Philadelphia ***Midwest***

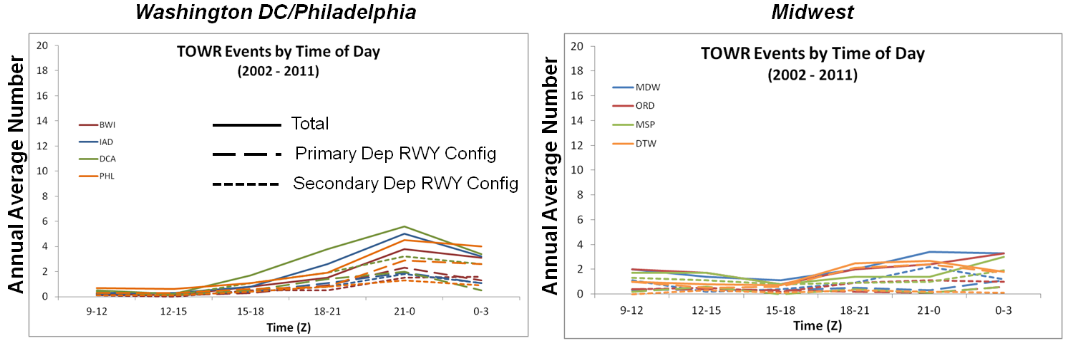


Figure 10: TOWR Event Variability by Time of Day (three-hour bins) for Washington DC/Philadelphia (left) and Midwest (right) Airports by Primary and Secondary Runway Configuration

Across all focus airports, most TOWR events occur between 18 – 00Z, with some regions like the Midwest and Texas/Memphis having a secondary peak in TOWR events between 09 – 12Z. Strong similarity was also seen among the airports in each region, suggesting that time of day may be a useful predictor for TOWR events.

Because strong similarities in annual TOWR frequencies by time of day and year have been shown among airports in each region, a monthly assessment of annual average TOWR events was conducted regionally to evaluate if month is a potential predictor for TOWR events. These regional monthly TOWR frequencies, normalized by the number of airports in each region, are broken down based on whether convection was ongoing (POWR-T) or was not ongoing (POWR) at the airport at the time of wind return and is shown in Figure 11.

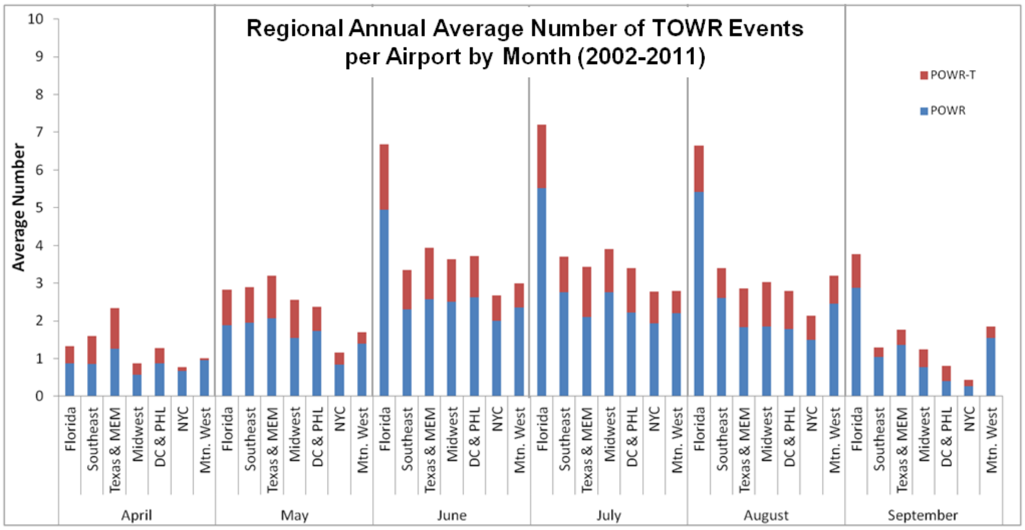


Figure 11: Regional TOWR Event Variability (2002 – 2011, Normalized by the Number of Airports in each Region) by Month, Stratified By POWR and POWR-T Events

Across all regions, there were more POWR than POWR-T events during the convective season, with the peak in TOWR events occurring during June, July, and August. This analysis suggests that for certain regions, the month during which the event occurs could be a useful predictor of whether a TOWR event will occur and whether it will be a POWR or POWR-T.

3.2 TOWR Length Assessment

The distribution of TOWR lengths, or the time between initial wind shift and its subsequent return to the pre-impact wind direction, was examined at all focus airports for POWR and POWR-T events to understand, among other things, how location is related to TOWR length (Figure 12). The median TOWR length varies only minimally across the focus airports for both POWR and POWR-T events, with TOWR being longest when there is no ongoing convection at the airport when the wind direction returns to its pre-impact direction (POWR). Too much significance should not be assigned to the TOWR length differences for POWR versus POWR-T events, as this difference is likely related to how these events are objectively defined and in relation, the limited storm residence time in one location (over an airport) for POWR-T events.

Moderate similarity in TOWR length exists among airports in each region, with interesting outliers being New York John F. Kennedy International Airport (JFK), George Bush Houston Intercontinental Airport (IAH), and Tampa International Airport (TPA)—airports each located in a coastal zone and thus perhaps influenced by unique convection forced in a sea breeze environment. Overall, the range of median TOWR for POWR events ranged from approximately 1.5 to 2.5 hours.

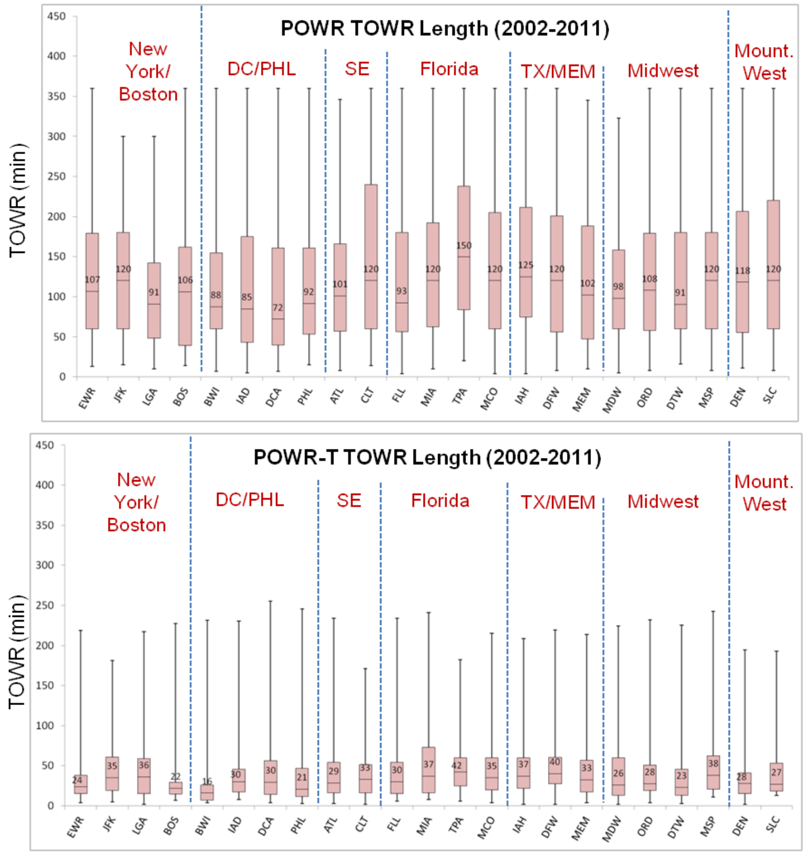


Figure 12: TOWR length for remaining 23 airports, grouped by region for POWR (top) and POWR-T (bottom) events. Pink sections denote 25th and 75th percentile values, error bars indicate maximum and minimum values, and median value is labeled.

Because of the difference in operational opportunity for proactive surface management between POWR and POWR-T events, the characteristics of both were examined further. In addition to the difference in TOWR lengths, it was found that the frequency of POWR-T and POWR events varies per airport. An in-depth study of POWR and POWR-T events at ATL revealed the following unique characteristics that may be used as TOWR predictors:

- POWR convection is initially more organized and typically weakens and/or propagates out of the terminal area.
- Wind-shift size for POWR is generally larger than POWR-T.
- Intensity of POWR convection is weaker than POWR-T at TOWR.

The significance of these characteristics to the prediction of TOWR is investigated in Section 5.

3.3 Sensitivity to Wind-Shift Size

All results that have been shown require an initial wind shift of 50 degrees from the pre-impact direction during a terminal convective event for it to be a candidate TOWR event (given a subsequent return). A sensitivity analysis has been conducted to examine TOWR and wind-shift event frequencies and characteristics using larger initial storm-induced wind shifts to define a potential TOWR event. Additional wind-shift sizes included as alternatives for defining TOWR events were 90 degrees and 130 degrees. TOWR events occurring with these larger wind shifts are part of the larger pool of TOWR events defined using the 50 degree shift, because if an initial wind shift exceeds either 90 or 130 degrees, it would have also exceeded 50 degrees. Wind shift and TOWR event frequencies were computed relative to this larger pool of "original" events. At most airports, roughly two-thirds of the original wind-shift events had shifts that also exceeded 90 degrees and about 40% exceeded 130 degrees. Similar fractions of original events, 66% and 40%, had subsequent wind returns after an initial wind shift of 90 degrees and 130 degrees, respectively.

Frequencies for windshift and TOWR events, similar to Table 1, for each wind-shift size definition were calculated (not shown). For the majority of airports, the fraction of all terminal convective events that are TOWR events (whether or not the airport was in its primary or secondary runway configuration) diminishes as the wind-shift size used to define a TOWR event increases, with values less than 20%. The percentage of wind-shift events for each considered wind-shirt size that also had a wind return (TOWR) remained similar as the size of the wind-shift increased, reflecting the decrease in overall number of both wind-shift and TOWR events with increased wind-shift size.

Median TOWR length was also examined for each considered wind-shift size at all focus airports (Section 3.2), stratified by whether convection was ongoing at the airport (POWR-T) or not ongoing (POWR). For POWR events, most airports had longer median TOWR lengths for events with the largest wind-shift size (130 degrees), suggesting that when there is no ongoing convection at the airport, wind-shift magnitude could potentially be a predictor for TOWR length. For POWR-T events, median TOWR length did not vary by wind-shift size at most airports.

4 AIRPORT OPERATIONS ASSESSMENT DURING TOWR EVENTS

This section presents an assessment of airport departure operations during TOWR events, specifically examining taxi-out times relative to a "no weather" baseline taxi-out time. Based on this analysis, airports with the highest annual taxi-out time impact at the end of a TOWR event are identified based on a combination of TOWR event frequency and taxi-out time impact.

4.1 Taxi-Out Time Evaluation

Average taxi-out times per aircraft were computed at the start (time of wind shift) and end (time of wind return) of TOWR events at each airport using ASPM data. To better understand how these times are related to a TOWR event itself, a baseline of taxi-out times was first calculated for days when the airport is not experiencing any weather impacts. In this manner, potential TOWR taxi-out delays take into account the fact that some airports experience high taxi-out times even during fair weather. This "no-weather" baseline was computed at each airport over the analysis period (2002-2011) when no precipitation or weather was reported by METAR in three-hour time windows.

To highlight impacts on taxi-out times during TOWR events (and thus, potential TOWR awareness and prediction benefits), the difference in taxi-out times between the no-weather baseline and both those at the time of wind shift and those at wind return (TOWR) was computed at each airport in three-hour time windows. A sample of this output is shown in Figure 13 for JFK, where taller columns are associated with greater taxi-out impacts relative to fair weather. This analysis facilitates the identification of times and airports where taxi-out impacts and thus potential operational improvements, are the greatest during a TOWR event—at wind shift or TOWR.

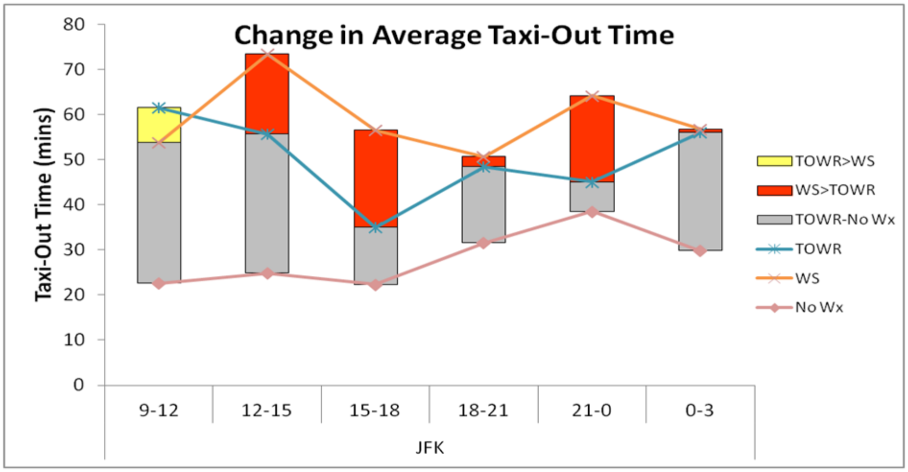


Figure 13: Average taxi-out times per aircraft for no-weather baseline (pink line), at the time of wind shift (orange line), and at the time of wind return (blue line) during three-hour time windows. Difference between average TOWR taxi-out time and baseline shown in gray, between average wind shift taxi-out time and baseline shown in red, when the taxi-out time is longer at time of wind shift and yellow when taxi-out time is longer at TOWR than at the time of wind shift.

Plots similar to the one in Figure 13 (but only including the stacked columns to highlight the taxi-out impacts based on taxi-out time differences), were generated for each airport and grouped regionally in the same manner as in Section 3. A comparison of two regions can be found in Figure 14, which shows these taxi-out impacts at airports in the New York/Boston and Washington DC/Philadelphia regions.

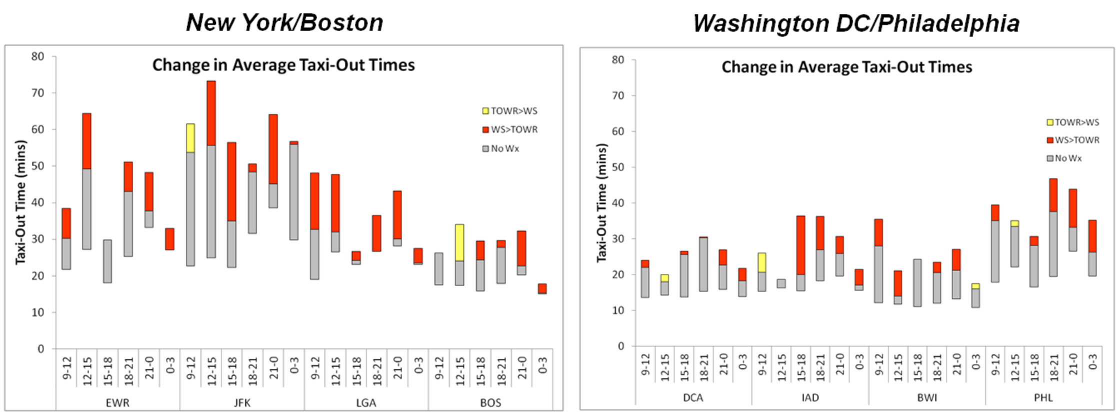


Figure 14: Same data as Figure 13, limited to only the stacked columns for airports in the New York/Boston (left) and Washington DC/Philadelphia (right) regions.

The largest impacts of all airports analyzed at both the time of wind shift and TOWR were associated with convection at the New York airports during peak departure demand periods. There was wide variation in both wind shift and TOWR taxi-out impacts across all airports, with the largest impacts outside of New York being Philadelphia International Airport (PHL), ORD, IAH, ATL, and Dallas/Fort Worth International Airport (DFW). Despite geographic and TOWR event characteristic similarities, as shown in Section 3, there is wide variation in taxi-out time impacts associated with TOWR events among airports in each region. This indicates that for a meteorological prediction and classification of TOWR events, airports may be grouped regionally but relating these events back to airport operations must be done by individual airport, or at least grouped in a manner that accounts for similar operational characteristics not associated with weather (e.g., demand, capacity, fleet and carrier mix, departure bank operations, ramp, taxi, and runway space and availability, etc.).

Focusing on potential operational improvements that could be made with an available TOWR prediction, the taxi-out impacts at TOWR (the gray columns in Figure 13 and Figure 14) were combined with the TOWR event frequency (Section 3) at all airports to evaluate those with the greatest annual taxi-out impacts. This combination was accomplished by multiplying the average taxi-out impact per aircraft per TOWR event by the annual average number of TOWR events to give an estimate of annual TOWR taxi-out impact per aircraft. The average taxi-out time impact per TOWR event was computed by averaging the taxi-out time impacts across all three-hour windows at each airport to get a daily average, and assuming that only one TOWR event occurs per day. This is an acceptable assumption given that it was quite rare across the analysis period that more than one TOWR event occurred in a given day. This annual TOWR taxi-out impact estimate was also ranked for each airport, along with its individual components (Table 2).

Table 2: TOWR event and taxi-out impacts and rankings with the top five rankings highlighted.

	FLL	MCO	MIA	TPA	DFW	MEM	IAH	MDW	ORD	MSP	DTW	PHL	DCA	IAD	BWI	ATL	CLT	SLC	DEN	LGA	JFK	EWR	BOS
Annual Average TOWR Events (A)	33	31	26	24	15	19	18	17	16	15	12	15	18	14	11	20	12	11	16	10	8	12	6
Avg. TOWR Taxi-Out Impact per Aircraft (B)	4	4	3	3	8	2	9	7	12	6	6	12	9	6	9	7	5	2	6	4	22	11	8
Annual TOWR Taxi-Out Impact per Aircraft (C = A x B)	132	124	78	72	120	38	162	119	192	90	72	180	162	84	99	140	60	22	96	40	176	132	48
Annual TOWR Event Rank (A)	1	2	3	4	12	6	7	9	10	13	16	13	8	15	20	5	16	19	11	21	22	18	23
Avg. TOWR Taxi-Out Impact per Aircraft Rank (B)	17	18	20	21	8	22	6	11	2	13	14	3	7	15	5	10	16	23	12	19	1	4	9
Annual TOWR Taxi-Out Impact Rank (C)	7	9	16	17	10	22	4	11	1	14	17	2	4	15	12	6	19	23	13	21	3	7	20

Rankings for each airport are different for each category, highlighting the importance of not only looking at TOWR event frequency or impacts alone, but also looking at them together in order to best understand the overall impacts of TOWR events. As was shown in Section 3 as well as Table 2, the Florida airports have the highest annual average TOWR events, but rank low for TOWR taxi-out impacts per aircraft, whereas several Northeast airports rank high in taxi-out impacts but much lower in TOWR event frequency. Overall, the highest ranking airports for combined annual per aircraft TOWR taxi-out impacts are ORD, PHL, JFK, IAH, and Ronald Reagan Washington National Airport (DCA).

These rankings have several caveats, including the limitation that this analysis only incorporates taxi-out information from ASPM data and does not account for other potential impacts/benefits associated with runway reconfiguration, taxi-in times, or arrival operations. These taxi-out times also include both avoidable and unavoidable impact, so it can only provide a ROM estimate, as a benefits “pool,” for potential improvement via enhanced TOWR awareness and prediction.

5 TIME OF WIND RETURN PREDICTOR: INITIAL TECHNICAL FEASIBILITY STUDY (EVENT CLASSIFICATION)

As described in the previous sections, it is clear that TOWR events occur with enough frequency and disruption at many Core-29 airports to cause significant operational impacts. These results therefore warrant follow-on research to determine if it is technically feasible to predict TOWR events in a manner that this guidance could be utilized by air traffic operations.

5.1 TOWR Event Classification Tree Diagram

The purpose for the creation of a TOWR event classification tree diagram is to provide **operationally-relevant** TOWR criteria. The TOWR event classification scheme, as shown in Figure 15, focuses on areas where TOWR prediction would provide an operational benefit. This diagram represents what we seek to predict given TOWR event predictors.

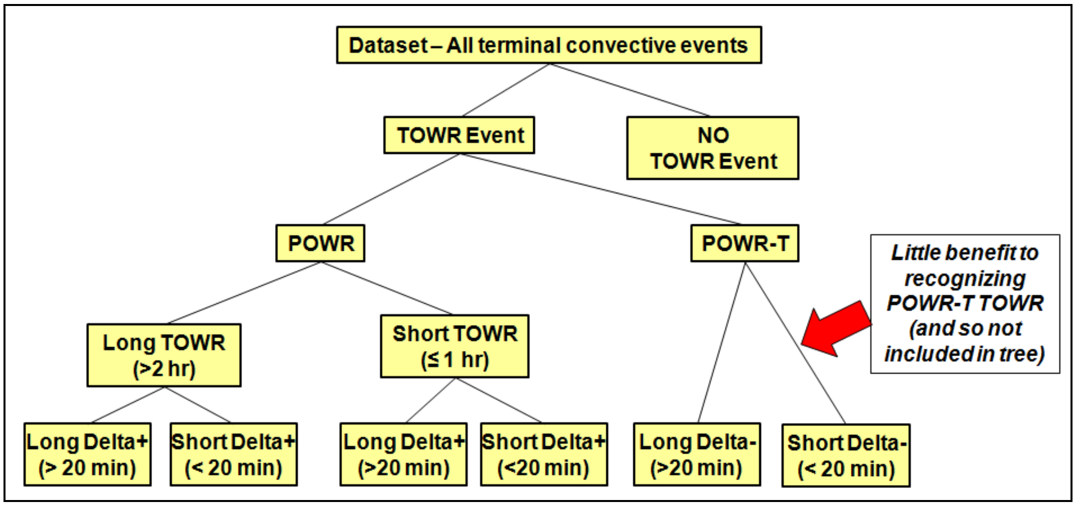


Figure 15: TOWR Event Classification Tree Diagram Displaying Operationally-relevant TOWR Criteria

Figure 16 describes the operational decisions that could be made at each level of the event classification tree diagram, given a TOWR predictor. For example (following the left side of the decision tree in Figure 16), knowing that a terminal convective event is going to be a TOWR event (and thus have a wind shift and wind return), airport operators should be prepared to coordinate and plan for multiple wind shifts. If the TOWR event is going to be a POWR, then the TOWR will be storm-free and it is possible for proactive runway and surface management. If the event is going to be a long TOWR, then operational benefits will be gained from multiple runway reconfigurations and taxi queues and holding stacks should be managed accordingly. If the time between the end of convection and wind return is going to be long (long Delta+), then the operators must plan for extended terminal operations in the wind-shifted environment. This example demonstrates the importance of investigating TOWR events with respect to operationally-significant criteria that will provide an operational benefit.

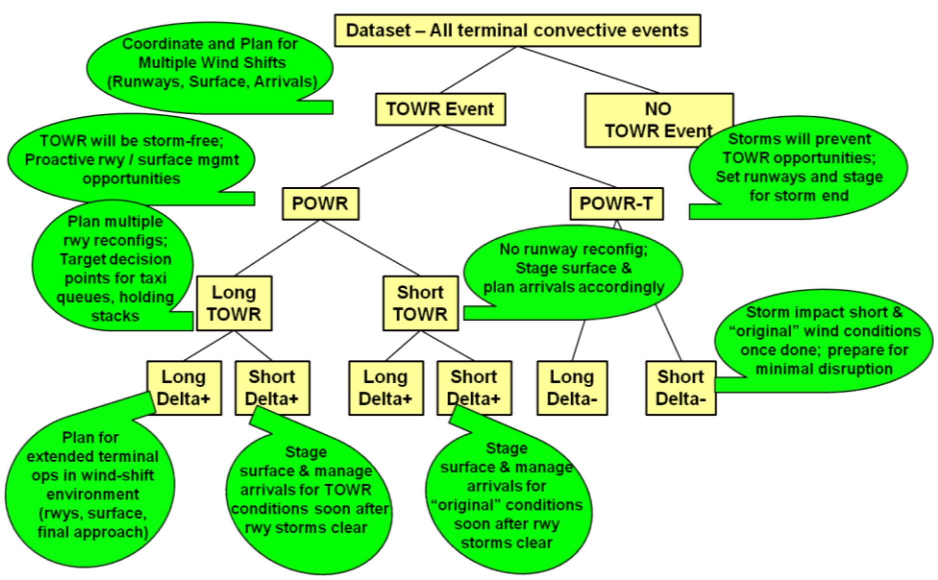


Figure 16: TOWR Event Classification Tree Diagram Displaying Operationally-relevant Decisions Associated with Each Branch of the Tree

5.2 Event Classification Methodology

The method for assessing the skill of potential TOWR predictors (or classifiers) applies a combination of empirical analyses and statistical modeling to several years of TOWR event data in order to create and populate the event classification tree diagram (Figure 15) that can be used for TOWR event prediction. Use of this method requires a sufficient historical data set of TOWR events and historical observations of potential predictor meteorological variables (i.e., wind direction, storm radar reflectivity) covering a comprehensive range of its potential values, as well as expertise of the target application domain to robustly create the event classification tree component categories. The data used for this initial study includes all TOWR events from 2005-2011 (April – September) at five target airports (ORD, ATL, Newark Liberty International Airport [EWR], Washington Dulles International Airport [IAD], and DFW). The pool of candidate meteorological classifiers related to wind characteristics, storm characteristics and event thermodynamics was derived from METAR, NCWD, and NOAA RUC hourly analysis data.

5.3 Preliminary TOWR Event Classification Scheme Results

The results from the empirical and statistical analysis were used to populate the branches of the tree diagrams for each of the five target airports. The resulting preliminary TOWR event classification schemes for the five target airports are shown in Figure 17 through Figure 21. Only the moderate (light green), moderately strong (green) and strong (dark green) meteorological classifiers are shown on the tree diagrams because they are the classifiers deemed to have some skill in predicting TOWR events. Values noted in parentheses next to each classifier represent the critical threshold value or range, indicating that in these critical value ranges for a given variable, one branch of event is most likely to occur. Gray text denotes classifiers that may be a skillful predictor for that TOWR event component, but more data is needed to confirm the result. Likewise, some levels of the tree diagram (denoted by red text) still require more data to perform the statistical analysis and will be evaluated when sample sizes are increased from five to 10 years of data.

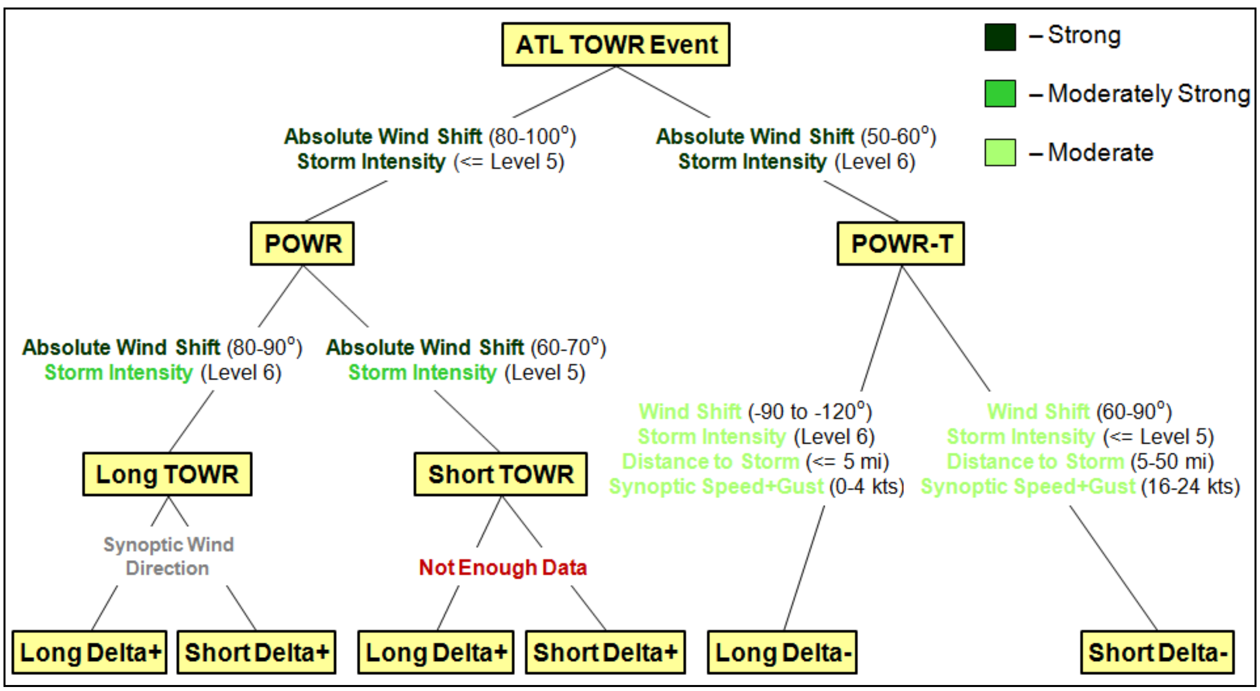


Figure 17: Preliminary TOWR Event Classification Scheme for ATL

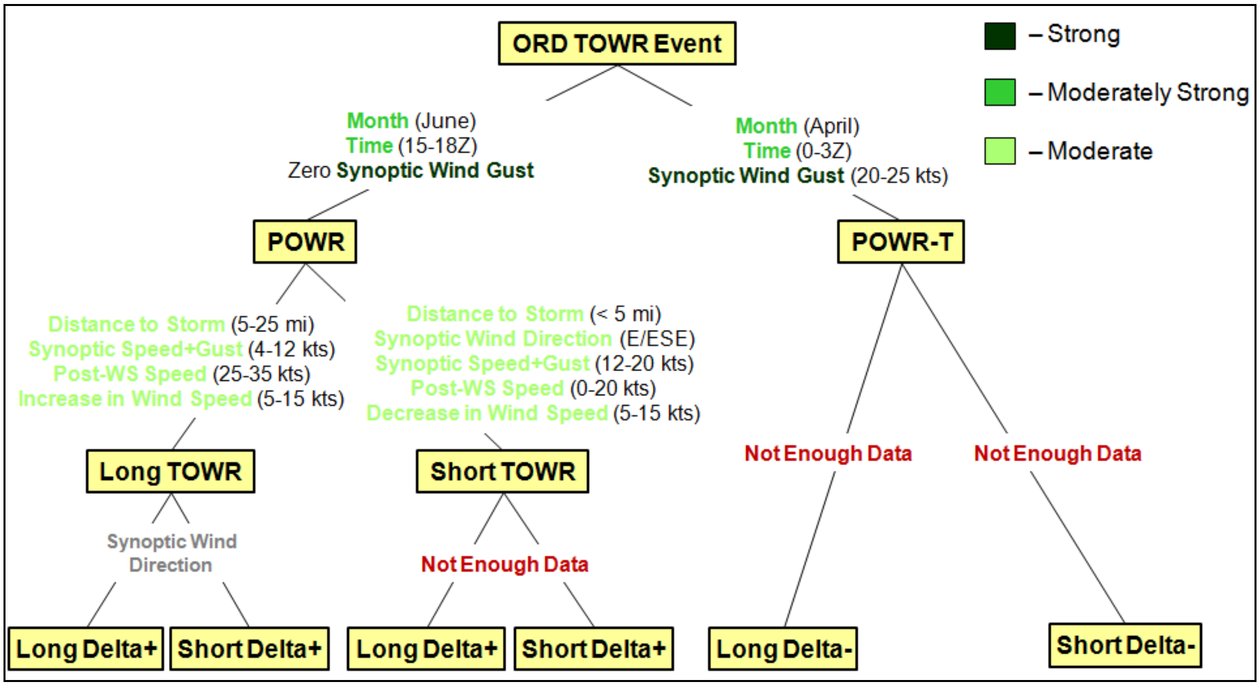


Figure 18: Preliminary TOWR Event Classification Scheme for ORD

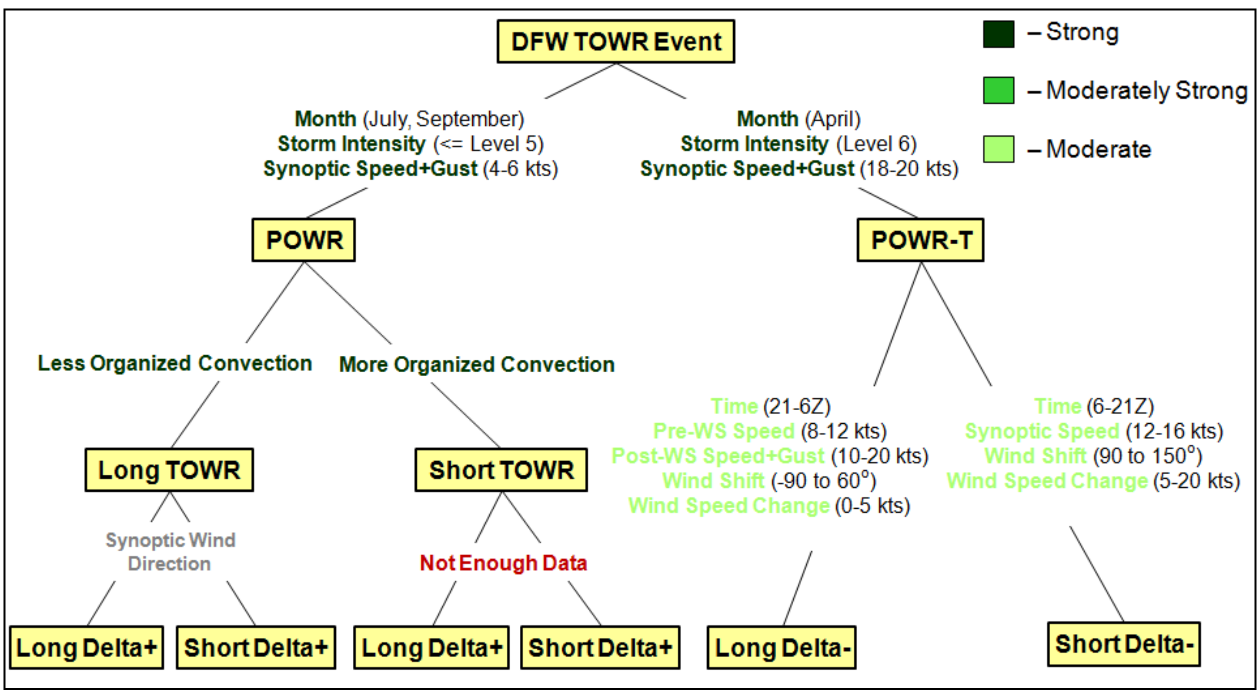


Figure 19: Preliminary TOWR Event Classification Scheme for DFW

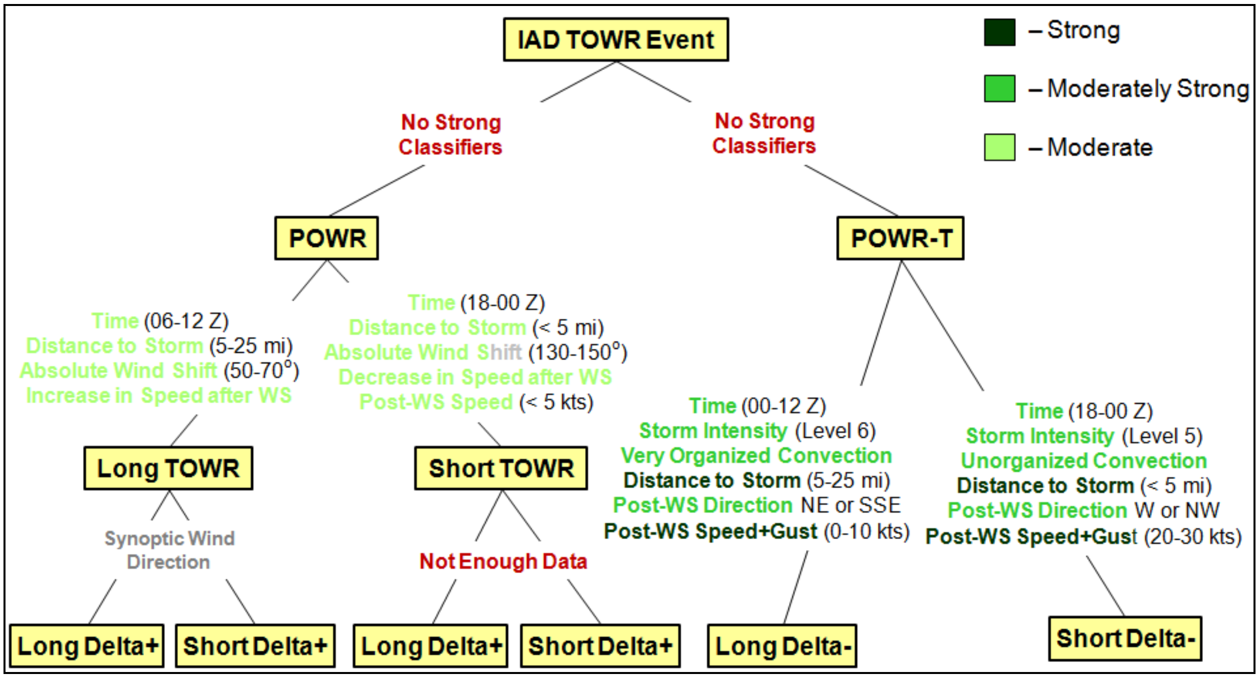


Figure 20: Preliminary TOWR Event Classification Scheme for IAD

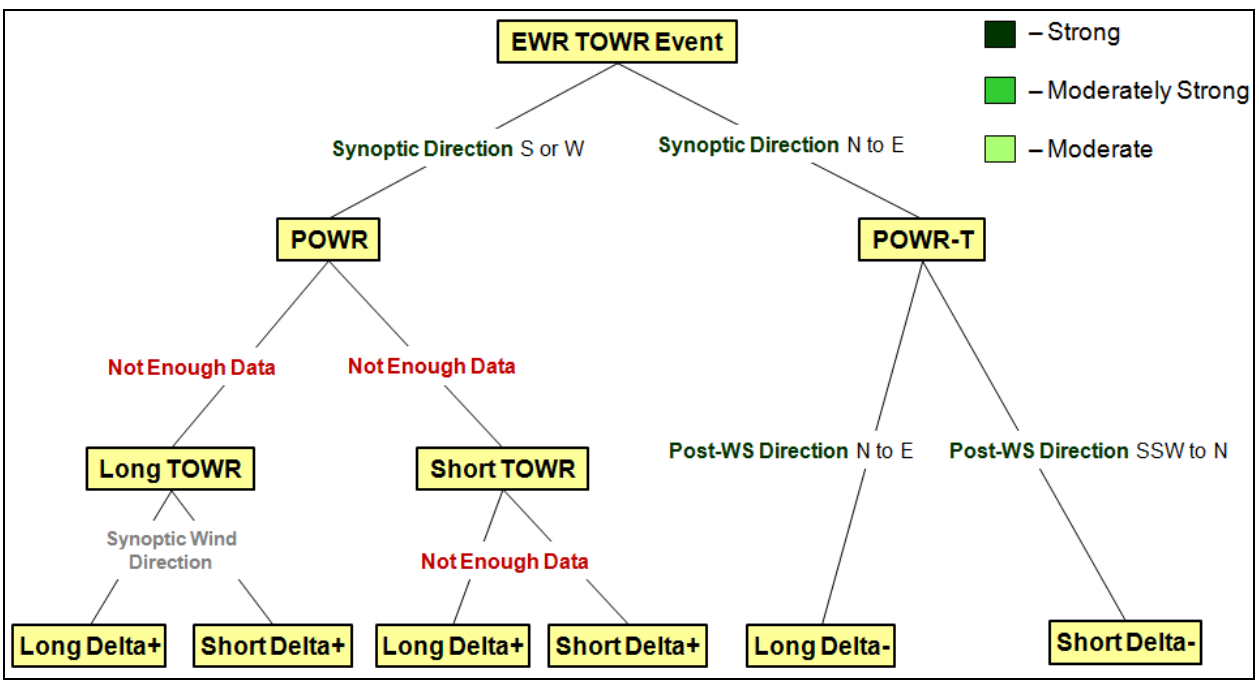


Figure 21: Preliminary TOWR Event Classification Scheme for EWR

Based on the information presented in Figure 17 through Figure 21, it is clear that there is significant variability in classifiers among the target airports. For example, synoptic wind gust is strong discriminator for the POWR versus POWR-T classification at ORD (Figure 18), but is not important at all for IAD (Figure 20); the importance of "distance to storm" ranges from no importance at EWR (Figure 21) to very important at IAD (Figure 20) for classifying POWR-T Delta-. A handful of strong or moderately strong classifiers are important at multiple airports:

- Storm intensity (four airports)
- Storm organization (two airports)
- Time of day (two airports)
- Wind-shift magnitude (two airports)

Storm intensity is the only strong classifier at multiple airports at the same level of the tree diagram (POWR/POWR-T), further demonstrating the need to examine classifiers by airport or, potentially, regionally. Other classifiers may increase in importance once more data is available for testing. Currently, one of the biggest constraints to the preliminary results is the small sample size. Appreciable quantities of cases containing a wide range of meteorological observations are needed to exercise the logistic regression model as defined. This preliminary research also did not test the importance of combination of classifiers (e.g., large wind shift and strong storm intensity). Future work will include expanding the data set from five to 10 years of data, substantially increasing the number of historical TOWR cases. In addition to the sample size limitation, more research is needed to translate the relative importance of classifiers to operational opportunities. Specifically, the ability to make ATM decisions pertinent to wind-shift planning in the terminal area based on collective capabilities of strong and moderate TOWR classifiers needs to be assessed. Even when considering the current limitations of the study, the results suggest that there may be classifiers with enough skill to accurately predict TOWR events at the target airports.

6 TIME OF WIND RETURN EVENT CLASSIFICATION/PREDICTOR RELATIONSHIP TO NEXTGEN OPERATIONS

Beyond the *current* shortfalls and operational air traffic management needs described and considered in this report, the importance and applicability of TOWR predictions will only increase with the increase in automation, seamless operations, and focus on environmental impact mitigation that will accompany NextGen. In fact, without the ability to anticipate TOWR and proactively plan for changing terminal conditions and operations, most targeted Solution Sets for NextGen may fail to mitigate avoidable delay in these weather impact conditions.

Figure 22 summarizes the NextGen Solution Sets and Operational Improvements (OI) and denotes those specific OIs that would either directly benefit from enhanced awareness and predictions for TOWR in terminal airspace or would be more efficiently utilized or implemented (and therefore less likely to be abandoned or "turned off") during the TOWR multiple terminal wind-shift environment. The Solution Set applications of TOWR are wide-ranging, and include potential contributions toward improved Trajectory-Based Operations (TBO)—since TBO is executed all the way to the airport runway, and proactive runway and surface management given TOWR conditions will enhance these operations—and even increased safety and environmental performance. Operational efficiency improvements that are envisioned with the High Density (HD) Airports Solution Set and planned HD capabilities such as "Surface Tactical Flow" and "Arrival Tactical" Trajectory Management will likely produce even greater delay/cost/environmental benefits with the availability of TOWR information during terminal convective post-impact-transition periods.

Most weather-specific OIs (and the Reduce Weather Impact [RWI] Solution Set) would likely benefit by including TOWR decision support and prediction at key NAS airports. Weather OIs such as 103119 (Initial Integration of Weather Information into NAS Automation and Decision-Making), 103121 (Full Improved Weather Information and Dissemination), and 103123 (Full Integration of Weather Information into NAS Automation and Decision-Making) are NextGen enhancement areas that aptly describe how potential TOWR prediction capabilities could contribution to mid-term operations.

Specific Decision Support Tools (DST) and capabilities designed in support of near and mid-term air traffic operations would also benefit by including TOWR guidance and predictions. Examples of these DSTs include:

- Tower Flight Data Manager (TFDM)
- Traffic Management Advisor (TMA)
- Collaborative Airspace Congestion Resolution (CACR)
- Traffic Flow Management System (TFMS)
- Surface Based Trajectory Operations (SBTO) / Surface Decision Support System (SDSS)
- Integrated Departure Route Planning (IDRP)

Each of these tools will need TOWR information in order to optimize efficiency and meet NextGen operational goals during terminal convective weather impact events.

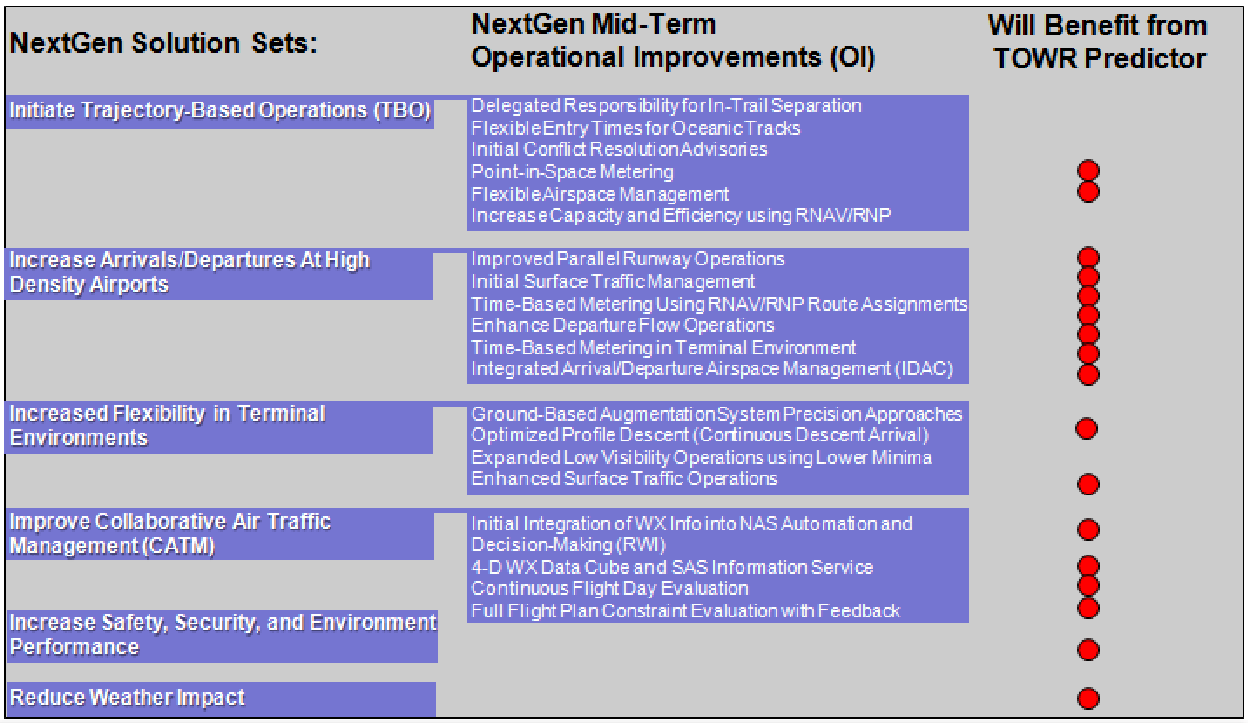


Figure 22: Applicability of TOWR Predictor to FAA NextGen Solution Sets and Associated Operational Improvements

7 CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

Research into transient terminal convection and associated TOWR phenomena seeks to better quantify the potential impacts of TOWR events on airport operations, and the potential applications and benefits of TOWR forecast decision support. This report outlines a process that begins to assess the technical feasibility of developing an operationally-relevant TOWR predictor.

Through this work it was found that wind speed and direction characteristics vary across the Core-29 airports, and TOWR events are pervasive among most Core-29 airports, as most wind-shift events have an associated wind return across all airports. Airports showed regional TOWR event similarities based on geographic proximity, suggesting airports could be grouped regionally and a TOWR event classification scheme could be used for multiple airports within the same geographic region. It was also found that time of day and month is important when examining TOWR event frequency and could potentially be used as TOWR predictors.

A sensitivity analysis was conducted to examine TOWR and wind-shift event frequencies and characteristics using larger initial wind shifts to define a potential TOWR event—90 degrees and 130 degrees (compared to the original value of 50 degrees). It was found that 66% and 40% of original wind-shift events had subsequent wind returns after an initial wind shift of 90 degrees and 130 degrees, respectively.

An assessment of airport departure operations focused on taxi-out times during TOWR events showed that the largest impacts of all airports analyzed at both the time of wind shift and TOWR were associated with convection at the New York airports during the peak departure demand period. The highest ranking airports for combined annual TOWR taxi-out impacts, and thus the airports with the highest potential benefits pool given an available TOWR prediction, are ORD, PHL, JFK, IAH, and DCA.

To test the feasibility of a TOWR predictor, a preliminary TOWR event classification scheme using a combination of empirical analyses and statistical modeling was developed and used to create preliminary TOWR event classification schemes for five target airports. It was shown that there is great variability in the importance of classifiers, e.g., a given classifier could be very important at one airport and not important at another, and that classifiers have varying importance at different levels of the classification scheme even at a given target airport, suggesting TOWR classification needs to be examined by individual airport or potentially regionally. Lastly, the TOWR event classification scheme can be related to operational decision-making through proactive runway management, improved surface and arrival operations, and improved operational productivity support for NextGen decision support.

7.2 Future Work

Future refinements remain for multiple aspects of the preliminary work presented in this paper. Additional analysis is needed to thoroughly examine characteristics of events based on the wind-shift magnitude used to define the TOWR events, and how it relates to the predictability of TOWR events. In addition, storm characteristics should be examined for TOWR events at all Core-29 airports for the entire analysis period (2002-2011).

The preliminary classification scheme will be refined with more data (all Core-29 airports, 10 years of data) so that combinations of classifiers can be tested, as well as other parts of the classification tree (e.g., TOWR versus non-TOWR event, POWR with a long TOWR and short Delta+). Also, the relationship of the TOWR event classification scheme to airport operations needs further investigation, and the technical feasibility must be refined by quantifying the benefits assessment and investigating the TOWR event scheme thresholds further. The TOWR operational analysis would benefit from a robust ASDE-X dataset for accurate taxi times. Once predictors are identified for each airport or region, the predictive capability based on the classification tree must be developed and tested for accuracy and integrated into NAS current and mid-term operations.

8 ACKNOWLEDGEMENTS

This research was funded through the Federal Aviation Administration (FAA) division ANG-C6.

APPENDIX A: LIST OF AIRPORTS BY REGION

Region	Airport ID	Airport Name
Northeast	BOS	Boston Logan International
	LGA	New York LaGuardia
	EWR	Newark Liberty International
	JFK	New York John F. Kennedy International
Mid-Atlantic	DCA	Ronald Reagan Washington National
	IAD	Washington Dulles International
	BWI	Baltimore/Washington International
	PHL	Philadelphia International
	CLT	Charlotte Douglas International
	ATL	Hartsfield-Jackson Atlanta International
Florida	TPA	Tampa International
	FLL	Fort Lauderdale/Hollywood International
	MCO	Orlando International
	MIA	Miami International
Midwest	ORD	Chicago O`Hare International
	DTW	Detroit Metropolitan Wayne County
	MSP	Minneapolis/St. Paul International
	MDW	Chicago Midway
Memphis/Texas	MEM	Memphis International
	DFW	Dallas/Fort Worth International
	IAH	George Bush Houston Intercontinental
Mountain West	DEN	Denver International
	SLC	Salt Lake City International
West Coast	SEA	Seattle/Tacoma International
	SFO	San Francisco International
	LAX	Los Angeles International

	SAN	San Diego International
	LAS	Las Vegas McCarran International
	PHX	Phoenix Sky Harbor International

APPENDIX B: LIST OF ACRONYMS

ACRONYM	DEFINITION
ASDE-X	Airport Surface Detection Equipment, Model X
ASPM	Aviation System Performance Metrics
ASQP	Airline Service Quality Performance
ATC	Air Traffic Control
CACR	Collaborative Airspace Congestion Resolution
CWSU	Central Weather Service Unit
DST	Decision Support Tool
FAA	Federal Aviation Administration
HD	High Density
IDRP	Integrated Departure Route Planning
METAR	Meteorological Terminal Aviation Routine Weather Report
NAS	National Airspace System
NCWD	National Convective Weather Diagnostic
NextGen	Next Generation Air Transportation System
NOAA	National Oceanic and Atmospheric Administration
OI	Operational Improvements
OOOI	Out-Off-On-In
POWR	Post-Occurrence Wind Return
RUC	Rapid Update Cycle
RWI	Reduce Weather Impact
SBTO	Surface Based Trajectory Operations
SDSS	Surface Decision Support System
TFDM	Tower Flight Data Manager
TFMS	Traffic Flow Management System
TMA	Traffic Management Advisor
TOWR	Time of Wind Return