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Initial Assessment of Wind Forecasts for Airport Acceptance Rate (AAR) and Ground Delay Program (GDP) Planning

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16. Abstract

The planning and execution of the Airport Acceptance Rate (AAR) for major metroplex airports is a complex and critical function of traffic managers in the National Airspace System (NAS). Despite the importance of AAR planning, traffic managers currently have no widely available decision support to provide guidance for runway selection and the determination of a sustainable AAR. The AAR Decision Support Capability (AARDSC), currently under development as part of the Collaborative Air Traffic Management Technology Work Package 4 (CATMT WP4), will provide such guidance.

This report provides an initial analysis of the impacts of surface winds and winds aloft on the key factors associated with the AAR (the selection of runway configuration and aircraft ground speed and spacing on final approach) and the capabilities of currently available weather forecasts to accurately predict those impacts. The report was limited in scope by the schedule and available resources, and is intended as a foundation for a comprehensive forecast assessment in follow-on work.

Surface wind forecasts from the Terminal Aerodrome Forecast (TAF) and numerical prediction models (the High Resolution Rapid Refresh [HRRR], Rapid Refresh [RAP] and Rapid Update Cycle [RUC], collectively described as "MODEL") were compared to observed winds gathered from METAR reports at Newark International Airport (EWR). TAF and METAR were compared for 639 days of operations from 2011–2013. MODEL forecasts and METAR were compared for 21 days of operation, 16 of which had Traffic Management Initiatives (TMI) in place to mitigate adverse weather impacts. Winds aloft were translated into several wind impact metrics. The impacts of winds aloft forecast errors were evaluated by comparing impact metrics calculated from MODEL forecasts with those calculated from analysis fields for the 21 case days. Forecasts were evaluated at horizons of 2, 4, 6, and 8 hours.

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EXECUTIVE SUMMARY

The planning and execution of the Airport Acceptance Rate (AAR) for major metroplex airports is a complex and critical function of traffic managers in the National Airspace System (NAS). Despite the importance of AAR planning, traffic managers currently have no widely available decision support to provide guidance for runway selection and the determination of a sustainable AAR. The AAR Decision Support Capability (AARDSC), currently under development as part of the Collaborative Air Traffic Management Technology Work Package 4 (CATMT WP4), will provide such guidance.

Critical factors that impact the AAR are the selection of the arrival runway(s) and the aircraft ground speed and spacing on final approach. These factors are affected by several characteristics of the weather and operations, including surface winds and winds aloft. This report provides an initial analysis of the impacts of surface winds and winds aloft on the key factors associated with the AAR (the selection of runway configuration and aircraft ground speed and spacing on final approach) and the capabilities of currently available weather forecasts to accurately predict those impacts. The report was limited in scope by the schedule and available resources, and is intended as a foundation for a comprehensive forecast assessment in follow-on work.

Surface wind forecasts from the Terminal Aerodrome Forecast (TAF) and numerical prediction models (the High Resolution Rapid Refresh [HRRR], Rapid Refresh [RAP] and Rapid Update Cycle [RUC], collectively described as “MODEL”) were compared to observed winds gathered from METAR reports at Newark International Airport (EWR). TAF and METAR were compared for 639 days of operations from 2011–2013. MODEL forecasts and METAR were compared for 21 days of operation, 16 of which had Traffic Management Initiatives (TMI) in place to mitigate adverse weather impacts. Winds aloft were translated into several wind impact metrics. The impacts of winds aloft forecast errors were evaluated by comparing impact metrics calculated from MODEL forecasts with those calculated from analysis fields for the 21 case days. Forecasts were evaluated at horizons of 2, 4, 6, and 8 hours.

Key findings of the baseline evaluations were:

1. Statistical differences between TAF and MODEL surface forecasts were small.
2. Statistical differences between different wind forecast horizons (ranging from 2 to 8 hours), for both surface and aloft winds, were small.
3. Several wind impact metrics, derived from winds aloft, show skill as predictors of significant operational impacts.
4. The apparent lack of improvement in forecast accuracy at shorter forecast horizons, and the lack of accurate short horizon forecasts (less than two hours) to support the execution of arrival management plans were identified as significant shortfalls.

To determine the impact of surface headwind forecast errors on runway selection, two probabilities were defined and calculated from TAF and MODEL forecasts: the probability of infeasible runway selection and the probability of optimal runway selection. The probability of infeasible selection was surprisingly low (<<1%) for both TAF and MODEL forecast, considering the frequency of operational difficulties attributed to surface wind conditions. The probability of optimal runway selection was between 0.55 and 0.60 for all forecast horizons from the TAF and MODEL forecasts.

Three statistical measures were defined to estimate of the effect of winds-aloft impact forecast errors on aircraft ground speed and spacing on final approach: probability of prediction of operational impact (PoPOI), probability of false operational impact (PoFOI), and probability of true operational impact (PoTOI). The measures were calculated for MODEL forecasts from the 21 case days. PoPOI generally ranged between 0.85 and 0.95 for all forecast horizons of all wind impact metrics. PoFOI ranged generally between 0.1 and 0.3, with higher value often associated with longer forecast horizons. PoTOI ranged from approximately 0.09 to 0.25, which suggests that wind impact conditions were commonly observed on high impact days, and seems reasonable considering that compression was explicitly noted in operational logs on 10 of the 21 case study days. These statistical measures may be applied to future analyses of potential benefits.

The forecast evaluation methodology did not capture the ability of forecasts to predict specific *events*, such as frontal passages with associated strong wind shifts or the onset of a sea breeze, that have potentially widespread or long-lived operational impacts. The accuracy and timing of forecasts of such significant events are critical aspects of forecasts that planners must assess, as they have a direct bearing on the type, scope, and timing of TMI to mitigate weather impacts.

Several follow-on research efforts have been identified:

1. Refinement of the results of this evaluation. The findings of this analysis were based on a limited data set from a single location (EWR). The scope of the analysis should be expanded to include several additional sites and case days.

2. Event-based forecast evaluation. The ability to forecast the onset and clearing of weather events that have significant impact on operations (e.g., frontal passages) should be evaluated.

3. Definition of forecast requirements and shortfalls. These follow from a potential benefits analysis that accounts for the impacts of forecast errors on translation and event forecasts.

4. Identification of forecast requirements and opportunities for improvement at shorter planning and execution horizons. The finding that there is little statistical difference between 2 and 8 hour forecast accuracy suggests a need to explore requirements and opportunities to improve short horizon wind forecasts for progressive planning and tactical execution.

5. Development of forecast uncertainty models that can be translated into confidence metrics for specific operational decisions. Models for the uncertainty of weather impact forecast metrics must be developed and translated into confidence metrics that apply to the specific impact mitigation decisions that planners must evaluate.

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1. INTRODUCTION

The Airport Acceptance Rate (AAR), which states the expected hourly landing capacity for an airport, is a fundamental driver for National Airspace System (NAS) operations. The AAR at any particular time depends on the runway configuration in effect at the airport, and may be further affected by adverse weather, type of aircraft that make up the arrival and departure demand, equipment outages, etc. Traffic planners and managers from the airport tower, the host Terminal Radar Approach Control (TRACON) and Air Route Traffic Control Center (ARTCC), and the Air Traffic Control System Command Center (ATCSCC) may confer several times per day to determine the preferred runway configuration and sustainable AAR, given the operational circumstances as the day unfolds. When factors such as adverse weather or equipment outages constrain airport capacity and arrival demand is expected to exceed the AAR by a significant amount, Traffic Management Initiatives (TMI) may be planned and implemented to restrict demand and restore the balance between demand and capacity at the airport. The most commonly used TMI for airport demand management is the Ground Delay Program (GDP), in which flights destined for the constrained airport are assigned pre-departure ground delays to reduce demand during the hours of constrained operations.

Figure 1 illustrates both the challenges and opportunities to improve AAR and GDP planning during adverse wind impact events. A stationary front settled in near EWR for much of the day on 27 October, 2011, with moderate northerly winds north of the airport, and weak-to-moderate southerly winds south of the airport. A GDP was in place for low ceilings, and the arrival rate fell far short of the GDP rate, resulting in a lengthy Ground Stop (GS) around 15Z, followed by a GDP revision to a lower arrival rate. Go-arounds and compression were reported in 17-18Z period, and a second GS ensued, followed by yet another downward revision of the GDP rate. In this instance, the front and winds were reasonably well-forecast, but traffic managers had no ready access to tools that could have provided a detailed display of winds and frontal boundaries similar to the one shown in Figure 1, nor did they have access to wind translations that would forecast likely compression due to winds aloft. The AAR Decision Support Capability (AARDSC) Preliminary Benefits Analysis estimated that similar operational challenges due to adverse winds are present approximately 15 days per year in operations at Newark International (EWR) and LaGuardia (LGA) Airports, with an annual potential benefits pool of approximately $5 million associated with excessive airborne holding and diversions [1].

Actual arrival rates and delays on October 27, 2011

Time (Z)	15	16	17	18	19	20	21	22	23	0	1	2
GDP rate		34	34	32	32	32	32	32	32	30	30	30
ASPM arrival rate	27	25	25	29	31	27	28	26	27	22	24	29
AAR	34	34	34	34	34	34	34	34	34	34	34	34
average arrival delay	6	25	49	64	74	55	80	83	90	80	80	60

Ground Stops

HRRR 3 hour forecast valid at 15Z

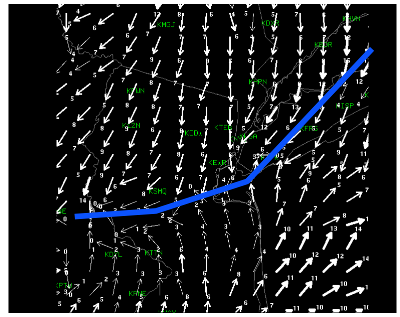

Figure 1. Illustration of adverse wind impacts at Newark International Airport (EWR).

Several factors impact the selection of runway configuration and the determination of AAR:

1. **Surface winds.** Headwinds and crosswinds at the surface determine the feasibility of use for a given runway. Surface winds may determine the feasibility of particular operational procedures such as Land and Hold Short Operations (LAHSO). Surface headwinds may also affect the ground speed of aircraft on final approach, which is closely related to the achievable arrival rate. Surface wind impacts may be exacerbated by adverse ceiling and visibility conditions.

2. **Ceiling and visibility.** Ceiling, visibility, and the ability to maintain visual separation affect the feasibility of different operational procedures, such as simultaneous landings on parallel arrival runways. The availability of such procedures may impact both the preferred runway configuration and the AAR achievable on the selected runway configuration.

5. **Winds aloft (up to approximately 12 kft).** Excessive wind speeds and/or vertical wind shear aloft are currently not considered in making the choice of runway configuration. (In fact, planners have limited access to information about winds aloft.) However, adverse wind conditions aloft can result in AAR reductions due to the increased complexity of merging arrival traffic streams and maintaining acceptable ground speeds and spacing as aircraft descend and change heading through strong or varying winds. In particular, winds aloft may result in *compression*, in which the spacing between pairs of arriving aircraft decreases rapidly as they descend to final approach. Compression arises when headwinds increase significantly along the arrival trajectory, causing the lead aircraft ground speed to decrease more rapidly than the ground speed of the following aircraft. The greater than anticipated difference in ground speed between lead and following aircraft results in a reduction in aircraft spacing that can make it difficult for controllers to maintain required aircraft separation. High winds aloft may also result in abnormally high or low aircraft ground speeds, which may make it difficult to speed up or slow down efficiently to the desired ground speed on final approach.

6. **Runway surface conditions.** The conditions of the runway surface affect the braking ability of arriving aircraft, and as a result may limit the feasibility of landing procedures such as LAHSO.

7. **Arrival demand fleet mix.** The weight class and type of aircraft that make up the arrival demand will determine the likely average landing speed and final spacing, both of which are key factors in the AAR estimation.

8. **Schedule.** Some airport schedules are characterized by alternating periods of high departure and high arrival counts ("banks"). Schedule banks may dictate that the preferred runway configuration favor departures or arrivals at different parts of the day, with the AAR changing to reflect the preference.

9. **Metroplex coordination.** In crowded metroplex airspaces like New York, runway configurations at metroplex airports may need to be coordinated to ensure that traffic patterns for one airport do not conflict with those for another. On occasion, the needs of one metroplex airport may dominate, and the selected runway configurations for all metroplex airports may be driven by the needs of the dominant airport, rather than individual airport optimality.

10. **Equipment outages.** Runways configurations or procedures may be infeasible if airport resources or equipment required to use the runway or implement the procedures are not in service.

As part of the Collaborative Air Traffic Management Technology Work Package 4 (CATMT WP4) implementation, scheduled for release into the NAS Traffic Flow Management System (TFMS) in the 2016-2020 timeframe, an Airport Acceptance Rate Decision Support Capability (AARDSC) is being developed. The AARDSC is intended to address the current lack of an objective forecast for AAR in the TFMS that takes into account the effects of predicted adverse weather (winds, ceiling, and visibility), fleet mix, surface conditions, and equipment outages. The AARDSC is expected to reduce airborne holding, diversions, and Ground Stops (GS) that result from poor AAR and GDP planning. Since adverse winds in the terminal area are a significant cause of operational problems in the TRACON, a key element of the AARDSC is improved capability to forecast wind impacts on AAR [2].

The AARDSC is based on the AAR Decision Support Tool spreadsheet (ADEST) developed by traffic manager Greg Callahan at Newark International Airport (EWR) [3]. ADEST accounts for the impacts of surface winds, ceiling, visibility, runway surface conditions, arrival demand fleet mix, and equipment outages on the sustainable AAR. The user provides fleet mix information and an average ground speed on final approach for each hour of operations. Weather forecast information for each hour (surface winds, ceiling, visibility, and surface conditions) are taken from the Terminal Aerodrome Forecast (TAF). ADEST uses a set of procedural and heuristic rules to determine the preferred runway configuration and average arrival spacing. The "base" runway AAR is calculated by dividing the average ground speed by the average spacing on final approach, and then adjusted further to account for the number of runways in operation, arrival fleet mix, etc. ADEST does not currently account for the impacts of winds aloft on AAR.

The AARDSC will provide the following enhancements to ADEST:

1. Incorporation of the impacts of adverse winds aloft on arrival operations (in particular, increases in spacing due to difficulties in merging multiple arrival streams and compression),

2. Prediction of the average ground speed on final approach for the calculation of the base AAR, taking into account the effects of surface and aloft winds, and

3. Refinements of the spacing algorithm to account for operational stresses that arise in the TRACON due to the combined effects of surface winds, winds aloft, ceiling, and visibility impacts.

This report presents the results of an initial assessment of wind forecasts for use in AARDSC to support improved AAR and GDP planning through the proposed ADEST enhancements. The analysis focuses on the ability of existing forecasts to support the first two enhancements (impacts of winds aloft on spacing and prediction of ground speed on final approach). As part of the analysis for this report, an initial exploration of operational stresses due to adverse weather was undertaken. However, a satisfactory objective metric for operational stress has not yet been defined, so the impact of wind forecast accuracy on the ability to predict and mitigate operational stresses (beyond limitations on ground speed and spacing on final approach) could not be determined. It is intended to provide the foundation for a comprehensive assessment of wind forecasts for AAR and GDP planning and arrival management which will guide the definition of wind forecast requirements for AAR and GDP planning and identify forecast shortfalls that should be addressed. Only wind forecasts that are expected to be operational in the WP4 time frame and that provide forecast products that can be translated into arrival trajectory impacts were assessed. The sources of wind forecast and "truth" data evaluated in this study are described in Table 1.

TABLE 1

Wind Forecasts Evaluated in This Study

Forecast	Type	Products	Update	Horizon	Status	Truth
Terminal Aerodrome Forecast (TAF)	Human, point forecast	Surface winds, gusts, ceiling, visibility, runway conditions	3 hours, special as needed	24 hours	Operational	METAR observation
Rapid Update Cycle (RUC)	Automated, gridded forecast	Surface winds, winds aloft (isobar levels)	Hourly	15 hours	Operational (prior to 1 May 2012)	RUC analysis, METAR (for surface forecasts)
Rapid Refresh (RAP)	Automated, gridded forecast	Surface winds, winds aloft (isobar levels)	Hourly	15 hours	Operational (starting 1 May 2012)	RAP analysis, METAR (for surface forecasts)
High Resolution Rapid Refresh (HRRR)	Automated, gridded forecast	Surface winds, winds aloft (isobar levels)	15 minutes	15 hours	Prototype (operational in 2015)	HRRR analysis, METAR (for surface forecasts)

Wherever available, the HRRR was evaluated for forecast of winds aloft.

This report is organized as follows. The methodology for forecast assessment is described in Section 2. The set of wind impact metrics—wind field characteristics that can be calculated from forecast and observed winds that are likely to have the greatest effect on the AAR—are described in Section 3. The results of the surface and aloft wind forecast assessment are presented in Section 4. A summary of the findings and recommendations for future work are presented in Section 5. An Appendix provides details of the analysis used to determine the wind impact metrics, and a description of as yet unmet challenges in defining an operational stress metric.

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2. METHODOLOGY

In order to assess the effectiveness of wind forecasts for AAR planning, it is necessary to understand how winds affect arrival operations. The following methodology, illustrated in Figure 2, was employed to determine the characteristics of winds fields that impact arrival operations and to guide the evaluation of wind forecasts:

1. **Identify the operational decisions most critical to the AAR planning process.** Key decisions were identified from discussions with subject matter experts: selection of the preferred runway configuration, and determination of a sustainable AAR for the selected configuration that accounts for adverse weather and other operational factors.

2. **Identify the factors that drive each decision.** The key weather impact factor driving the runway selection decision is the feasibility of use for each runway. The key factors affecting the sustainable AAR are the average ground speed and spacing of aircraft on final approach.

3. **Identify signs of operational stress.** Since stress is likely to arise when airborne arrival inventory exceeds capacity for the current conditions, the observed AAR performance during periods of stress can be assumed to be the "best possible" under the observed conditions. Periods of operational stress also identify a portion of the potential benefits pool. This evaluation does not include an in-depth analysis of operations during periods of operational stress, as the definition of objective metrics for operational stress is still being developed.

4. **Define and validate objective wind field characteristics ("wind impact metrics") that may be associated with decision-driving factors and operational stress.** Runway feasibility is determined in large part by the headwinds and crosswinds for the runway at the surface. Several metrics based on surface and aloft winds that may impact ground speed and spacing on final approach were considered. These are described in Section 3.

5. **Define forecast evaluation metrics based on impact metrics and how they impact decisions.** Where possible, thresholds that relate wind impact metrics to specific decisions (e.g., the maximum tailwind for which a runway is feasible) are defined, and the forecast error is assessed in terms of the accuracy of decisions based on the forecast of the exceedance of operational thresholds.

6. **Develop forecast requirements and identify shortfalls.** The specification of forecast requirements and shortfalls follows from the forecast evaluation through an assessment of the impact of forecast capabilities on decision making, operational performance, and the benefit associated with operational performance as a result of improved decision making. The development of forecast requirements is beyond the scope of this report.

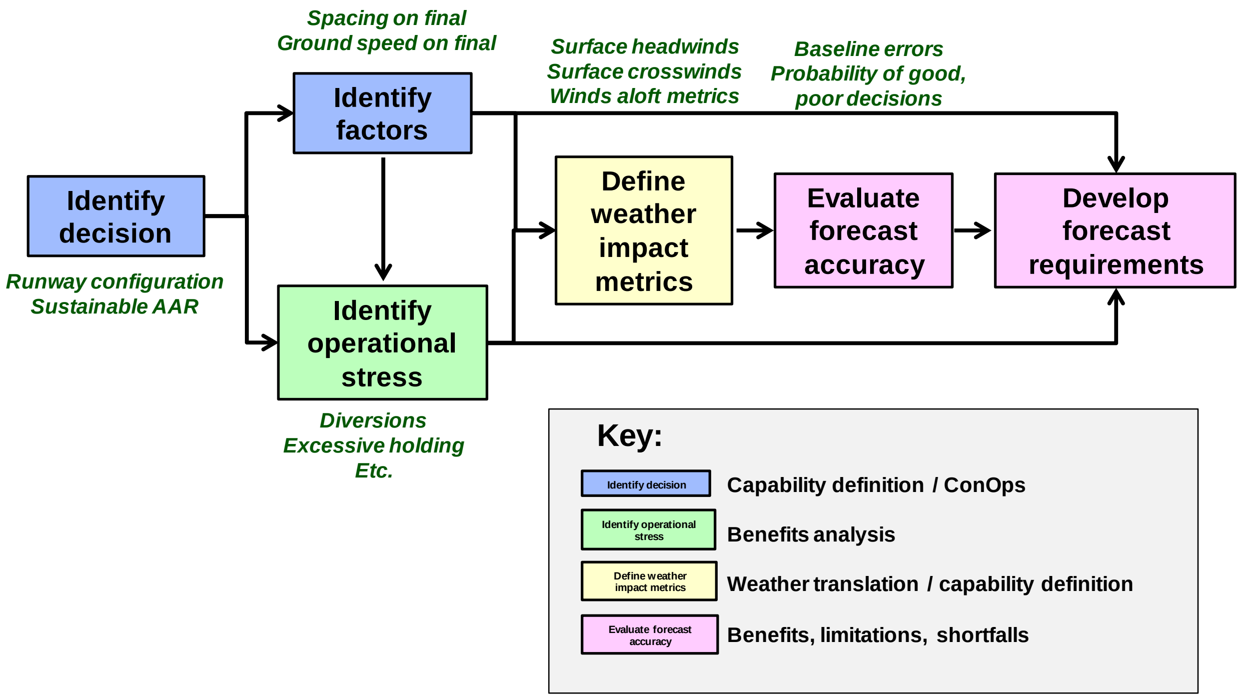


Figure 2. Forecast evaluation methodology.

The assessment data set consisted of winds and operational data from 21 days at EWR from 2011–2013. EWR was selected as the initial test site because of the high number of GDP due to winds, the high number of GS observed during GDP (evidence of a challenging, highly stressed operational environment) (Figure 3), the complexity of EWR and New York TRACON operations, and the opportunity for significant potential benefits from improved AAR and GDP planning at the site. The data set includes 6 days of "nominal" operations (no observed adverse weather or operational impacts), and 15 days where adverse weather impacted operations (14 days with GDP, one day with a GS only). Additional information about operational conditions was taken from the National Traffic Management Log (NTML) for the day. Table 2 summarizes the operating conditions on the case days.

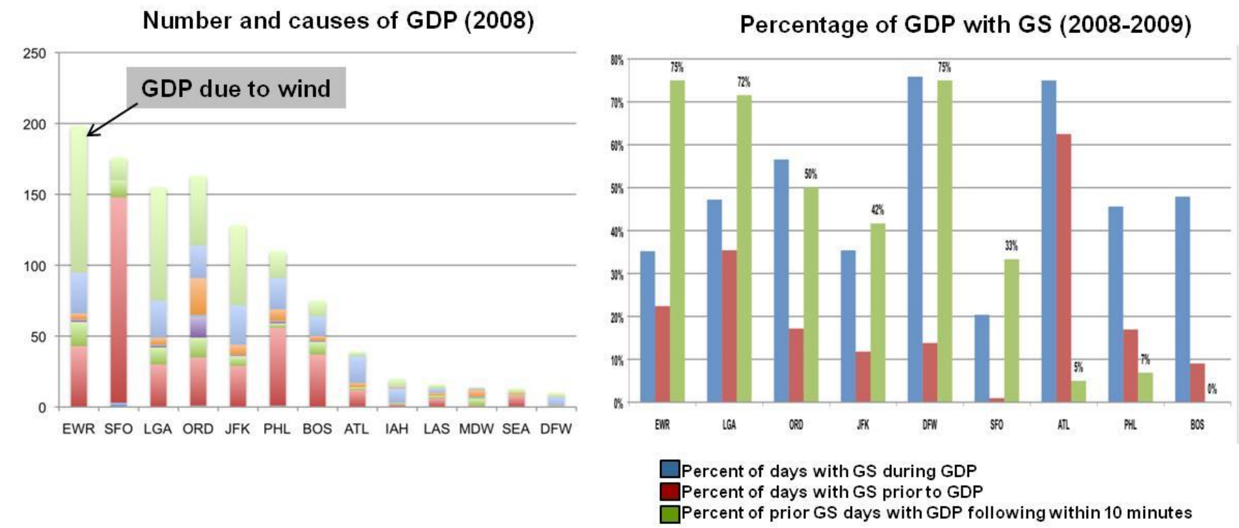


Figure 3. GDP and stated reasons (left) [4] and percentage GDP with GS (right) [5].

TABLE 2

Summary of Case Study Days from EWR

Date	GDP (wind)	GDP (C&V)	GS	VMC	IMC	NTML
06 Sept. 2011		X	X	X	X	Compression
13 Oct. 2011		X	X (2)		X	EWR, LGA GS (compression)
23 Jan. 2012		X	X (4)		X	N90 compression on final approach
26 Feb. 2012	X			X		EWR gusts, compression on final approach
26 Mar. 2012	X		X	X		EWR compression, wind shear
27 Apr. 2012	X			X		EWR wind GDP
14 Oct. 2012	X			X		N90 compression (“strong winds”)
15 Oct. 2012	X			X	X	JFK compression on final approach; gusts

28 Oct. 2012	X			X	X	Compression; day before hurricane Sandy
12 Nov. 2012			X	X	X	N90 go-rounds, compression on final approach
13 Nov. 2012	X			X	X	N90 compression
27 Nov. 2012		X		X	X	
28 Nov. 2012	X		X	X		
29 Nov. 2012	X			X		EWR wind GDP
21 Dec. 2012	X			X	X	Strong low altitude winds (70 kts @ 1 kft)
No impact days						
01 Jan. 2012						
13 Sept. 2012						GDP related to construction
20 Dec. 2012						
04 Apr. 2013						
27 Apr. 2013						
02 May 2013						
Summary	**10**	**5**	**10**	**13**	**10**	

For the evaluation of surface wind forecasts, TAF and METAR data from 639 days of operations in 2011–2013 when both were available were also analyzed. HRRR was used for the winds aloft forecast 15 of the 21 case days where model data were available; RUC was used for 5 days and RAP for 1 day when HRRR was not available. Forecasts were evaluated at horizons of 2, 4, 6, and 8 hours.

The forecast evaluation methodology is illustrated in Figure 4. For a particular decision or impact factor (e.g., runway selection), the relevant wind impact metrics are identified (runway headwind). A baseline forecast error is calculated by comparing forecast winds and wind impact metrics to true metric values derived from forecast truth (histogram of runway headwind forecast error). Operational thresholds are identified for each wind impact metric (maximum tailwind for which a runway is feasible), and criteria for decision making or significant operational impact are defined (headwind conditions required to select a particular runway). By applying the decision making criteria to the forecast and true winds, the predicted decision and true outcome can be defined and compared (the runway selection based on forecast headwinds was deemed correct or infeasible based on true headwinds).

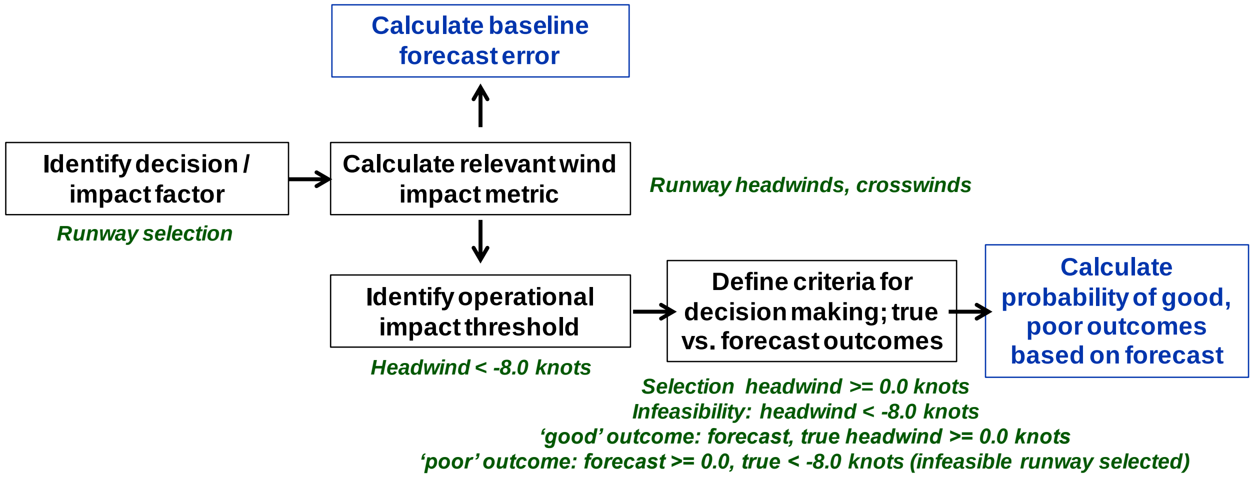


Figure 4. Illustration of the forecast evaluation methodology. Green text describes the evaluation of the runway selection decision evaluation.

The following probabilities are associated with the decision forecasts and outcomes, based on the forecast and observed exceedance of operational thresholds for runway selection:

1. **Probability of infeasible runway selection.** This was defined as the percentage of forecasts of runway headwinds >= 0.0 knots (the runway selection criterion) for which observed runway headwinds were < –8.0 knots (the runway infeasibility criterion).

2. **Probability of "better" runway selection.** This was defined as the percentage of forecasts of runway headwinds >= 0.0 knots (the runway selection criterion) that were correct.

For the impacts of winds aloft on ground speed and spacing on final approach, the following probabilities are associated with decisions:

Probability of predicted operational impact (PoPOI). PoPOI is defined as the ratio

(correct predictions that threshold will be exceeded) /
(observations where threshold was actually exceeded)

Probability of false operational impact (PoFOI). PoFOI is defined as the ratio

(erroneous predictions threshold will be exceeded) / (total predictions that threshold will be exceeded)

Probability of true operational impact (PoTOI). PoTOI is defined as the ratio

(observations where threshold was exceeded) / (total observations)

The consequence of a low PoPOI is that significant operational impacts will not be predicted, resulting in over-delivery of arrivals, excessive airborne holding in or near the TRACON, high numbers of diversions, and disruptive Ground Stops. The consequence of a high PoFOI is that arrival rates will be overly constrained, resulting in lower efficiency. The PoTOI gives a sense of how often operations might be affected by adverse conditions associated with the specific wind impact metric. The PoTOI provides an impact baseline that is applicable to the requirements and benefits analysis. Wherever possible, predictions are tuned to achieve an optimal balance between PoPOI and PoFOI, where "optimal" is determined by weighing the costs of over-delivery versus lost efficiency.

A shortcoming of this methodology is that it does not explicitly assess the ability of forecasts to predict significant *changes* in conditions that may require proactive planning to mitigate the adverse impacts or take advantage of improving weather. The accuracy of each forecast is evaluated independently of all other forecasts, and simply aggregated into the probabilities. For example, a forecast may predict a frontal passage at 15Z that will result in a wind shift of 60 degrees and 8 knots that remains in place for the remainder of the day. Assume that the forecast of wind shift is correct, but that the passage occurs at 13Z instead of 15Z. The statistics will show that 2 forecasts out of 24 for the day were incorrect, suggesting very good performance for the forecast. However, the frontal passage is an *event* that results in a significant operational impact, and the consequences of poor timing may be an extended period of inefficient operation as traffic management first reacts to the changed circumstances and then recovers from the disruption due to the reaction. Viewing the forecast this way suggests that the forecast for the day was only fair, as the operational impacts of poor timing may have been felt for several hours after the frontal passage. A comprehensive evaluation must include event-based probabilities in the assessment of the decision-making impacts of forecast error.

3. WIND IMPACT METRICS

The two key decisions associated with AAR planning are the selection of the runway configuration and the determination of the sustainable AAR, given the selected runway configuration, weather conditions, demand, etc. The critical factors in the determination of the AAR that are impacted by winds are the aircraft ground speed and spacing on final approach. The relationship between winds and each of these decisions and factors is described in Sections 3.1 and 3.2.

3.1 SELECTION OF RUNWAY CONFIGURATION

The EWR runway layout is shown in Figure 5. There is a single pair of parallel runways (4R/22L and 4L/22R) and in typical operations, departures use one runway (4L/22R) and arrivals use the other (4R/22L). When ceilings are extremely low, operations may be restricted to the use of a single runway for both departures and arrivals. There is also single crossing runway (11/29) that may be used to increase arrival or departure capacity ("overflow"). The configuration decision is a three-step process: select the primary arrival flow direction (4 or 22 are preferred; 11/29 is used only when both 4 and 22 are infeasible), determine if 11/29 may be used for arrival overflow, and determine if LAHSO is feasible (Runway 4 only).

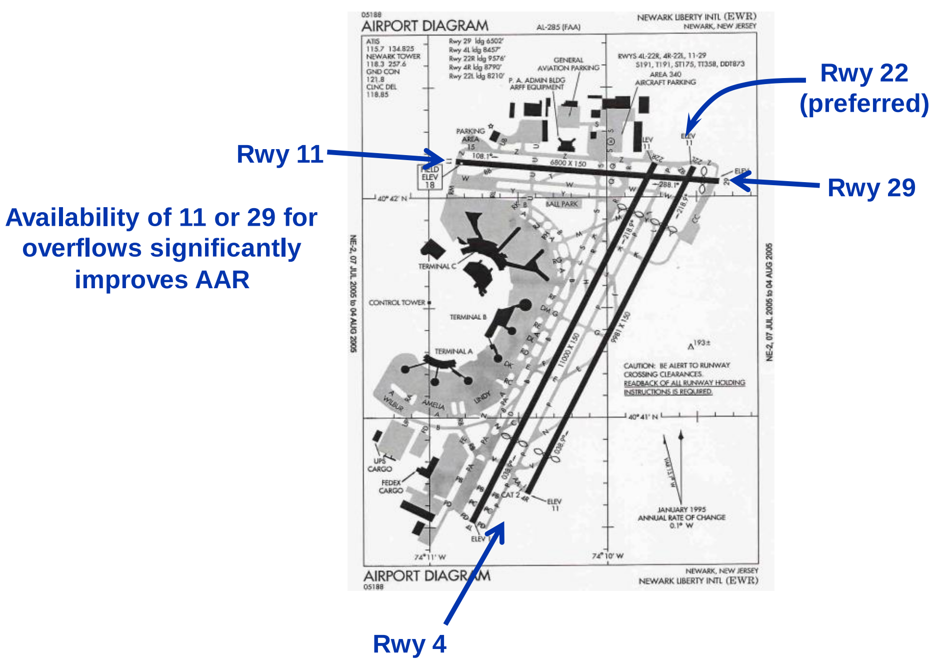


Figure 5. EWR runway layout.

The selection of the flow direction is limited by which runways are feasible. The surface headwind (wind component along the direction of approach to the arrival runway) is the fundamental determinant of runway feasibility. Excess tailwinds result in arrival ground speeds that may be too high for the runway—landing aircraft may not be able to come to a stop before the end of the runway. High surface crosswinds (perpendicular to the direction of the arrival runway) may limit the use of LAHSO, an overflow runway, or, in extreme conditions, a primary arrival flow. Headwind and crosswind feasibility thresholds are related to runway length and the type of aircraft that typically use the runway, and are fairly well-established (ADEST encodes specific thresholds for runway and procedure feasibility). If wind gusts are strong, gust speeds rather than sustained winds may determine feasibility. This assessment focused only on sustained headwinds at the surface, as instances of high gusts and crosswinds in excess of operational thresholds were rare or difficult to identify in the dataset.

In this assessment, surface winds from the regular and amended ("AMD") TAF reports were compared to observed surface winds recorded in the regular and special ("SPECI") METAR reports. In total, the TAF assessment data set included over 19,000 TAF (each with several forecast horizons) from 639 days when both TAF and METAR were available in 2011–2013. In addition, surface wind forecasts from the HRRR/RUC RAP models (model sources for the forecasts were not differentiated and forecasts from HRRR/RUC/RAP will be designated as "MODEL") were compared to observed METAR surface winds from the 21 EWR case days described above (approximately 450 forecasts per forecast horizon). The following baseline and decision impact forecast evaluation metrics were calculated:

1. **Surface wind vector errors (baseline).** The distribution of error vector magnitudes as a function of forecast horizon is reported to provide an overview of surface forecast accuracy and behavior.

2. **Surface headwind errors (baseline).** The error in headwind forecast was calculated for all EWR runway directions. Since headwind errors are the projection of the error vector along the runway direction, they will always be less than or equal to the error vector magnitude.

3. **Runway selection and prediction of runway feasibility (decision impact).** ADEST runway feasibility rules specify headwind thresholds for the use of the primary landing directions (Runway 4 and 22) and the overflow runways (11 and 29). (See Table 3: note that a headwind <0 is a tailwind.) In this analysis, only the prediction of feasibility for the primary landing directions is evaluated. The runway selection criterion used in this assessment was "select the direction with headwind >= 0 (assumed to be the 'better' runway)" (since the 4 and 22 arrival directions are 180 degrees opposite, one runway always has a headwind and the other a tailwind, unless the wind is exactly 0). A poor runway selection forecast was defined as follows:

Forecast headwind >= 0.0 knots AND true headwind < –8.0 knots (i.e., runway is infeasible), and the observed probability of a poor selection was calculated for both TAF and MODEL forecasts.

TABLE 3

Runway Feasibility Thresholds for EWR

Runway	Minimum Feasible Headwind (knots)	Maximum Feasible Crosswind (knots)
4	–8	32
22	–8	35
11	–17	25
29	–10	25

3.2 DETERMINATION OF SUSTAINABLE AAR

ADEST estimates the sustainable AAR by calculating a "base" AAR as a function of runway configuration and weather impacts, and adjusting it for additional constraints that arise as a result of the expected arrival demand fleet mix. The base AAR, which is defined by the ratio

(average aircraft ground speed on final approach) /
(average weather-adjusted aircraft spacing on final approach),

is fundamental to the estimation of the sustainable AAR. Adverse winds aloft and at the surface may be translated into operational impacts through modeling of their effects on average ground speed and spacing on final approach. However, there are no established wind metrics or operational thresholds for the estimation of ground speed or spacing on final approach as there are for runway feasibility. Therefore, it was necessary to define wind impact metrics and impact translation models in order to evaluate wind forecast performance.

Candidate wind impact metrics were defined with the help of New York TRACON and EWR operational subject matter experts. A key concept stressed by the subject matter experts is *recovery*. TRACON air traffic controllers are often able to maintain high AAR in the presence of adverse winds through the use of trajectory management techniques that enable them to absorb the impacts of adverse winds over the course of the arrival trajectory in the TRACON. It is easier to recover from impacts at higher altitudes than from those at lower altitudes. Furthermore, operational sensitivity to a particular wind characteristic—for example, vertical wind shear along an arrival trajectory—is likely to be different at low and high altitudes. The set of wind impact metrics is intended to capture not only the nature of the winds that affect operations—headwinds that impact ground speed, compression and headwind differences between merging streams that impact spacing—but also the different stages of the arrival trajectory where the operational sensitivity to these phenomena may be different.

The wind impacts metrics are associated with 20 × 20 nautical mile "capture boxes" that capture characteristics of the winds at critical locations along the nominal arrival trajectories. These characteristics are a set of headwinds and headwind differences along one or more trajectories that are related to ground speed differences among merging aircraft, compression, and difficulties in maintaining optimal spacing. Headwinds associated with each capture box are defined as the average value of all forecast or analysis grid points within the capture box. Wind impact metric forecasts were calculated from MODEL forecasts, and impact metric truth was calculated from MODEL analysis fields. The wind impact metrics, illustrated in Figures 6 and 7, are defined as follows:

1. **Surface headwinds.** Surface headwinds that fall within the feasibility threshold may also impact ground speed on final approach; higher headwinds in the feasibility range can result in lower ground speeds. Surface headwinds were calculated and evaluated for both TAF and MODEL forecasts against METAR truth.

2. **Headwinds at the "downstream capture box" (DCB).** The DCB identifies the segment of the arrival trajectory where the merged arrival streams are set up for final approach. There is a different DCB for each arrival runway approach. DCB altitudes for different approaches range between approximately 1.5 and 2.0 kft.

3. **Difference between headwinds at DCB and surface (DCB-to-surface headwind difference).** The DCB-to-surface headwind difference relates to the likelihood of compression between the surface and 2.0 kft.

4. **Difference between headwinds at merge and DCB (merge-to-DCB headwind difference).** The merge points are where arrivals from different directions (north, west, south) merge into a single stream for preparation for final approach, and are associated with merge point capture boxes. Each arrival runway approach has a different merge point. The merge altitude ranges between approximately 2.5 and 3.0 kft, so the merge-to-DCB headwind difference relates to the likelihood of compression roughly between 2 and 3 kft.

5. **Headwind at TRACON entry capture box.** The aircraft ground speed at TRACON entry, dependent in part on headwind, represents the initial condition for TRACON flow management. High tailwinds at TRACON entry, and the resulting high ground speeds, may present significant challenges to TRACON controllers as they try to reduce aircraft ground speeds on final approach to acceptable levels. There is a TRACON entry capture box for each STAR/arrival runway combination. Standard Terminal Automation Replacement (STAR) entry capture boxes encompass altitudes ranging approximately between 5.0 and 7.0 kft.

6. **Maximum difference between headwinds at TRACON entry capture boxes (maximum merge headwind difference).** Excessive differences in headwinds and the resulting differences in ground speed increase the difficulty of merging traffic from different STARs onto final approach.

7. **Maximum difference between headwinds at TRACON entry capture boxes and DCB (maximum STAR-to-DCB difference).** This metric is a rough measure of the possibility of compression in the approximate altitude range between 7.0 and 2.0 kft.

8. **Maximum compression segment headwind gain (maximum segment gain).** Compression segments are defined as segments of the arrival trajectory along which the headwind increases monotonically. Compression segment headwind gain is the total increase in headwind from the beginning to the end of the segment. Compression segments may be defined for each STAR/arrival runway combination. This metric provides a rough measure of the possibility and severity of compression anywhere along the arrival trajectory.

9. **Maximum difference in compression segment headwind gain.** This difference is analogous to the maximum merge headwind difference, and gives a sense of the potential difficulty of maintaining acceptable spacing while merging arrival streams.

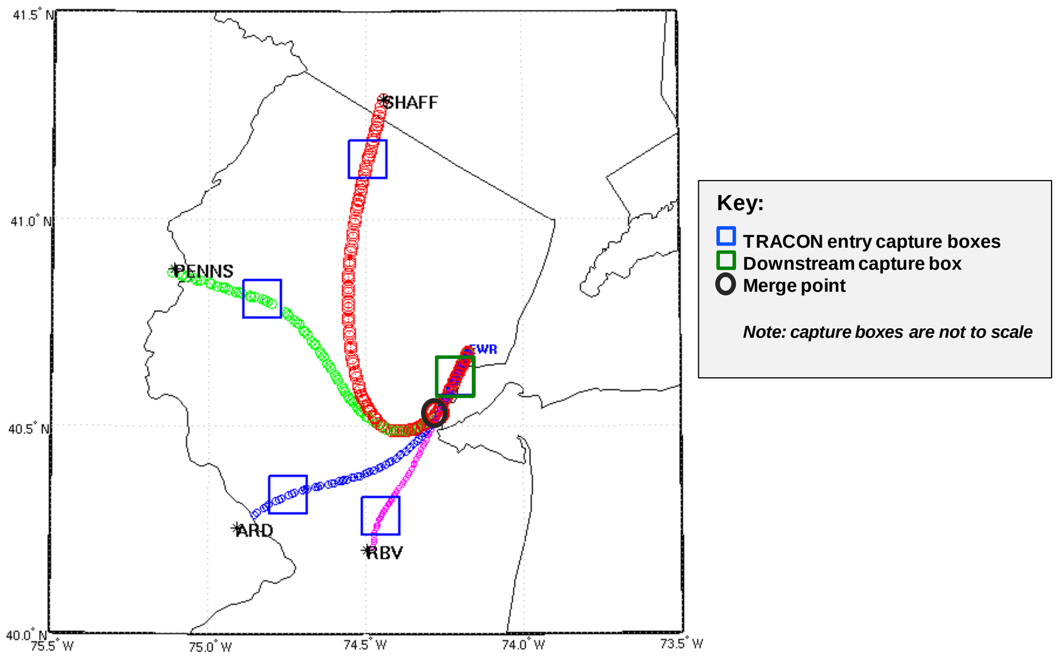


Figure 6. Nominal EWR arrival trajectories and wind impact capture boxes for arrivals on Runway 4.

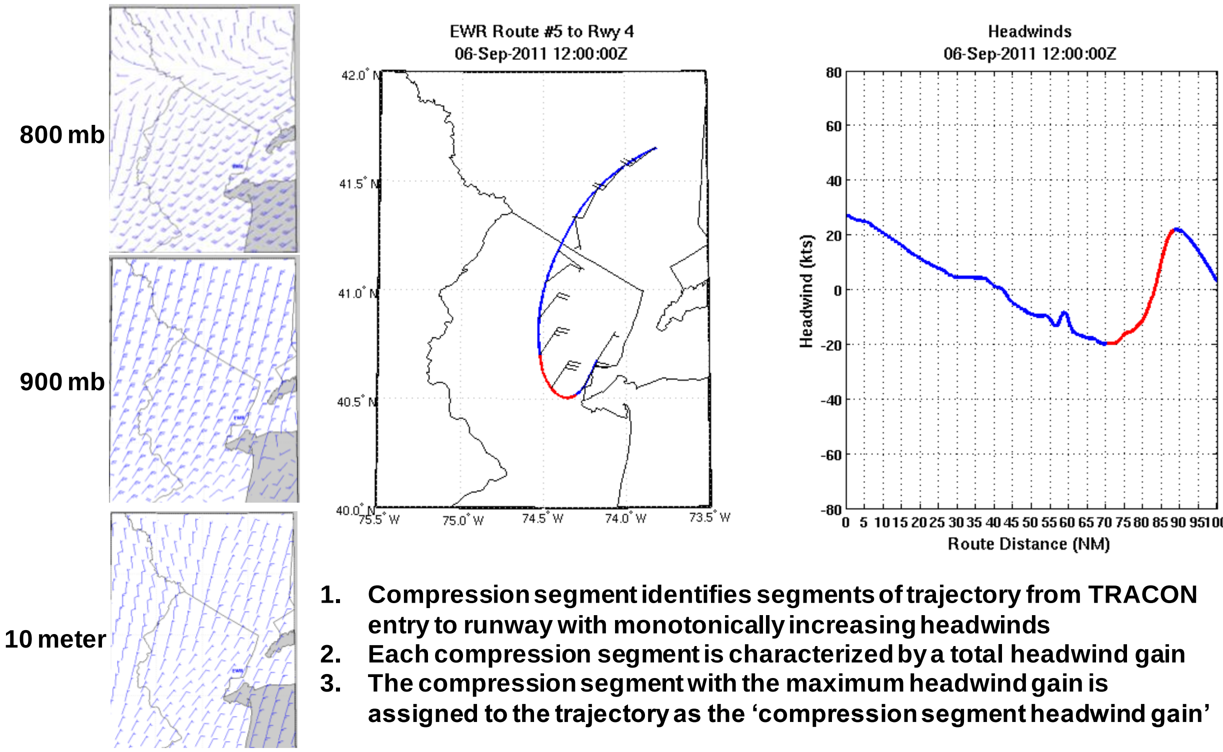


Figure 7. Compression segment wind impact metric.

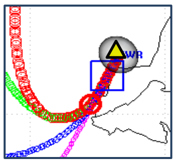
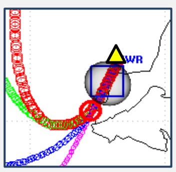
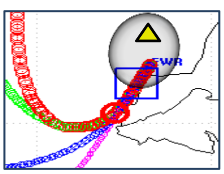
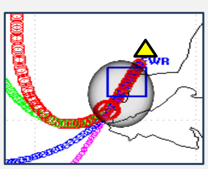
Table 4 summarizes the wind impact metrics evaluated, impacted operational factors (runway configuration, ground speed and/or spacing on final approach), and the sources of forecast and truth. Table 5 presents the decision thresholds used in the evaluation and the percentage of *true* data samples that exceeded the decision threshold. The frequency at which the operational thresholds are actually exceeded gives a sense of how often significant operational impacts may occur as a result of conditions measured by each wind impact metric. The frequency of occurrence provides a baseline for the analysis of potential benefits from the use and improvement of forecasts. Note that for winds-aloft metrics, which were assessed from the case day dataset, this percentage represents the percentage of potential impacts from the 21 case days where MODEL data were available.

A larger data set will be needed to develop a quantitative multivariate translation model that maps these metrics to impacts on ground speed and spacing on final approach. However, an analysis of the available data identified several metrics and corresponding "operational impact thresholds" that appear related to significant observed changes in ground speed and spacing on final approach, and these were used in the decision impact forecast evaluations. The decision-related forecast probabilities reported here may be adjusted as the models for use of these metrics are refined.

A detailed analysis of the weather impact metrics and heuristic operational thresholds is presented in the Appendix.

TABLE 4

Wind Impact Metrics Assessed in Forecast Evaluation

Metric	Decision/Impact	Forecast/Truth	Wind Impact Metric Evaluated	Approximate # of True Data Samples
Surface winds[1,2] 	Runway configuration	TAF/METAR HRRR (RAP) /METAR	Runway headwind Runway crosswind	38963
	Ground speed[2]		Runway headwind	10384
DCB winds[3] 	Ground speed	HRRR (RAP) forecast/HRRR (RAP) analysis	Trajectory headwind	896
DCB-to-surface[3] 	Spacing		Difference in trajectory headwind (DCB-surface)	896
Merge-to-DCB[4] 	Spacing (observed correlation very weak)	HRRR (RAP) forecast/HRRR (RAP) analysis	Difference in trajectory headwind (merge-DCB)	1792

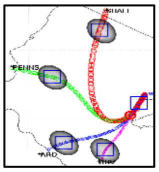
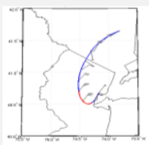
TRACON entry[4] 	Spacing	HRRR (RAP) forecast/HRRR (RAP) analysis	Maximum difference between capture boxes	1792
Compression segment[5] 	Spacing	HRRR (RAP) forecast/HRRR (RAP) analysis	Compression segment headwind gain	6848

Table 4 notes:

1. METAR were available from 1270 days in 2010–2013, for several hours per day.

2. Forecasts were evaluated for Runways 4 and 22 for all days in 2011–2013 for which both TAF and METAR were available. Approximately 6000 TAF were issued during the analysis period; one TAF may have been compared to multiple METAR observations, resulting in a number of comparisons higher than the number of TAF.

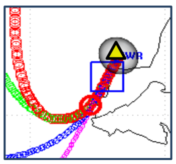
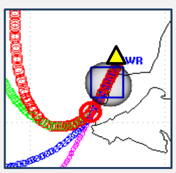
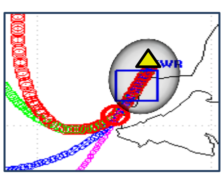
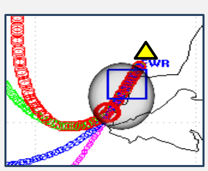
3. Forecasts were evaluated for Runways 4 and 22 for all 18 EWR case study days (total = 448 forecast hours × 2 runways).

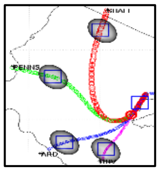
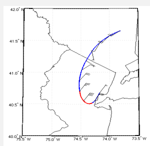
4. Forecasts were evaluated for Runways 4, 22, 11, and 29 for all 18 EWR case study days (total = 448 forecast hours × 4 runways).

5. Forecasts were evaluated for all 18 EWR case study days (total = 448 forecast hours × 4 runways × 4 STARs).

TABLE 5

Wind Impact Metric Decision Thresholds and Frequency that Thresholds Were Exceeded

Metric	Decision/Impact Threshold	% of Truth Exceeding Threshold
Surface winds 	Headwind < –8.0	11.2% (4367 out of 38963)
	Headwind >10.0	3.6% (403 out of 10364) (Runways 4 and 22)
DCB winds 	Headwind >20.0	9.2% (82 out of 896)
DCB-to-surface 	Difference >10.0	17.2% (154 out of 896)
Merge-to-DCB 	Difference >20.0	12.4% (222 out of 1792)

TRACON entry 	Difference >50.0	25.0% (448 out of 1792)
Compression segment 	Gain >40.0 Note: Heuristic relationship strongest for maximum *difference* in gain >40.0	15.0% (1026 out of 6848)

4. RESULTS

All errors are defined as

forecast value – observed value

4.1 BASELINE SURFACE FORECAST EVALUATION

The magnitude of surface wind forecast error vectors was calculated for the TAF (approximately 6000 TAF issued at each forecast horizon from 2011–2013) and MODEL surface forecasts (approximately 450 forecasts at each forecast horizon from the 21 EWR case study days). Figures 8 (TAF) and 9 (MODEL) present the probability distribution and cumulative probability distributions of the errors; Figure 10 compares the 10th, 25th, 50th, 75th, and 90th percentile of forecast errors for TAF and MODEL.

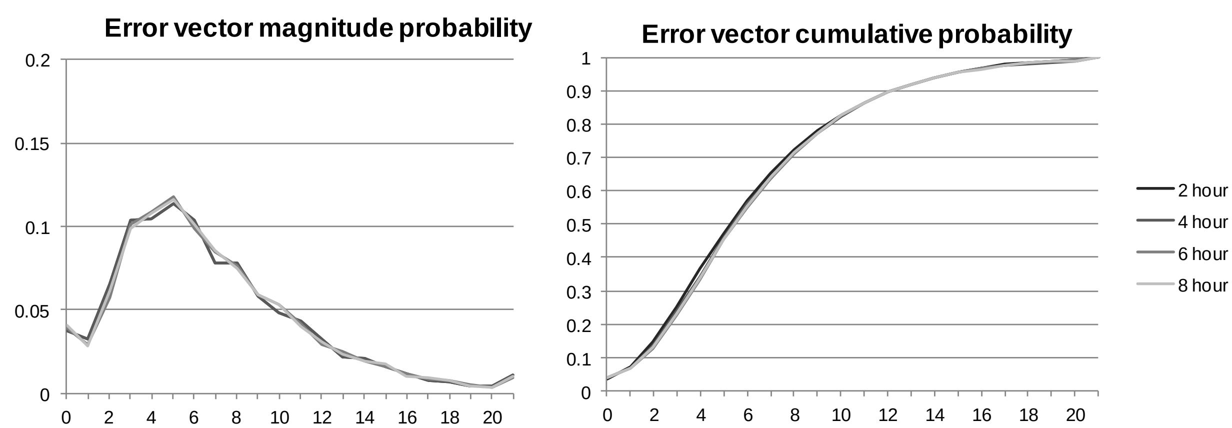


Figure 8. Distributions of TAF surface wind error vector magnitudes.

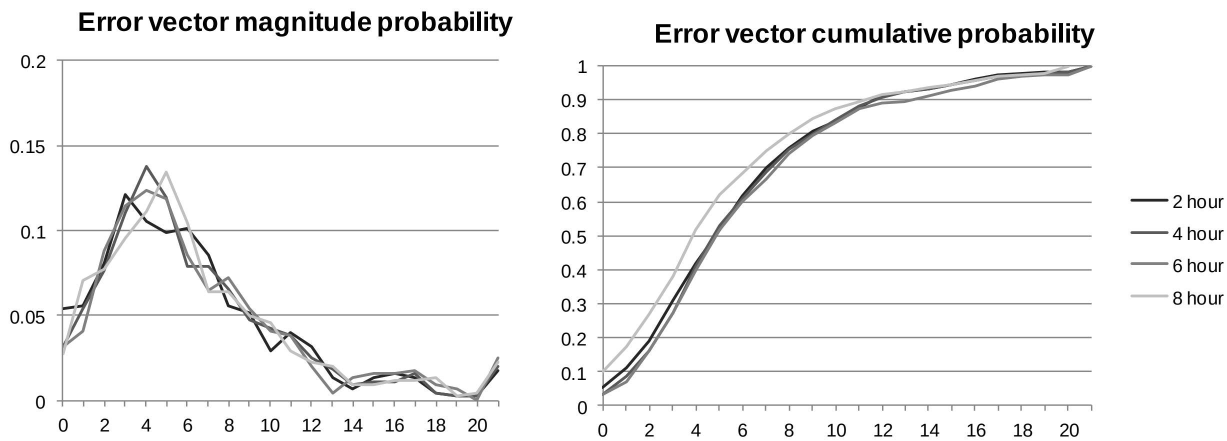


Figure 9. Distributions of MODEL surface wind error vector magnitudes.

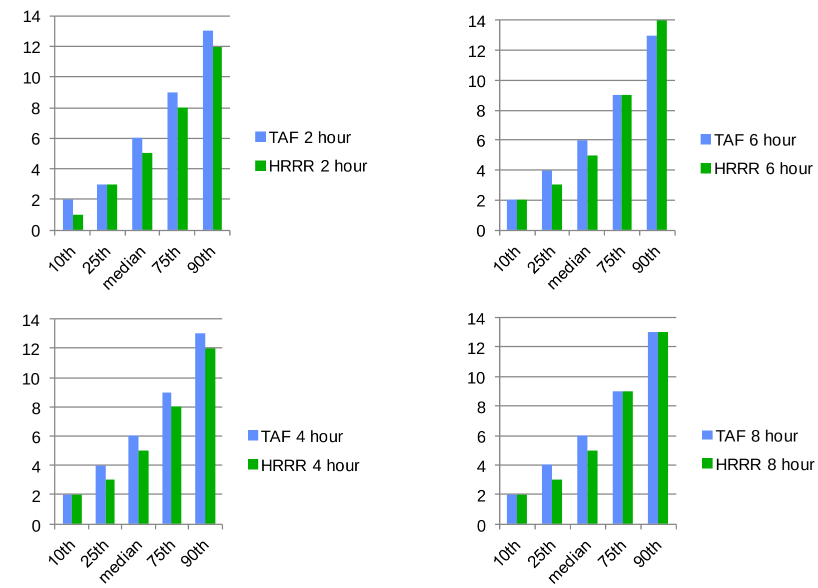


Figure 10. Comparison of TAF and MODEL surface wind error vector magnitudes.

Three forecast characteristics are evident:

1. TAF and MODEL forecast errors are similar. This is not particularly surprising, since models are likely to be considered by the forecaster who is responsible for the TAF. TAF and MODEL forecasts may diverge in circumstances where surface winds may be driven by local weather processes that are not captured by the MODEL.

2. Forecast errors are similar over all forecast horizons for TAF and MODEL. Modeled winds change slowly from one time frame to the next within a given forecast, which may explain why errors are so consistent across all forecast horizons on average.

3. Roughly 80% of forecast errors for the TAF and MODEL fall between 2.0 and 14.0 knots.

Finer details of the forecast error characteristics, such as the conditions that differentiate days with high forecast errors from low ones, analysis of the specific differences between TAF and MODEL, and the apparent constancy of forecast errors over all forecast horizons, were not analyzed due to schedule constraints and may be addressed as future work.

Forecast errors for runway headwinds for all runway approaches were also calculated for TAF and MODEL forecasts. Figures 11 and 12 present the results for Runway 4. Approximately 80% of errors fell between –8.0 and 6.0 knots. Errors for other runways were similar.

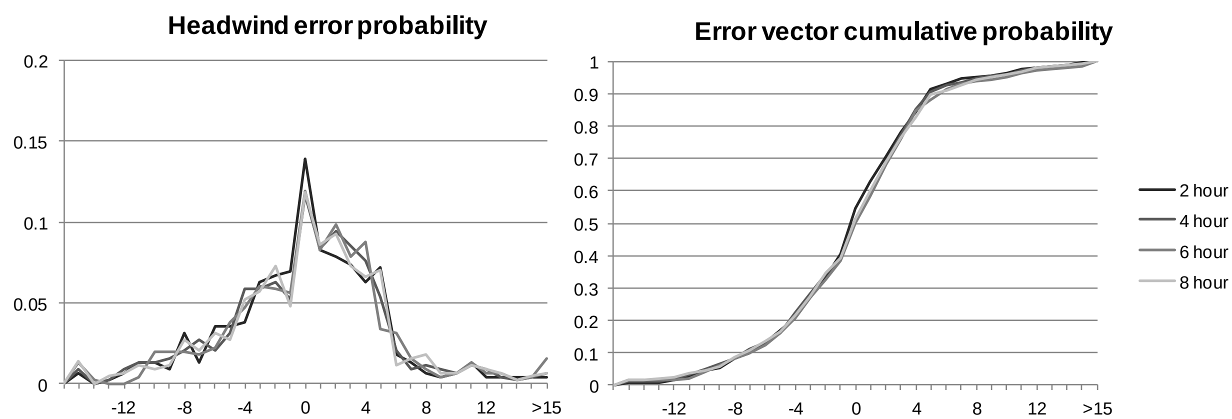


Figure 11. Runway 4 TAF surface headwind forecast errors.

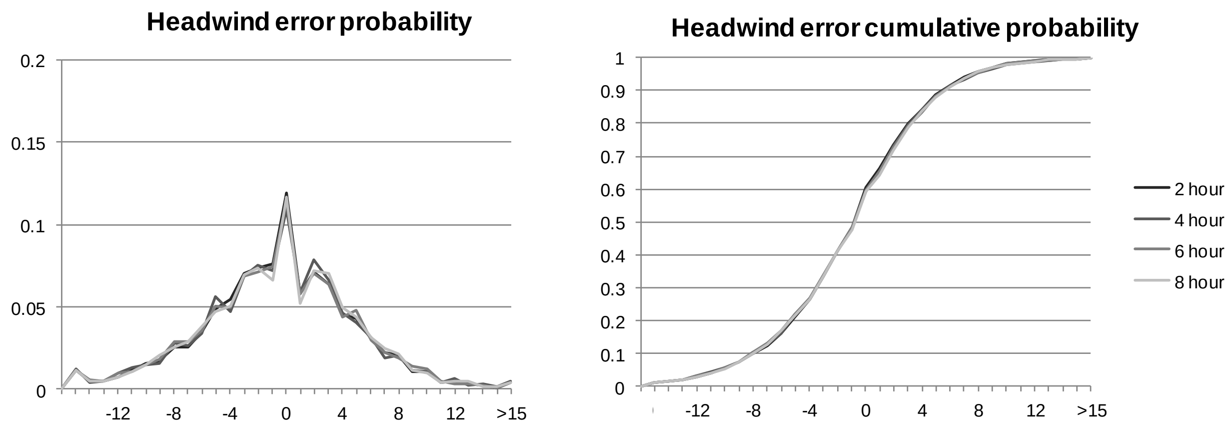


Figure 12. Runway 4 MODEL surface headwind forecast errors.

4.2 BASELINE EVALUATION OF WINDS-ALOFT FORECAST

The errors in MODEL forecasts of average headwinds at the DCB and merge point were calculated on all four runway approaches for the 21 EWR case study days. Forecast errors were defined relative to the MODEL analysis field, which was assumed as truth. Since the DCB and merge point altitudes range from roughly 1.5 to 3.0 kft, these errors are indicative of the magnitude of forecast errors at low altitudes, where the controller's ability to recover from wind impacts may be limited.

Errors were similar for all four runway approaches, with minor differences attributable to the differences in altitude of the DCB and merge points for different runway approaches. Since headwind errors are a projection of the wind vector error onto the trajectory heading, the wind vector error magnitude is the upper bound of headwind error, so headwind forecasts will be more forgiving than wind vector forecasts. Forecast errors increase slightly as a function of forecast horizon and altitude (merge altitudes are higher than DCB altitudes), possibly due to the higher forecast errors associated with stronger winds that are more often present at higher altitudes [6]. Figures 13 and 14 illustrate the error probability distribution for the Runway 4 approach for the DCB (Figure 13) and the merge point (Figure 14). The forecast errors in the headwind *difference* between the merge point and DCB for Runway 4 is illustrated in Figure 15; note that the difference operation removes the slight forecast bias evident in Figures 13 and 14. Forecasts of the *difference* in headwinds may be more robust than forecasts of the headwinds themselves, since differencing will remove biases that may be present in forecasts.

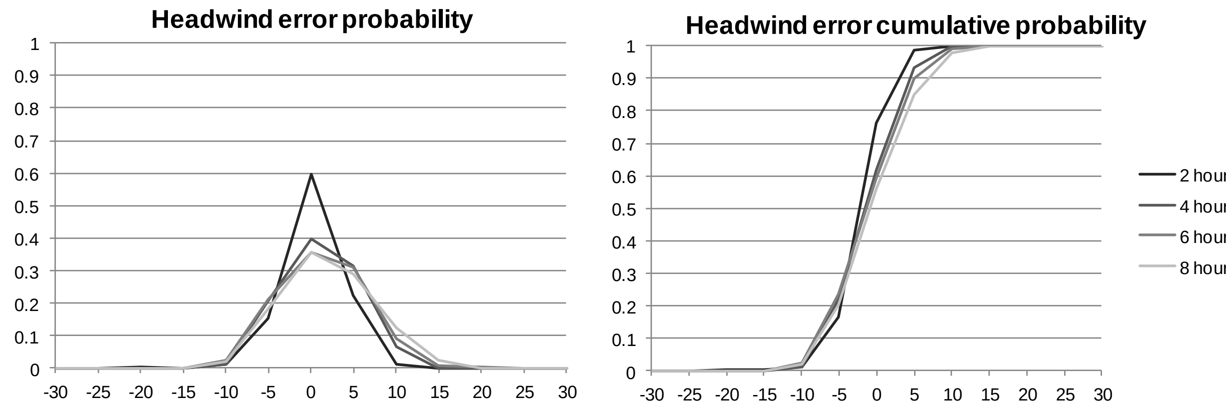


Figure 13. Runway 4 MODEL DCB headwind forecast errors.

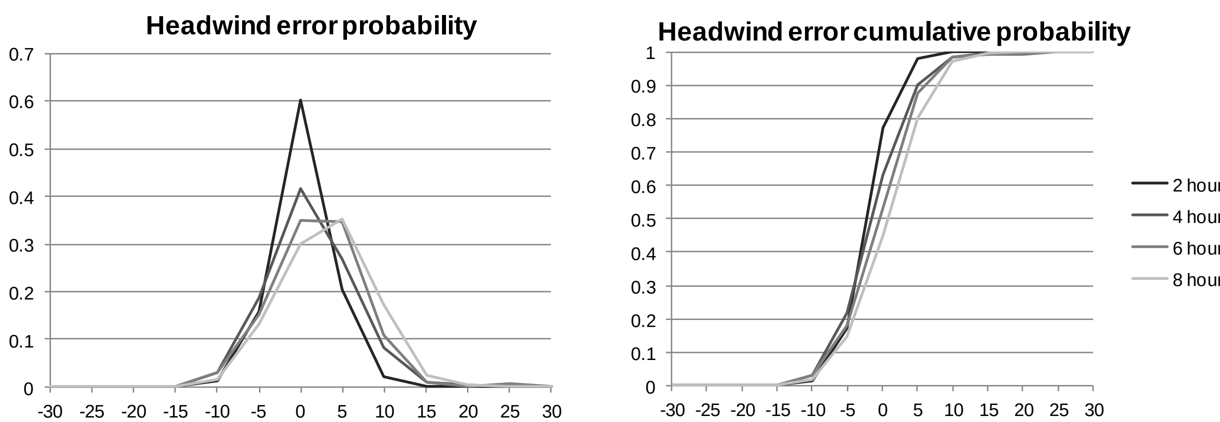


Figure 14. Runway 4 MODEL merge point headwind forecast errors.

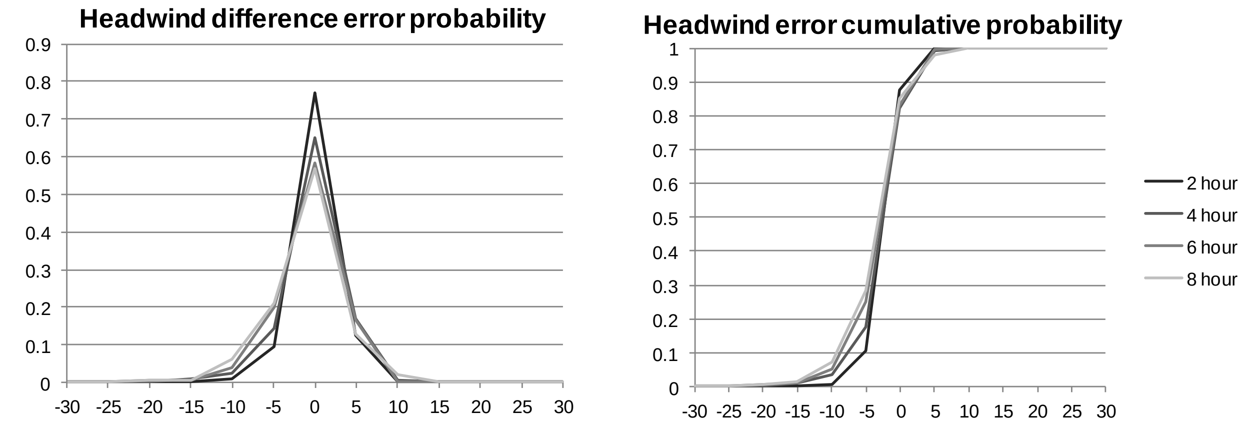


Figure 15. MODEL forecast errors for the difference between merge point and DCB headwinds for Runway 4 approach.

The maximum difference between ground speed at the different TRACON entry capture boxes provides a measure of the potential difficulty in merging different arrival streams due to winds in the altitude range of 5.0 to 7.0 kft. Errors in forecasting the ground speed differences also provide insight into the accuracy of the horizontal spatial distribution of winds in the altitude range. Forecast errors were similar for TRACON entry capture box differences from all four runway approaches. Forecast errors increased with the forecast time horizon, possibly as a result of the typically stronger winds (and correspondingly higher forecast error) at higher altitudes. Figure 16 illustrates the error probability distribution for the Runway 4 approach.

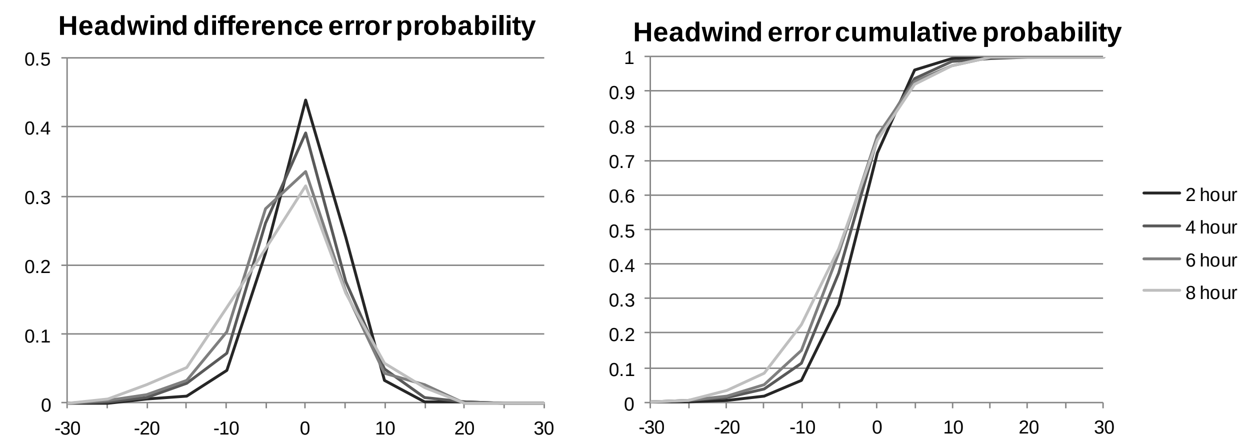


Figure 16. MODEL forecast errors for the maximum difference in headwinds at the TRACON entry capture boxes for the Runway 4 trajectory.

Finally, the forecast error for compression segment headwind gain from all four runway approaches was calculated. Since compression segments are calculated over the full length of the arrival trajectory, the compression segment headwind gain provides an operationally relevant measure of the horizontal and vertical spatial characteristics of the wind field encompassing the whole arrival airspace. Again, error increases with forecast horizon, although not as rapidly as in the TRACON entry capture box differences. Figure 17 illustrates the error probability distribution for the Runway 4 arrival trajectory.

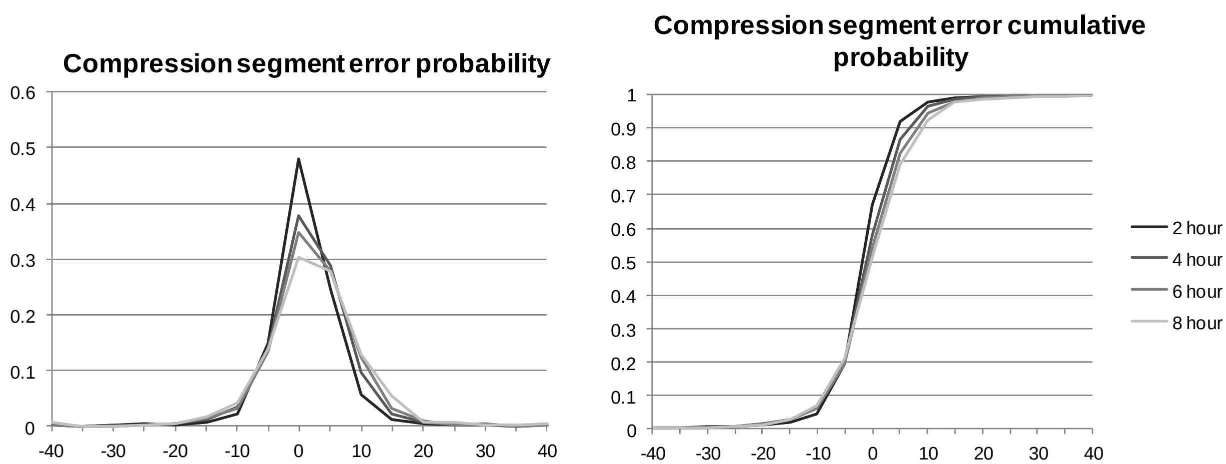


Figure 17. MODEL forecast errors for the compression segment for Runway 4 trajectory.

4.3 EVALUATION OF FORECAST IMPACTS ON DECISION MAKING

The performance of several wind impact metric forecasts was evaluated in the context of decision making, as described in Section 2. Methodology. Forecast error impacts were analyzed for three critical decisions and AAR impact factors: runway selection, average aircraft spacing on final approach, and average aircraft ground speed on final approach.

Runway selection. The probability of selecting an infeasible runway as a result of surface wind forecast error was estimated to be very low for both the TAF and MODEL forecasts (<1.0%). The probability of correctly selecting the better arrival runway (i.e., the direction with headwind >= 0) was roughly 0.6 for all forecast horizons. In these cases, the forecast error would result in the selection of the arrival direction with a tailwind that fell short of the threshold for infeasibility. The results are presented in Table 6.

TABLE 6

Probability of Incorrect Runway Selection as a Result of Forecast Error

Forecast Horizon	TAF			MODEL		
	P(infeasible)	P(better)	# forecasts	P(infeasible)	P(better)	# forecasts
2 hour	<0.01	0.57	5877	<0.01	0.56	446
4 hour	<0.01	0.57	5920	<0.01	0.56	444
6 hour	<0.01	0.56	5956	<0.01	0.56	445
8 hour	<0.01	0.56	5976	<0.01	0.56	440

Two factors may be responsible for the very low estimate of decision impact. The threshold for a poor decision is very high; headwind forecast errors must be in excess of true headwinds by at least 8.0 knots, and must be significantly higher if higher headwinds are forecast (for example, if the forecast calls for a headwind of 4.0 knots, forecast error must be in excess of 12.0 knots). Headwind errors are always less than (or in rare occasions, when winds line up exactly with the runway, equal to) the forecast error vector magnitude, since they are the projection of the forecast error onto the runway direction. Nonetheless, considering the high number of GDP and GS associated with wind impacts in EWR operations, this estimate seems very low. Possible explanations are that surface wind gusts or impacts of winds aloft may be responsible for difficulties in optimal runway selection, or that traffic management may choose to run with a tailwind under many circumstances, lowering the real operational margin for error. Further research is needed to assess the frequency and severity of operational difficulties due to suboptimal runway selection and to identify specific factors that relate surface wind forecast errors to poor runway selections.

Figure 18 presents a scatter plot of observed vs. forecast headwinds with regions of correct forecasts, P(better), suboptimal but feasible forecasts, and runway selection forecasts that selected infeasible runways, P(infeasible), highlighted. From the scatter plot, it is evident that surface wind forecasts tend to be high. The tendency appears at all forecast horizons; the figure illustrates observed vs. forecast for the 2 and 8 hour forecasts. Figure 19 illustrates the effect on the margin for error and likelihood of selecting an infeasible runway when the arrival runway selection criterion accepts a tailwind of 6.0 knots or less.

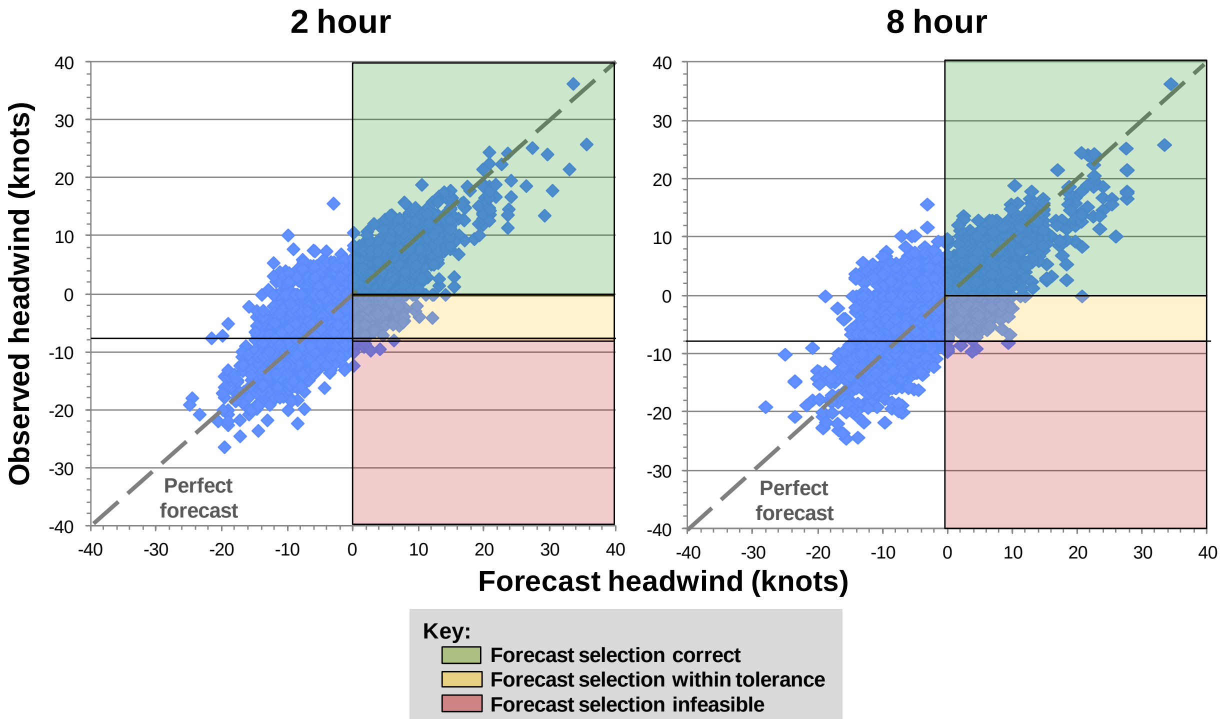


Figure 18. Scatter plot of observed METAR vs. TAF surface headwinds for the Runway 4 approach, showing where runway selection outcomes are correct, within tolerance, and infeasible.

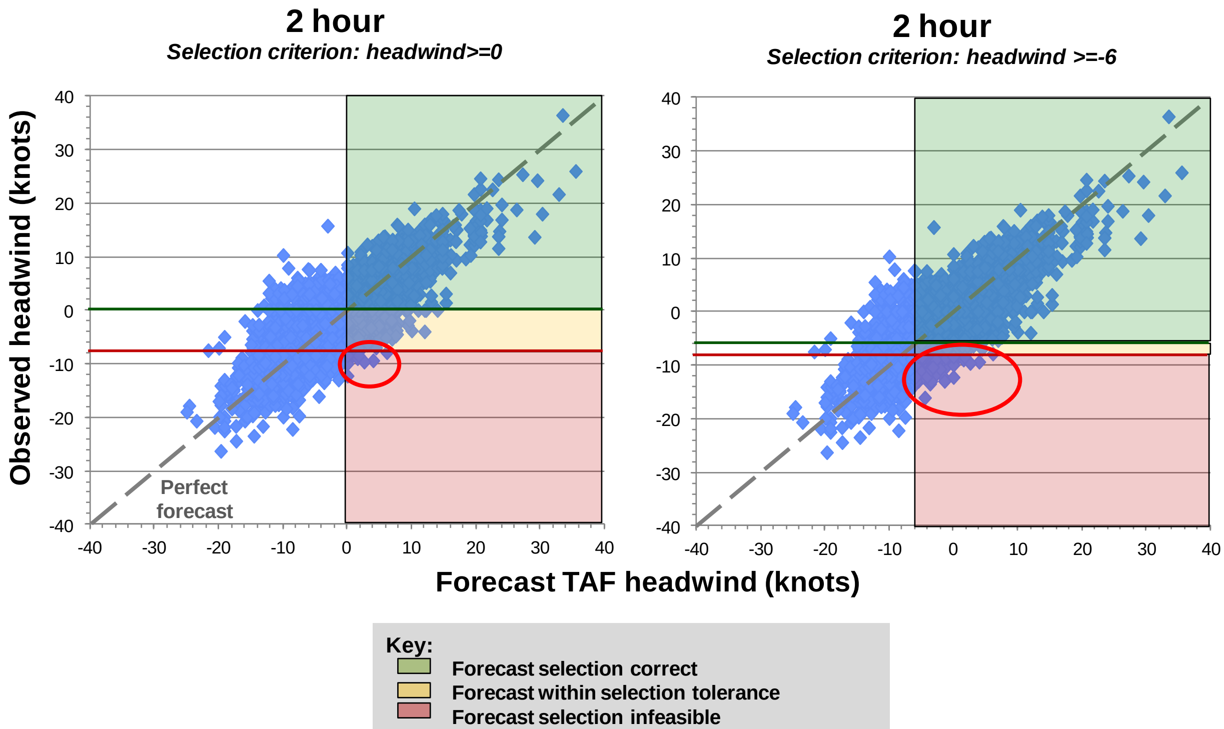


Figure 19. Comparison of runway selection outcomes with stricter headwind selection criterion (headwind >= 0.0 knots, at left) and relaxed headwind selection criterion (headwind >= –6.0 knots, at right). Note the reduction in error tolerance as the selection criterion approaches the infeasibility criterion.

Spacing and ground speed. Figure 20 presents a scatter plot of PoPOI vs. PoFOI that result from MODEL forecast errors at all forecast horizons for wind impact factors based on winds aloft. Data points for progressively longer forecast horizons are displayed by symbols with progressively less-saturated colors.

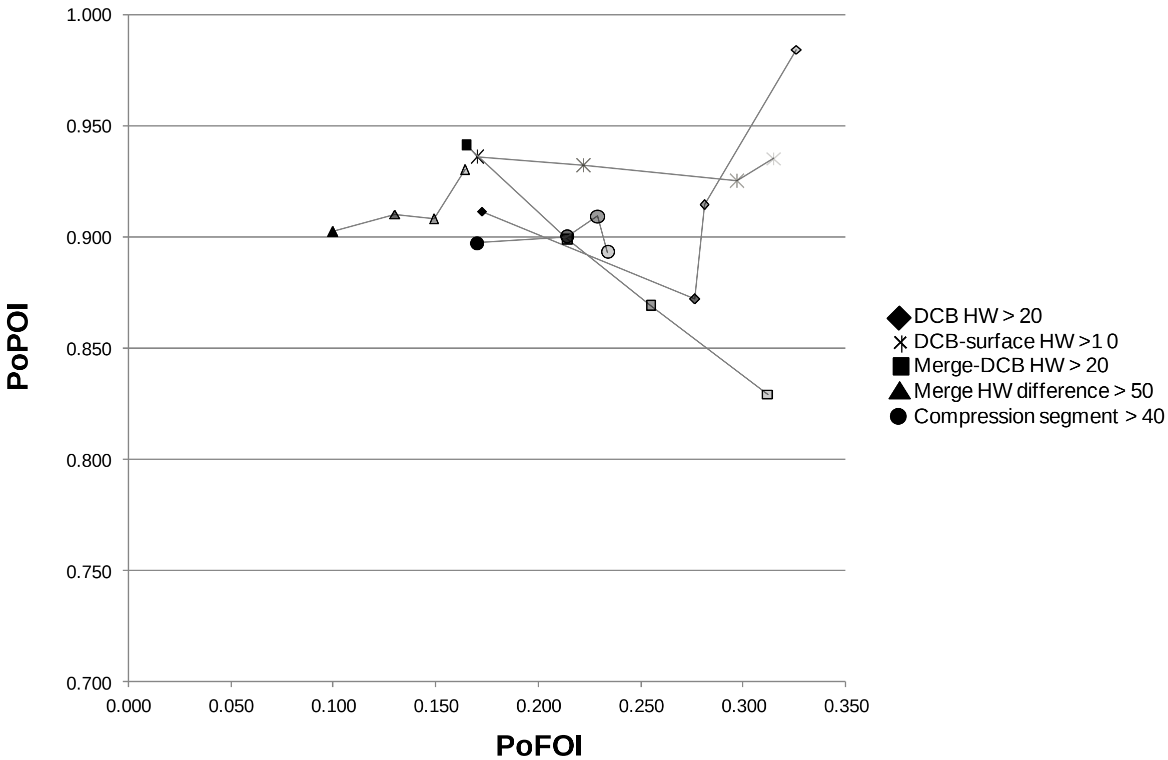


Figure 20. Probability of correct forecast of operational impact (PoPOI) vs. probability of false prediction of operational impact (PoFOI) as a result of MODEL wind impact metric forecast errors.

Forecast performance is fairly good, with PoPOI clustered in the range of 0.85 to 0.95. PoFOI clusters in the range of 0.1 to 0.3. Few strong trends are evident, most likely a result of the small data set. For most metrics, the PoFOI increases with forecast horizon, suggesting that longer horizon forecasts tend to over-forecast the severity of impacts. However, since both wind measurement and wind difference metrics exhibit the same behavior, the observed over-forecast is not simply due to a bias in longer range forecast toward higher winds.

In any event, it is inadvisable to draw strong conclusions from decision outcome probabilities based on a rudimentary translation model derived from limited data. A more comprehensive and reliable evaluation requires further work:

1. Expansion of the analysis data set to include more days at EWR and additional sites,
2. Refinement of the translation model to identify more precise operational thresholds and to assign relative importance to different metrics in decision making, and
3. Cost/benefit analysis to inform the optimal tradeoff between PoPOI and PoFOI.

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5. SUMMARY AND RECOMMENDATIONS

5.1 SUMMARY

The planning and execution of the AAR for major metroplex airports is a complex and critical function of traffic managers in the NAS. The key decisions that impact the AAR are the selection of the arrival runway(s) and specification of an AAR that that can be sustained in the runway configuration. Two primary factors that determine the sustainable AAR are the aircraft ground speed and achievable spacing on final approach. Despite the importance of AAR planning, traffic managers currently have no widely available decision support to provide guidance for runway selection or the determination of a sustainable AAR, nor do they have tools that provide predictions of ground speed or achievable spacing on final approach. The AARDSC, currently under development as part of the CATMT WP4, will provide such guidance.

Several factors must be taken into account in identifying the most advantageous runway configuration and determining a sustainable AAR: surface winds and winds aloft, ceiling, visibility, runway surface conditions, mix of aircraft types in the arrival demand, balance between arrival and departure demand, coordination of arrival and departure traffic flows in the TRACON among metroplex airports, and the availability of airport resources such as Instrument Landing Systems (ILS), runways and taxiways, etc. This report provides an initial analysis of the impacts of surface winds and winds aloft on the selection of runway configuration and the achievable aircraft ground speed and spacing on final approach, and the capabilities of currently available weather forecasts to accurately predict those impacts. The report was limited in scope by the schedule and available resources, and its findings should not be viewed as complete or comprehensive. The methodology and initial findings provide a foundation for a comprehensive forecast assessment in follow-on work.

Surface wind forecasts from the TAF and numerical prediction models (HRRR, RAP, and RUC, collectively described as “MODEL”) were compared to observed winds gathered from METAR reports at EWR. TAF and METAR were compared for 639 days of operations from 2011–2013. MODEL forecasts and METAR were compared for 21 days of operation, 16 of which had TMI in place to mitigate adverse weather impacts. MODEL forecasts of winds aloft were compared to MODEL analysis winds for the same 21 days of operations. Forecasts were evaluated at horizons of 2, 4, 6, and 8 hours.

For both surface and aloft winds, the forecast assessment included a baseline evaluation of forecast accuracy and an estimation of the impact of forecast errors on the prediction of key AAR factors. For surface forecasts, the baseline evaluation included the magnitude of forecast error vectors and runway headwind forecast errors. For forecasts of winds aloft, the baseline evaluation consisted of forecast errors for several wind impact metrics that were defined to translate winds into operational impacts. In addition to the baseline forecast evaluation, an assessment of the impacts of forecast error on the likely quality of decisions based on forecasts of wind impacts.

Key findings of the baseline evaluations were:

1. **Statistical differences between TAF and MODEL surface forecasts were small.** Since TAF forecasters consult forecast models, the TAF will in most cases resemble MODEL forecasts. It is conceivable that the TAF could identify conditions not resolvable by forecast models that could impact surface winds (e.g., sea breezes), adding value to the MODEL forecasts by correcting for such "invisible" impacts. An analysis of the differences between the two forecasts was beyond the scope of this report, but should be considered as follow-on work.

2. **Statistical differences between different wind forecast horizons (ranging from 2 to 8 hours) were small.** Models winds change slowly, as small perturbations are smoothed out to maintain mass continuity and thermal balance. Findings were similar for surface and aloft wind forecasts, although at higher altitudes, some improvement in forecast accuracy at shorter forecast horizons was evident. As planning horizons shorten over the course of the day and operations transition from large scale planning to small scale planning to execution, it would be advantageous to have forecasts with accuracy and resolution that improve to meet operational needs.

3. **Several wind impact metrics, derived from winds aloft, showed promise as predictors of significant operational impacts.** Important points in nominal arrival trajectories—TRACON entry (between 5.0 and 7.0 kft altitude), arrival stream merge points (~3.0 kft), and the head of final approach (between 1.5 and 2.0 kft)—were identified from discussions with subject matter experts, and 20 × 20 km. wind forecast capture boxes were defined for each point. Wind impact metrics included capture box average headwinds and headwind differences between capture boxes. Operationally significant thresholds—metric values that appeared to be associated with decreases in ground speed on final approach >10 knots, or increase in spacing on final approach to 4 or more nautical miles—were identified for several impact metrics. Four metrics were of particular interest: headwinds at the surface and at the head of final approach, the difference in headwinds between the head of final approach and the surface, and the difference in headwind gain (a likely cause of compression) along arrival trajectories from different TRACON entry points to the surface. However, further work is needed to validate and refine the definition of the impact metrics and their translation into operational impacts.

To determine the impact of surface headwind forecast errors on runway selection, two probabilities were defined and calculated from TAF and MODEL forecasts:

1. **Probability of infeasible runway selection.** This was defined as the percentage of forecasts of runway headwinds >= 0.0 knots (the runway selection criterion) for which observed runway headwinds were < –8.0 knots (the runway infeasibility criterion).

2. **Probability of "better" runway selection.** This was defined as the percentage of forecasts of runway headwinds >= 0.0 knots (the runway selection criterion) that were correct.

The probability of infeasible selection was very low (<<1%) for both TAF and MODEL forecast. This result was surprising, even accounting for the relatively generous forecast accuracy criterion, considering the frequency of operational difficulties attributed to surface wind conditions. However, as the runway selection criterion is relaxed to allow the selection of a runway with a tailwind, the margin for error between selection and infeasibility is reduced, and the probability of an infeasible selection increases accordingly.

Three statistical measures were defined to estimate of the effect of winds-aloft impact forecast errors on aircraft ground speed and spacing on final approach:

1. **Probability of Prediction of Operational Impact (PoPOI).** PoPOI was defined as the ratio

(correct predictions that threshold will be exceeded) /
(observations where threshold was actually exceeded)

2. **Probability of False Operational Impact (PoFOI).** PoFOI was defined as the ratio

(erroneous predictions threshold will be exceeded) / (total predictions threshold will be exceeded)

3. **Probability of true operational impact (PoTOI).** PoTOI was defined as the ratio

(observations where threshold was exceeded) / (total observations)

The measures were calculated for MODEL forecasts from the 21 case days. PoPOI generally ranged between 0.85 and 0.95 for all forecast horizons of all wind impact metrics. PoFOI ranged generally between 0.1 and 0.3, with higher value often associated with longer forecast horizons. PoTOI ranged from approximately 0.09 to 0.25, which seems reasonable considering that TMI were implemented on 16 of the 21 case days, and compression was explicitly noted in operational logs on 10 of the 21 case days. Follow-on research is needed to refine the operational impact thresholds and to determine the impact and tradeoff between PoPOI and PoFOI in potential benefits.

The analysis of runway selection highlights an important shortcoming of the analysis. Forecast errors for each location, forecast horizon, and issuance time were treated as independent measurements and aggregated into the various decision-related forecast accuracy probabilities. This method does not capture the ability of forecasts to predict specific *events*, such as frontal passages with associated strong wind shifts or the onset of a sea breeze or low level jet that results in compression, that have significant and potentially widespread or long-lived operational impacts. *The accuracy and timing of forecasts of such significant events are critical aspects of forecasts that planners must assess, as they have a direct bearing on the type, scope, and timing of TMI to mitigate weather impacts.*

5.2 RECOMMENDATIONS FOR FUTURE WORK

As a result of this evaluation, several follow-on research efforts have been identified:

1. **Refinement of the results of this evaluation.** The definition of weather impact metrics and assessment of the impact of forecast error on weather translation and decision making were based on the analysis of a limited data set from a single location (EWR). The scope of the analysis should be expanded to include several additional sites and case days to refine translation models and ensure that results apply to a wide range of geography and operations, and should include a more detailed comparison of TAF and MODEL surface wind forecast accuracy.

2. **Event-based forecast evaluation.** The ability to forecast the onset and clearing of weather events that have significant impact on operations (e.g., frontal passages) should be evaluated, since such events drive decision making and planning of TMI for mitigation of weather impacts. This will require defining objective metrics for the onset and clearing of such events and the collection of data from several case days where such events occurred.

3. **Analysis of implications of forecast performance on potential benefits.** The probabilities of different decision outcomes that have been defined in this report should be mapped into impacts of forecast error on potential benefits by associating costs/benefits with different decision outcomes.

4. **Identification of forecast requirements and opportunities for improvement at shorter planning and execution horizons.** The finding that there is little statistical difference between 2 and 8 hour forecast accuracy suggests a need to explore requirements and opportunities to improve short horizon wind forecasts.

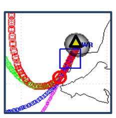
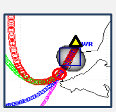
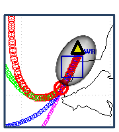
5. **Development of forecast uncertainty models that can be translated into confidence metrics for specific operational decisions.** Models for the uncertainty of weather impact forecast metrics must be developed and translated into confidence metrics that apply to the specific impact mitigation decisions that planners must make. This may be viewed as a longer-range effort.

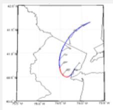
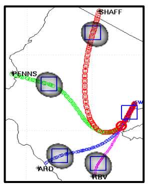
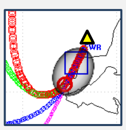
APPENDIX A
WIND IMPACT METRICS

The operational threshold for a given wind impact metric was determined by examination of the distributions of ground speed and aircraft spacing on final approach as a function of the wind impact metric value. Wind impact metrics were calculated from the analyzed (i.e., observed/interpolated) wind field for wind-aloft metrics or from METAR for surface wind metrics for the 21 EWR case study days. Figures A-1–A-4 present heat maps that illustrate distributions for the wind impact metrics that showed the strongest correlation with either ground speed or spacing on final approach. Figures A-5 and A-6 present distributions for wind impact metrics with weaker correlations. Table A-1 summarizes the wind impact metrics.

TABLE A-1

Wind Impact Metrics

Metric	Decision/Impact	Wind Impact Metric Evaluated	Operational Impact Threshold
Surface headwinds 	Ground speed on final approach	Runway headwind	Headwind >10.0 knots (ground speed reduction = ~10 knots)
DCB headwinds 	Ground speed on final approach	Trajectory headwind at DCB	Headwind >20.0 knots (ground speed reduction = ~10 knots)
DCB-to-surface 	Spacing on final approach	Difference between DCB and surface trajectory headwinds (DCB – surface)	Difference >10.0 knots (spacing increase = ~1.0 nautical mile)

Compression segment 	Spacing on final approach	Maximum difference between compression segment headwind gain from STARs	Difference >40.0 knots (spacing increase = ~1.0 nautical miles)
TRACON entry 	Spacing on final approach (observed correlation weak)	Maximum difference between TRACON entry capture box headwinds	Difference >50.0 knots (spacing increase = ~0.5 – 1.0 nautical miles)
Merge-to-DCB 	No correlation observed	Difference between merge and DCB trajectory headwind (Merge – DCB)	

Each column of a heat map represents a range of wind impact metric values. Each row represents a range of observed output values (ground speed or spacing on final approach). Data were sampled from each individual flight (ground speed) or flight pair (spacing) from the 21 case days. Warm colors represent higher concentrations of data samples; cool colors are lower concentrations. Data sample concentrations are normalized by the number of data samples in the bin with the maximum number of samples in the column; the darkest red bin in each column has the maximum number of samples (normalized to 1.0), the yellow bins (normalized to 0.6) contain roughly 60% of the number of samples in the darkest red bin, etc. The bar charts below each heat map give the sample count for each heat map column.

Looking at the heat maps, it is apparent that the selected operational thresholds are somewhat impressionistic, although in Figures A-1 through A-4, trends appear to be fairly strong. It is expected that the analysis of a larger data set and more sophisticated multivariate modeling will result in sharper statistical distributions, possibly a reduced set of weather impact metrics (as correlations between impact metrics are accounted for), and more refined operational thresholds for forecast evaluation and sensitivity analysis.

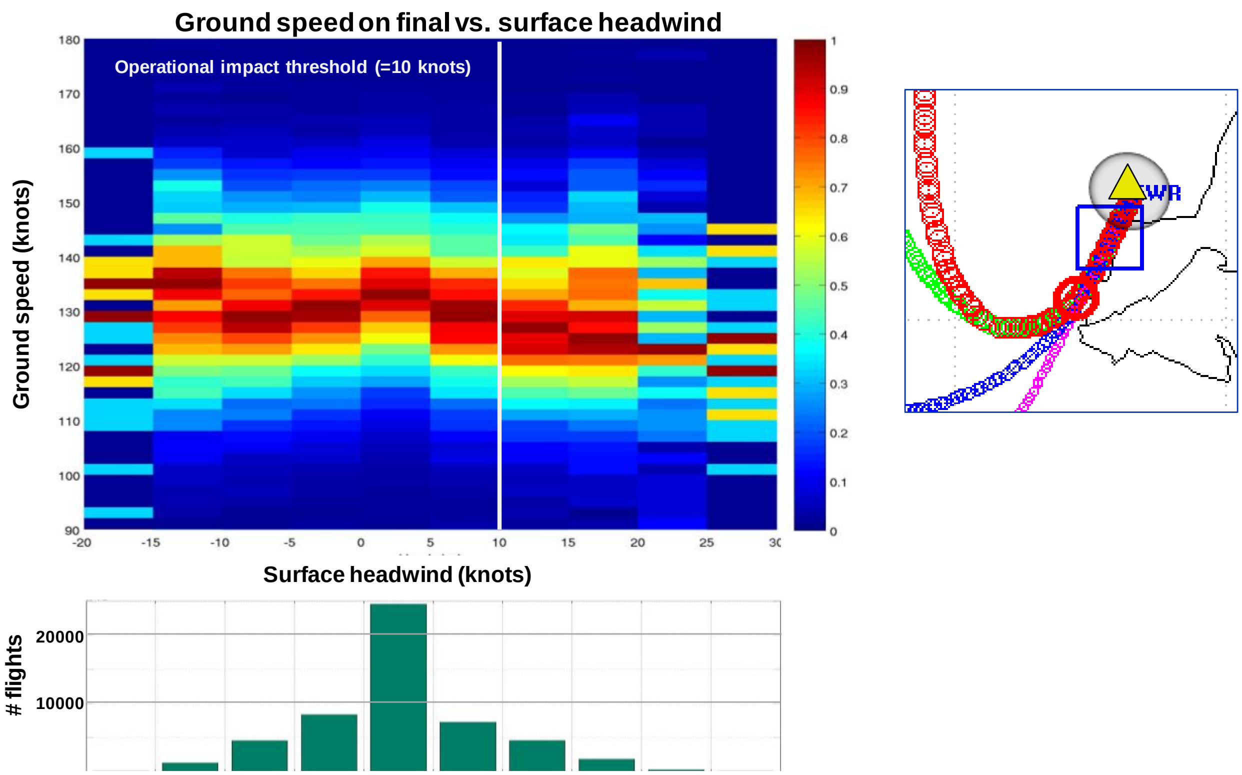
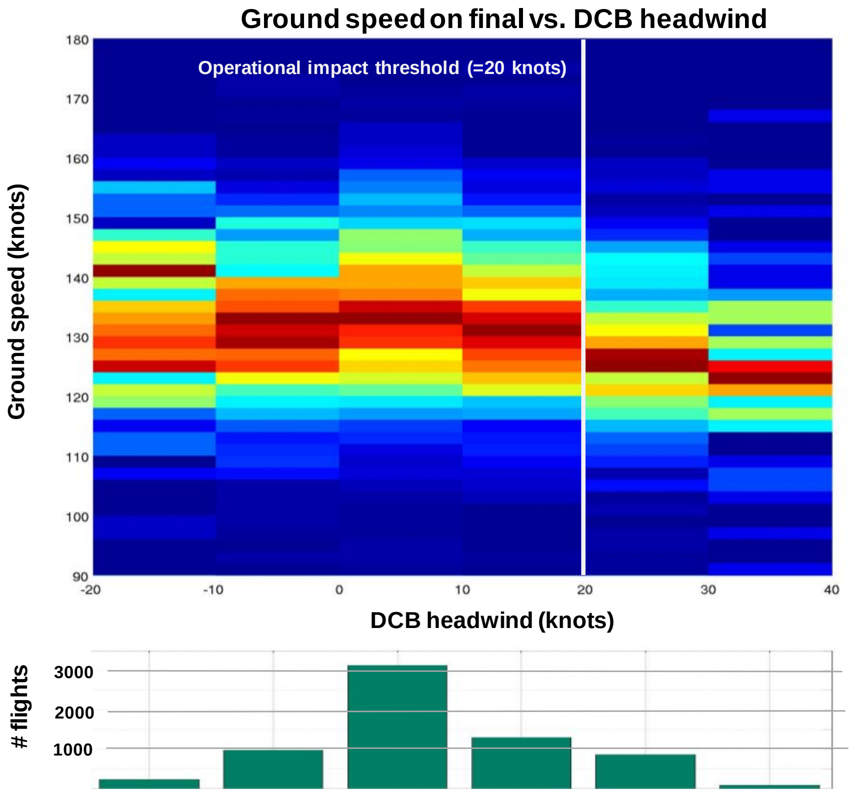


Figure A-1. Correlation between observed surface headwind and ground speed on final approach.



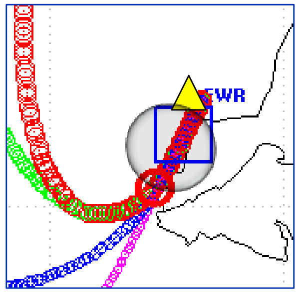


Figure A-2. Correlation between observed DCB headwind and ground speed on final approach.

From Figures A-1 and A-2, the correlation between surface or DCB headwinds and the ground speed on final approach is evident. The correlations are not surprising, since stronger headwinds translate directly to slower ground speeds, and the impacts at the DCB and surface impact the trajectory near or on the final approach. Headwinds at the DCB and surface are also likely to be highly correlated, so these wind impact metrics are probably redundant as predictors of ground speed on final approach.

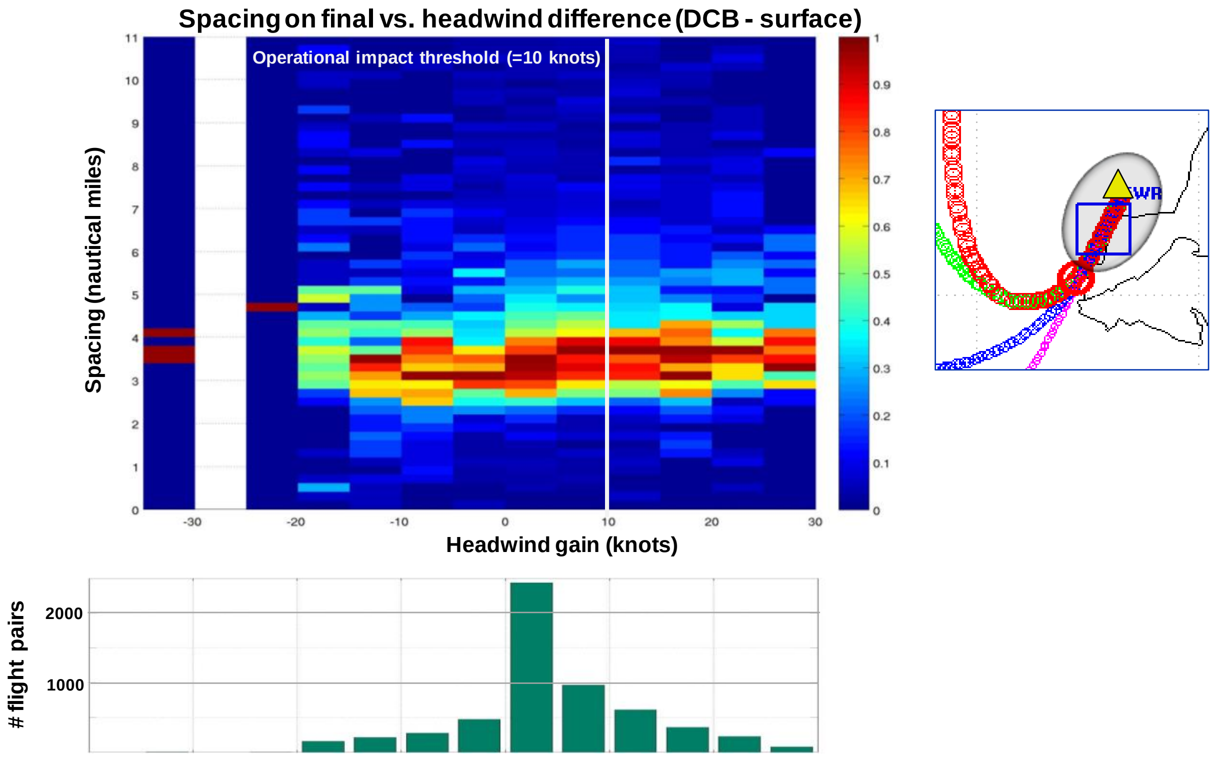


Figure A-3. Correlation between observed difference between DCB and surface headwind and aircraft spacing on final approach.

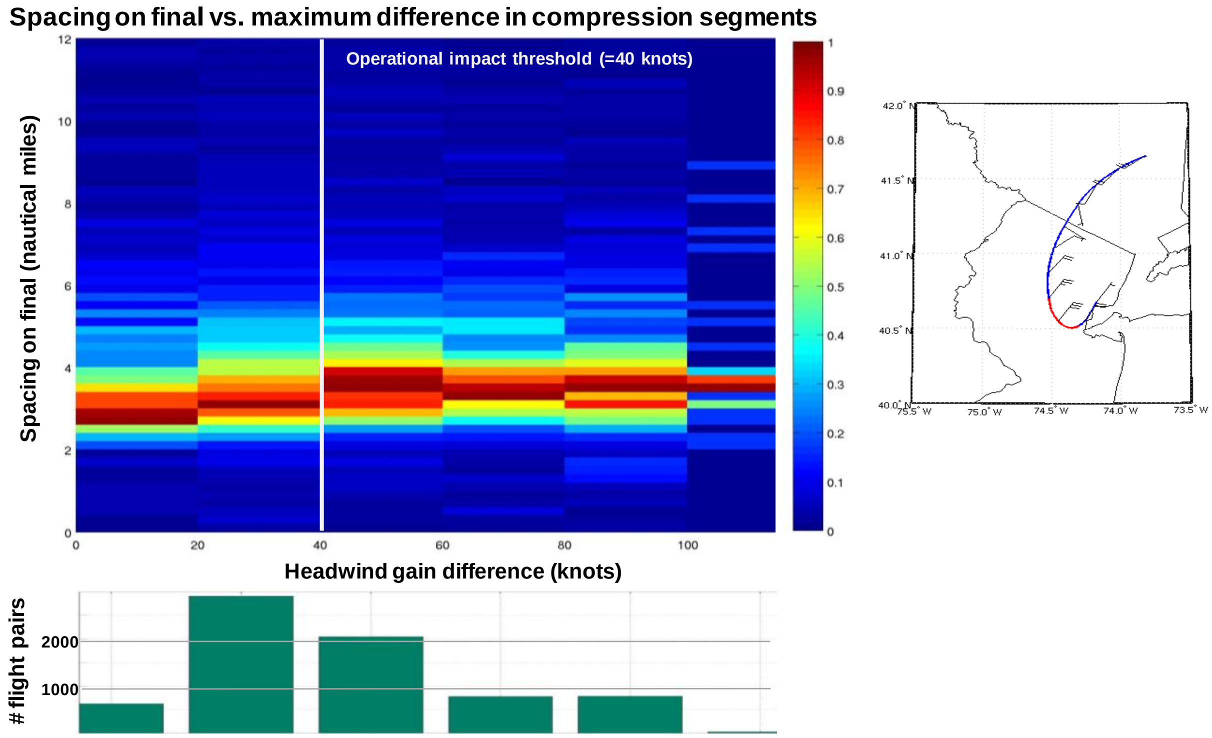


Figure A-4. Correlation between observed maximum difference between compression segment headwind gain and aircraft spacing on final approach.

Figures A-3 and A-4 illustrate the relationship between two compression-related wind impact metrics (headwind difference between the DCB capture box and surface, maximum difference between compression segment headwind gain from all STAR trajectories) and spacing on final approach. The compression segment difference metric is more complex, multifactor translation, as it provides a information about both compression and merging difficulty. Again, the possibility that compression-related wind impact metrics are related to observed spacing on final approach is reasonable; the two metrics presented in Figures A-3 and A-4 capture different aspects of compression in the TRACON, and may provide complementary information about wind impacts.

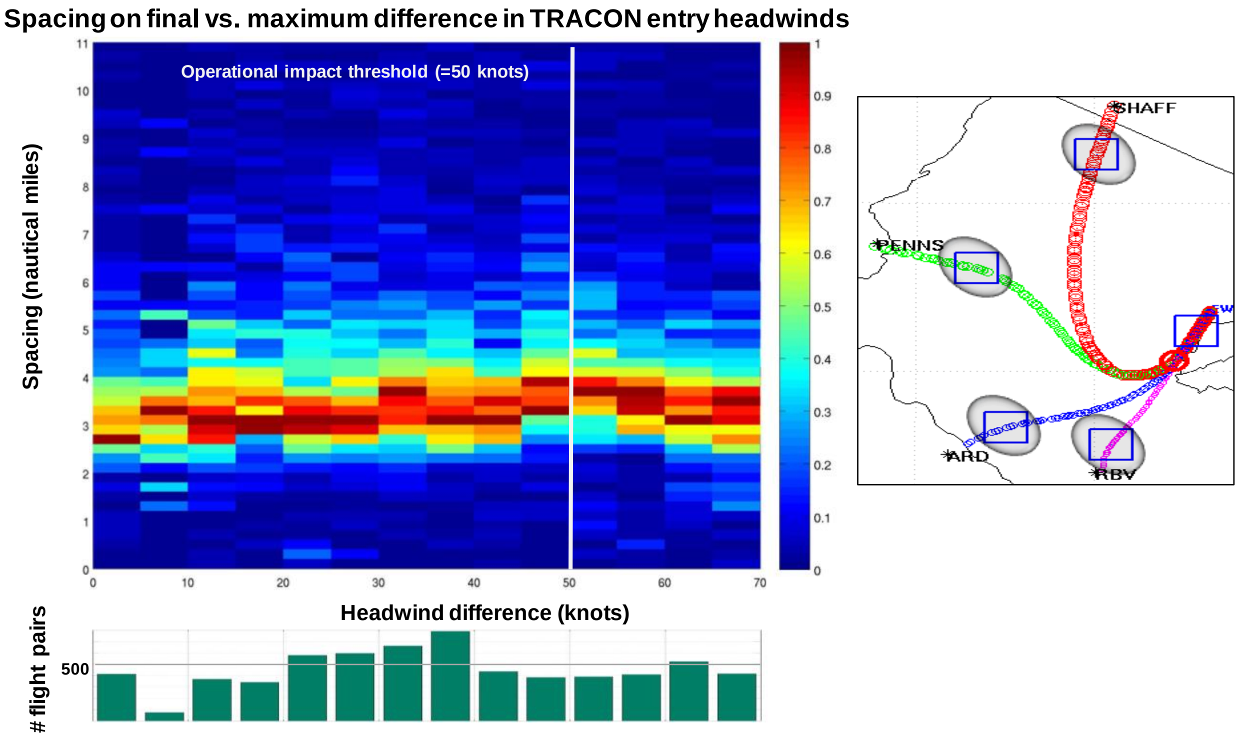


Figure A-5. Correlation between observed maximum difference between headwinds at TRACON entry capture boxes and aircraft spacing on final approach.

Figure A-5 illustrates a weak correlation between the headwind differences at the TRACON entry capture boxes and the observed aircraft spacing on final approach. Strong winds at the TRACON capture box entry altitudes could result in different headwinds and hence ground speed differences between arrival streams. Greater differences in ground speeds complicate merging. However, under circumstances where there are no complicating factors (such as strong compression), it may be possible for air traffic control to recover as the arrivals descend through TRACON airspace—a conjecture that may be tested as part of a more comprehensive analysis on a larger data set.

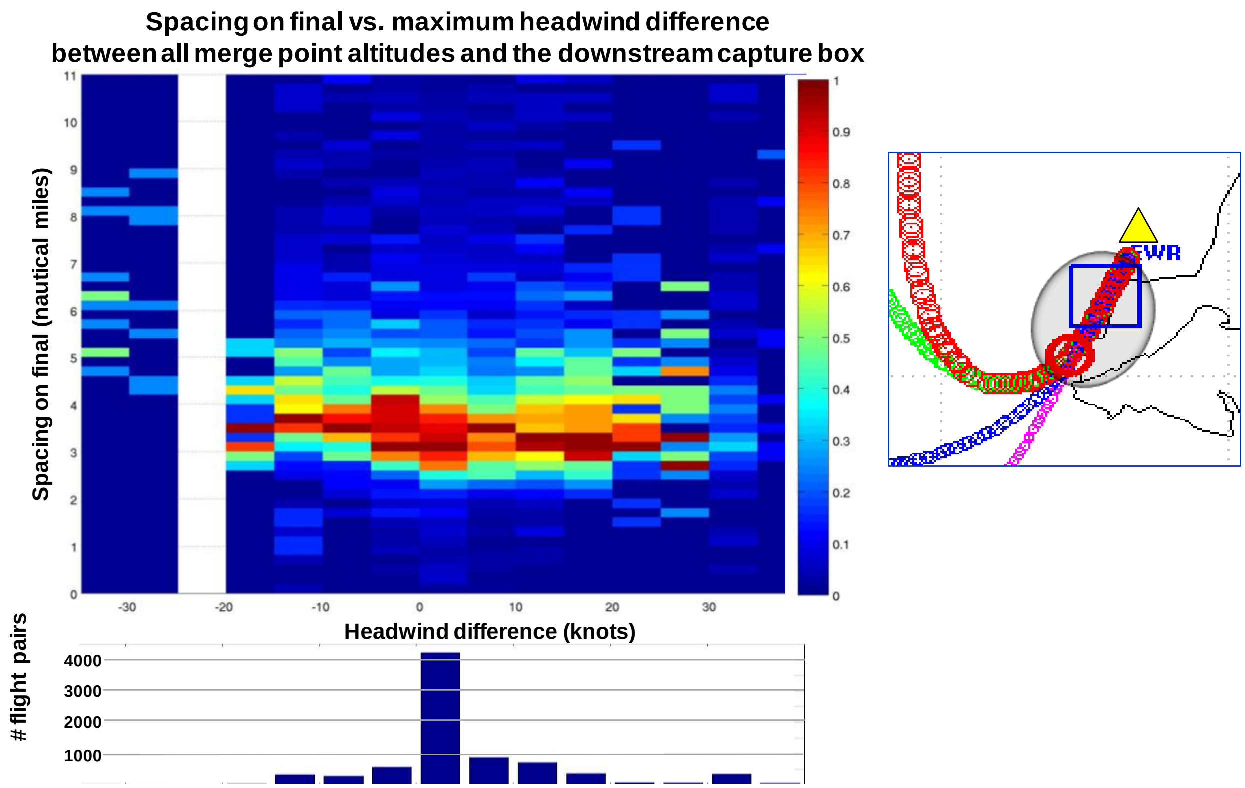


Figure A-6. Correlation between observed difference between headwinds at the merge point and the DCB and aircraft spacing on final approach.

Figure A-6 illustrates a wind impact metric—difference between headwinds at the merge point and the DCB—that appears uncorrelated to key operational factors (spacing on final approach is shown). The lack of correlation may be due to the concentration of the data sample in a single sample bin (difference between 0.0 and 5.0 knots), or it may reflect operational reality; this metric characterizes impacts over a very limited range of the arrival trajectory.

APPENDIX B
SEARCHING FOR SIGNS OF OPERATIONAL STRESS

Periods of operational stress are expected to be the precursors of the most costly and disruptive results of poor planning for arrival management: no-notice Ground Stops, diversions, and surface gridlock at the arrival airport (due to the need to use departure resources to accommodate excessive airborne arrival demand). Several trajectory and operational metrics were examined in an effort to find a measurement or combination of measurements that could identify periods of operational stress:

1. Abnormally low arrival rates.
2. Abnormally low departure rates.
3. Arrival rates falling significantly short of GDP rates.
4. High number of holding aircraft in or just outside TRACON airspace.
5. Abnormally large spacing between arrivals on final approach.
6. High variation in spacing between arrivals on final approach.
7. Unusually high time of TRACON occupancy for arriving flights.
8. Unusually long downwind leg(s) for arriving traffic.
9. IMC, ceiling, and/or visibility constraints.

We examined several of the 15 high-impact case study days from EWR to see if we could identify extended periods of operations where one or several stress signs were observed, followed by Ground Stops, diversions or reports of gridlock. Unfortunately, the data set was too small to provide many situations with severely adverse outcomes, and the circumstances leading up to the adverse outcomes that were observed were too varied and diverse to support an objective definition of "operational stress." A larger data set and a better understanding of the conditions that result in adverse outcomes should inform the "search for operational stress" and result in the definition of an objective measure that applies to potential benefits assessments.

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GLOSSARY

AAR	Airport Acceptance Rate
AARDSC	Airport Acceptance Rate Decision Support Capability
ADEST	Airport Acceptance Rate Decision Support Tool
AMD	amended
ARTCC	Air Route Traffic Control Center
ATCSCC	Air Traffic Control System Command Center
CATMT WP4	Collaborative Air Traffic Management Technology Work Package 4
DCB	downstream capture box
EWR	Newark International Airport
GDP	Ground Delay Program
GS	Ground Stop
HRRR	High Resolution Rapid Refresh
ILS	Instrument Landing Systems
kft	kilofeet
LAHSO	Land and Hold Short Operations
LGA	LaGuardia Airport
METAR	weather report observations
MODEL	RUC, RAP, and HRRR model sources of analyzing and forecasting weather
NAS	National Airspace System
NTML	National Traffic Management Log
PoFOI	Probability of false operational impact
PoPOI	Probability of prediction of operational impact
PoTOI	Probability of true operational impact
RAP	Rapid Refresh
RUC	Rapid Update Cycle
SPECI	special
STAR	Standard Terminal Automation Replacement
TAF	Terminal Aerodrome Forecast
TFMS	Traffic Flow Management System
TMI	Traffic Management Initiatives
TRACON	Terminal Radar Approach Control
Z	Zulu time (GMT)

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