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Initial Methodology and Evaluation of Airspace Restrictions Adapted in the En Route Automation Modernization System

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16. Abstract

Airspace restrictions may be applied to both or either types of ERAM trajectory predictions, referred to as flight plan and aircraft trajectories. Controllers may apply restrictions to help with timing, or to keep a flight out of an airspace (e.g. not cutting a corner of a neighboring sector) with the goal of avoiding unnecessary sector entry and increased workload for air traffic control. Restrictions are also useful in coordinating optimized profile descents. However, controllers may choose to ignore a restriction entirely if operational conditions warrant it, which creates a challenge for the ERAM automation. This study provides metrics and a methodology that identifies problematic airspace restrictions, illustrates the potential improvement on trajectory and conflict predictions, and can be easily extended to all en route facilities where ERAM has been deployed.

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Executive Summary

The Separation Management and Modern Procedures Project is an initiative of the Federal Aviation Administration (FAA) under the Next Generation Air Transportation System (NextGen) Program to implement improvements in the En-Route Automation Modernization (ERAM) system, which supports all en route facilities in the United States. The FAA's Air Traffic Organization En Route Program Office (ATO-E) has tasked the FAA's Concept Analysis Branch (ANG-C41) to execute several studies investigating the impacts from various proposed prototypes and parameter changes in ERAM's Conflict Probe Tool (CPT). The overall objective is to improve the performance of the ERAM's CPT subsystem in preparation for integration of the CPT alert notification into the flight data block on the radar controller's main display. This specific study is designed to evaluate airspace restrictions.

Airspace restrictions are intended to support the controller by allowing the automation to capture behaviors specified in Letters of Agreement (LOAs) and Standard Operating Procedures (SOPs) when building trajectories. They represent preliminary intent information that has not yet been entered by a controller and are not clearances. However, as part of the ERAM adaptation, restrictions serve an important function by directing trajectory modeling based on anticipated controller intent that cannot be easily entered into the automation on a per flight basis. They can be useful if properly modeled, but if restrictions do not match the reality of where aircraft fly, they can have a negative effect on the automation performance. This occurs in the form of inaccurate predicted trajectories, particularly during the arrival phase of flights. Inaccurate trajectories can cause considerable degradation in the ERAM CPT, resulting in invalid or unwanted alerts.

The purpose of this study is to demonstrate a preliminary methodology to identify restrictions that may require revision. The motivation for this analysis is that refinement of restrictions will ultimately improve ERAM's trajectory and conflict predictions. In order to establish and verify this methodology, four days of recorded traffic and trajectory data were collected along with relevant airspace adaptation information from ERAM in the Chicago and Boston en route centers. Software was developed specifically for this experiment to match recorded flight track to modeled restrictions and determine whether or not the restrictions were met in a timely fashion. Three categories were introduced that capture the following instances: (1) flights that meet a restriction that is modeled on the active trajectory, (2) flights that meet a restriction when it is not modeled on the active trajectory, and (3) flights that do not meet a restriction that is modeled on the active trajectory. Information was captured with respect to both the flight plan trajectory and aircraft trajectory. The activity in each category is compared in order to observe the relative usage of restrictions and identify restrictions that are being used in unexpected ways. A trajectory accuracy analysis followed that contrasted trajectory predictions associated with airspace restrictions that were met to those that were missed. It was shown that the average vertical trajectory error increased as much as 3000 feet when modeling an airspace restriction that was not flown.

The study provides metrics and a methodology that identifies problematic airspace restrictions, illustrates the potential improvement on trajectory and conflict predictions, and can be easily extended to all en route facilities where ERAM has been deployed.

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1. Introduction

The Separation Management and Modern Procedures Project is an initiative of the Federal Aviation Administration (FAA) under the Next Generation Air Transportation System (NextGen) Program to implement improvements to the National Airspace System (NAS) in the United States. The FAA's Air Traffic Organization En Route Program Office (ATO-E) has employed the FAA's Concept Analysis Branch (ANG-C41) to execute several studies investigating the impacts from various proposed prototypes and parameter changes in the Conflict Probe Tool (CPT) of the En-Route Automation Modernization (ERAM) system. The overall objective is to improve the performance of the CPT subsystem in ERAM in preparation for integration of the CP alert notification into the flight data block on the radar controller's main display. This specific study is designed to evaluate airspace restrictions, part of the ERAM system adaptation.

Airspace restrictions are a direct input to predicting the path an aircraft will fly and influence what air traffic control clearances shall be implemented. There may be different motives of applying restrictions, and they can be applied to both Flight Plan and/or Aircraft trajectories as appropriate. Controllers may apply restrictions to help with timing, or to keep a flight out of an airspace (e.g. not cutting a corner of a neighboring sector) with the goal of avoiding unnecessary sector entry and increased workload. Restrictions are also useful in coordinating optimized profile descents. However, controllers may choose to ignore a restriction entirely in their management of a flight.

Results from a study by ANG-C41 [Schnitzer *et al*., 2013] show that some current restriction adaptations are not modeled properly and result in limited operational value to controllers and decreased accuracy in flight plan trajectories. Improvements in restriction adaptations would increase accuracy of flight plan and aircraft trajectories, and thereby improve the CPT performance. In an effort to gain understanding about this issue, an empirical analysis is conducted on the usage of altitude restrictions in the NAS today. A methodology for an automated metric driven approach was developed that can be applied to identify potentially problematic restriction adaptations on a NAS-wide scale and determine what if any changes need to be made in order to improve TM and CPT performance. This technical note documents both the methodology and the results of the analysis.

The analysis also provides an initial quantification of current issues with ERAM's aircraft altitude restrictions to support the suggestions for trajectory related enhancements by the FAA's Second Level Maintenance Team presented in an internal white paper [Maxwell, 2013]. In the paper the team has proposed eleven candidate trajectory related enhancements, four of which are as follows:

- Item #2 called for improvements to modeling terminal airport runway configuration,
- Item #3 called for a means for air traffic control to cancel or alter restrictions that were being modeled by ERAM,
- Item #4 requested a method to support blocked altitudes from being properly captured in ERAM's restriction adaptation database, and
- Item #7 called for improvement to the reliability of the climb and descent model in ERAM.

For item #2 the details of runway configuration are an extension of the modeling of preferential arrival and departure routes, which are in turn supported by their active restrictions modeled by

ERAM. The improvement in item #3 would have a direct impact on the accuracy of ERAM's aircraft restrictions because this would allow air traffic control to modify them very easily on a flight-by-flight basis. Items #4 and #7 call for enhancements to the data and resulting modeling that ERAM's restriction adaptation data allows. The analysis documented here provides a method for describing how altitude restrictions are used and helps document some of the current issues with ERAM's aircraft altitude restrictions in support of the four items listed above.

2. Methodology

This study is designed to identify airspace restrictions in the ERAM adaptation that may be either unused or adapted improperly. The goal is to provide a method for evaluating the restrictions NAS-wide in an efficient manner in an effort to mitigate the negative effects on information dissemination, trajectory building, and conflict probe performance.

2.1. *Data Flow*

Data recorded from the following dates was converted into four 24-hour scenarios and utilized for this study:

- Boston ARTCC (ZBW) – 4229 flights on 04/17/2014 and 4076 flights on 05/06/2014
- Chicago ARTCC (ZAU) – 6126 flights on 02/06/2014 and 6166 flights on 02/11/2014

This study used recorded Common Message Set (CMS) messages as a means of obtaining the input radar surveillance and air traffic clearance data provided to ERAM and trajectory data from Lockheed Martin's SARBot tool as a means of obtaining ERAM's output data. CMS is the message format used for data exchanged between ERAM and other Air Traffic Management (ATM) applications. In addition to other information, this data contains the flight plans, converted routes, and clearances entered into ERAM and used by ERAM's TM and CP. The recorded CMS messages used for this study were obtained from the FAA's NASQuest system. The trajectory data was comprised of Flight Plan Trajectories (FPT) and Aircraft Trajectories (AT), and contains the 4-Dimensional (4D) trajectories built for a given flight, including latitude, longitude, altitude, ground speed, and time for each node of the aircraft's path as well as the restrictions that are modeled as part of each trajectory.

Since the scenarios are recorded unmodified data, no simulation tools were used in this process. The CMS scenarios were used as an input to the FAA Concept Analysis Branch's *CPATTools*. These are comprised of a set of customized software that converts input traffic files into a linked set of relational database tables and filters the data to produce a scenario. The surveillance radar track data, air traffic control cleared routes and vertical clearances, predicted 4D trajectory data, and restriction information were paired by using software designed and written specifically for this experiment, *RestrictionAltitudeCalculator*. No conflict prediction alert data was considered for this study.

2.2. *Analysis Methods*

The goal of this analysis was to evaluate each Flight Plan Trajectory (FPT) and Aircraft Trajectory (ACT) for a given flight and determine whether the restrictions modeled by any of these trajectories were actually flown by the flight by examining the surveillance radar track. For the purposes of this study, each flight that contained track data and at least one flight plan message was considered for analysis. All data was included with the following exceptions:

- Flights with either a military aircraft type or ACID, as these flights sometimes operate in a manner inconsistent with commercial and general aviation traffic.
- Flights for which trajectory data indicated that restrictions were modeled but no track data existed in the recording during the time the restriction was modeled. As a result, an evaluation cannot be made for these flights and restrictions.
- Flights with a significant gap in track data were excluded. It was observed that duplicate or inaccurate data were common when these flights were considered. This situation often occurred when:
    - A flight received a different CID, as in the case where a flight exits the center and returns to the center or when a CL message drops the flight from the automation and then the flight is added back with a different CID.
    - When coverage from a specific radar site dropped out over a given region and the flight was correlated with a different CID throughout that region.
- Data points obtained from either the first or last 10 second track segment of a given flight that were also classified as a restriction 'Miss.' It is impossible to determine whether the flight followed the restriction during this period of unavailable track data preceding or following the start or end, respectively.

2.2.1. Data Collection and Reduction

Software developed within ANG-C41 specifically for this analysis, *RestrictionAltitudeCalculator*, collected data for each scenario. Scenario information necessary for processing is as follows:

- Track data smoothed and interpolated at 10 second intervals, is collected from the set of linked tables described in 2.1
- Information about each restriction within the given scenario
- Aircraft Trajectory (ACT) data and the restrictions modeled by each trajectory
- Flight Plan Trajectory (FPT) data and the restrictions modeled by each trajectory

In order to treat ACT and FPT data independently, *RestrictionAltitudeCalculator* wass run twice; once for ACT and once for FPT. The data are compared at a later stage of analysis.

Trajectory data was obtained solely to determine which restrictions were modeled for a given flight and at what time. A restriction was considered to be modeled if any of the cusp points for a single trajectory refer to that restriction, and restrictions were often modeled for multiple consecutive trajectories which implied a range of time during which the restriction was modeled.

Once the data was collected, flights were considered one at a time. For each flight, the track was evaluated continuously via linear interpolation using a custom designed algorithm until the track either penetrated a restriction boundary in the horizontal dimension or the track reached its minimum horizontal distance from the boundary. This evaluation included calculating the spatial distance to the restriction – horizontal (NM) and vertical (ft.) dimensions were treated independently – in order to determine whether the track was within a parametric distance of a given restriction boundary. In addition, the temporal distance to the restriction (sec) was calculated in order to determine whether the reported track occurred during the time that the restriction was being modeled. The resulting point was reported. The track was considered to have met the restriction if it was within parametric distance of the restriction (2.5 NM horizontally, 300 ft. vertically). Temporal distance was measured as the time from the last trajectory that modeled the restriction under consideration; positive values indicated that the restriction was no longer being modeled at the time of the reported track position, negative time values indicated that the restriction had not yet been modeled, and ‘0’ indicated that the restriction was being modeled at the reported point. Track was evaluated against restrictions modeled on any of the associated trajectory type for a given flight – either Aircraft or Flight Plan – depending on which trajectory data was collected. The results were stored separately for each trajectory source.

2.2.2. Metrics

Metrics for this study are based on the characterization of the track point reported by the *RestrictionAltitudeCalculator* program. Horizontal distance (NM) is defined as the distance between the track and the nearest point of the restriction under consideration. The track was said to have met the horizontal condition for any region with a calculated distance to restriction boundary of less than or equal to 2.5 NM. Vertical distance (ft.) is defined as the distance between the track and the altitude of the restriction. Since there are different altitude qualifiers, vertical distance was met in different ways depending on the altitude qualifier:

- At or Above – The restriction is said to be met vertically for any region of the track that is greater than or equal to the altitude 300 ft. below the restriction.
- At Altitude – The restriction is said to be met vertically for any region of the track that is within 300 ft. of the restriction.
- At or Below – The restriction is said to be met vertically for any region of the track that is less than or equal to the altitude 300 ft. above the restriction.

Altitudes within the region specified above for a given restriction are considered to have met the restriction in the vertical dimension.

Logical classification of reported track points is shown in Table 1 and is described as follows:

- A classification of “Hit” was assigned if the reported point penetrated the restriction boundary (spatial), and requires that both the horizontal and vertical conditions are met. It also requires that the reported point occur during the time that the restriction was modeled on the active trajectory. If a point exists on the track that meets this condition it will be reported regardless of classification of the remainder of the track.

- A classification of “Spatial Only” was assigned if the reported point penetrated the restriction boundary (spatial) as in “Hit” but the point occurred during a time when the restriction was not modeled on the active trajectory. Sign of the temporal distance indicates whether the flight reached its minimum spatial distance to the restriction before or after the restriction was modeled. If a point exists on the track that meets this condition and there is no point classified as a “Hit” it will be reported regardless of classification of the remainder of the track.

- A classification of “Miss” was assigned if the reported point did not penetrate the restriction in the spatial dimension (i.e. horizontal, vertical, or both) but the point occurred during a time when the restriction was modeled on the active trajectory. If a point exists on the track that meets this condition and there is no point classified as a “Hit” or “Spatial Only” it will be reported regardless of classification of the remainder of the track.

Table 1. Classification of reported track point.

Classification	Horizontal <= 2.5 NM	Vertical <= 300 ft.	Temporal Distance (sec)
Hit	True	True	0
Spatial Only	True	True	Nonzero value
Miss	One or Both False		0

A fourth classification, "Discard," was applied when the reported point closest to the restriction did not penetrate the restriction and did not occur during the time the restriction was modeled. This classification was included only for logical completeness. Points with this classification were not considered for analysis as no inference can be made about whether the restriction in questions was met when no track was available during the time the restriction was modeled.

3 Analysis

This section presents the statistical results for restriction usage associated with the data analysis methods described in Section 2.2, results from an analysis of trajectory accuracy, and finally detailed flight examples that illustrate how particular patterns of interest in the statistical results materialize in flight data.

3.1 Statistical Analysis of Restriction Usage

This sub-section section presents data based on two days each from the ZAU and ZBW ARTCCs discussed previously. The amount of data suitable for analysis collected and classified as a Hit, Spatial Only, or Miss is depicted as "TotalN" in Figure 1 and Figure 2 for the ZAU and ZBW centers, respectively. Each column represents the data associated with a single restriction. Note that the vertical axes of both graphs use the same scale to allow for direct comparison. A breakdown of all data (Hits, Spatial Only, Misses) for each restriction, combined within ARTCC, is presented in Appendix A: ZAU and Appendix B: ZBW.

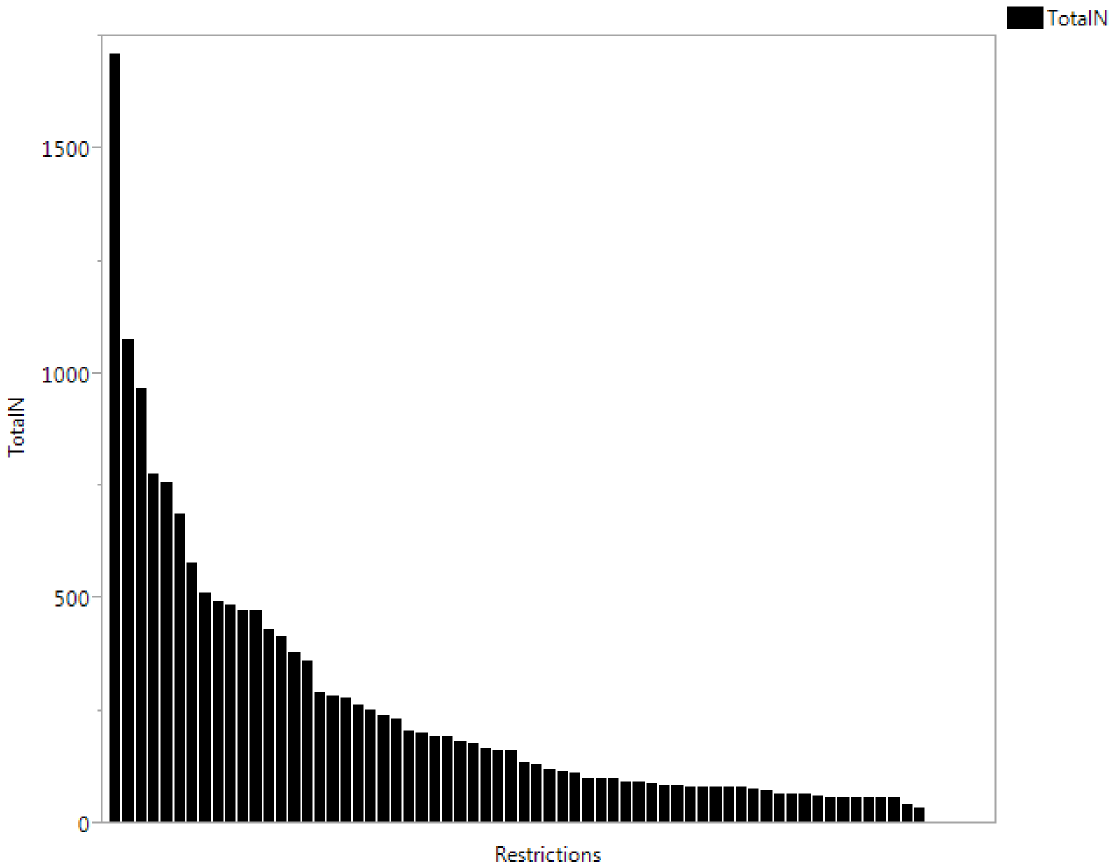

Figure 1. ZAU: Number of sampled events collected per restriction.

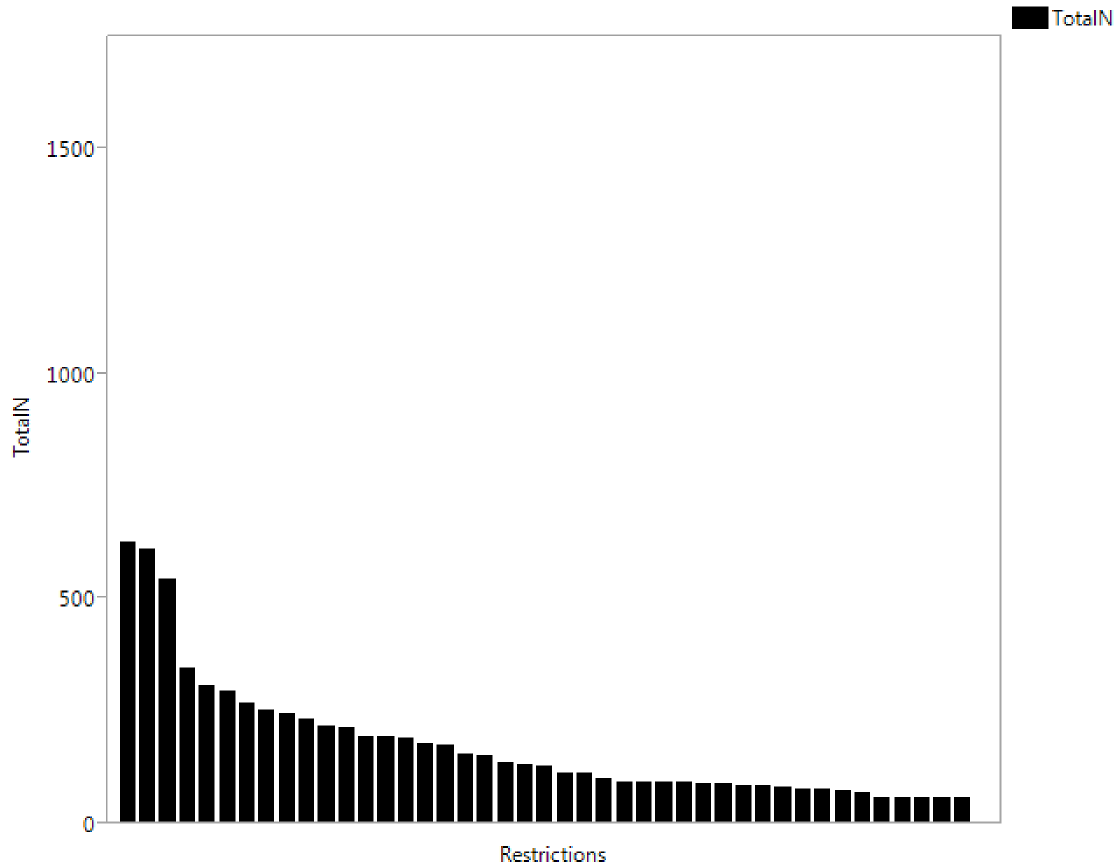

Figure 2. ZBW: Number of sampled events collected per restriction.

To help mitigate statistical anomalies, only data samples with $N \geq 30$ were considered. Upon reviewing the data (excluding restrictions with less than 30 data points), it is apparent that when flights miss their restrictions it's almost always in the vertical dimension. Figure 3 shows that for the ZAU scenarios about 99% of the instances where track did not pass through restrictions were due at least in part to a miss in the vertical dimension. Only about 3% of the misses could be attributable to horizontal deviation. In Figure 4, ZBW scenarios show a similar trend; 98% of the miss events are due at least in part to the vertical dimension while only about 4% are due in part to horizontal deviation. This suggests that flights consistently follow their route and that the majority of adapted restrictions are accurate in the lateral dimension. Possible reasons for vertical deviation include improper altitudes or altitude qualifiers (at_or_above, at_altitude, at_or below), controller preferences that are inconsistent with adapted restrictions, or restrictions that are improperly paired with assigned routes.

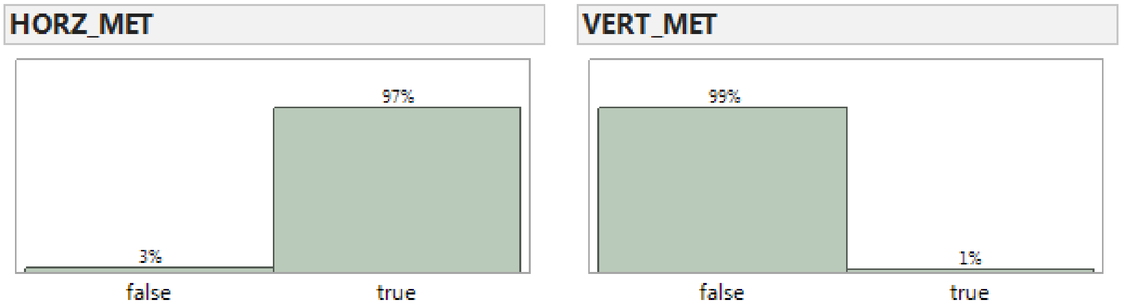

Figure 3. Miss classification, ZAU Aircraft Trajectories.

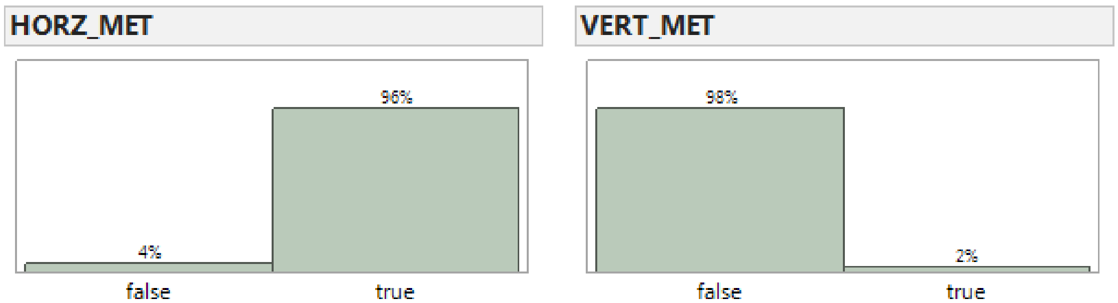

Figure 4. Miss classification, ZBW Flight Plan Trajectories.

When considering the quality of individual restrictions, examining the proportion of hits, misses, spatial only, or some combination can yield useful information. We first considered the hit percentage, or how often a restriction was met when it was modeled in a trajectory. Hit percentage was calculated by counting the number of instances a given restriction was met spatially while the restriction was modeled by the active trajectory and dividing by the total number of instances that the restriction was modeled in a trajectory regardless of whether or not it was hit, i.e. the ratio (Hit) : (Hit + Miss). This metric can be further categorized into hit percentage for a restriction when it is modeled by an aircraft trajectory or when it is modeled by a flight plan trajectory. Figure 5 illustrates the hit percentages for all sampled restrictions in the ZAU scenarios, with the blue diagonal line representing an equal hit rate in both the FPT and ACT domains. There are 8 restrictions with significant data ($N \geq 30$) that have zero hits in either category for ZAU. Figure 6 illustrates the hit percentages for all sampled restrictions in the ZBW scenarios. There are 7 restrictions with significant data that have zero hits in either category. Markers that fall above the blue line indicate that the restriction in question is hit more frequently when the FPT domain is examined whereas markers that fall below the blue line indicate that the restriction in question is hit more frequently in the ACT domain.

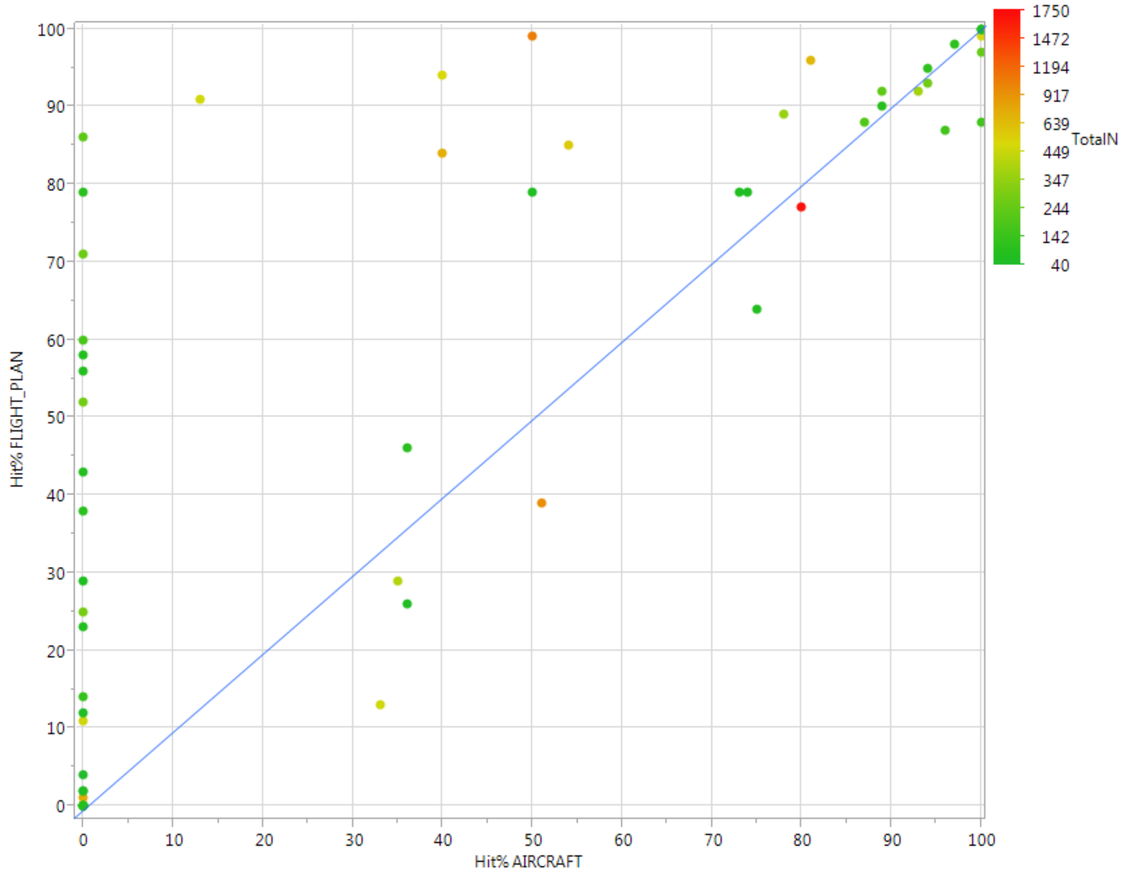

Figure 5. Hit percentages for ZAU scenarios.

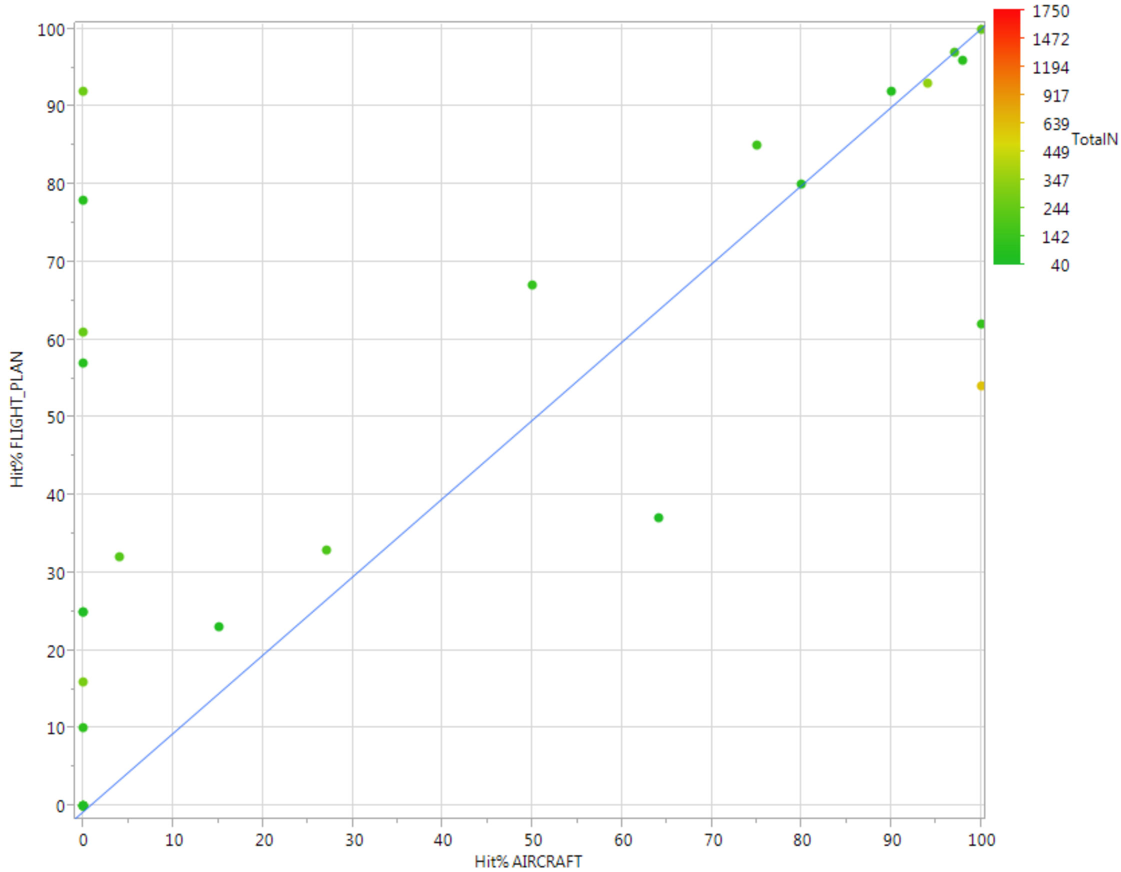

Figure 6. Hit percentages for ZBW scenarios.

Restrictions that have low hit percentages are good candidates for initial investigation, as these restrictions are not being met regularly in the spatial dimension in spite of being modeled. In addition, restrictions that have disproportionate differences between FPT and ACT hit percentages (upper left/lower right of figures) should be examined, as there may be restrictions that should be applied to FPTs or ACTs only and not to both trajectory types, as is the most common case in adaptations today. Since it's already been established that the vast majority of misses are in the vertical dimension (Figure 2 and Figure 3) a low ACT miss percentage suggests that the restriction in question may be adapted improperly (incorrect altitude or altitude qualifier), may not reflect controller intent, or could be applied to the wrong STAR (Standard Terminal Arrival Route) in the case of arrival restrictions.

Another metric of interest is the proportion of restrictions that the flight meets spatially even though the restriction is no longer being modeled on the active trajectory. This is defined by considering all instances where a restriction was met spatially and calculating how often in that group the restriction was not modeled at the time the restriction was met spatially. Again, the analysis is broken into two parts for ACTs and FPTs. The metric corresponds to the ratio (Spatial Only) : (Hit + Spatial Only), and is illustrated in Figure 7 and Figure 8 for ZAU and ZBW scenarios, respectively.

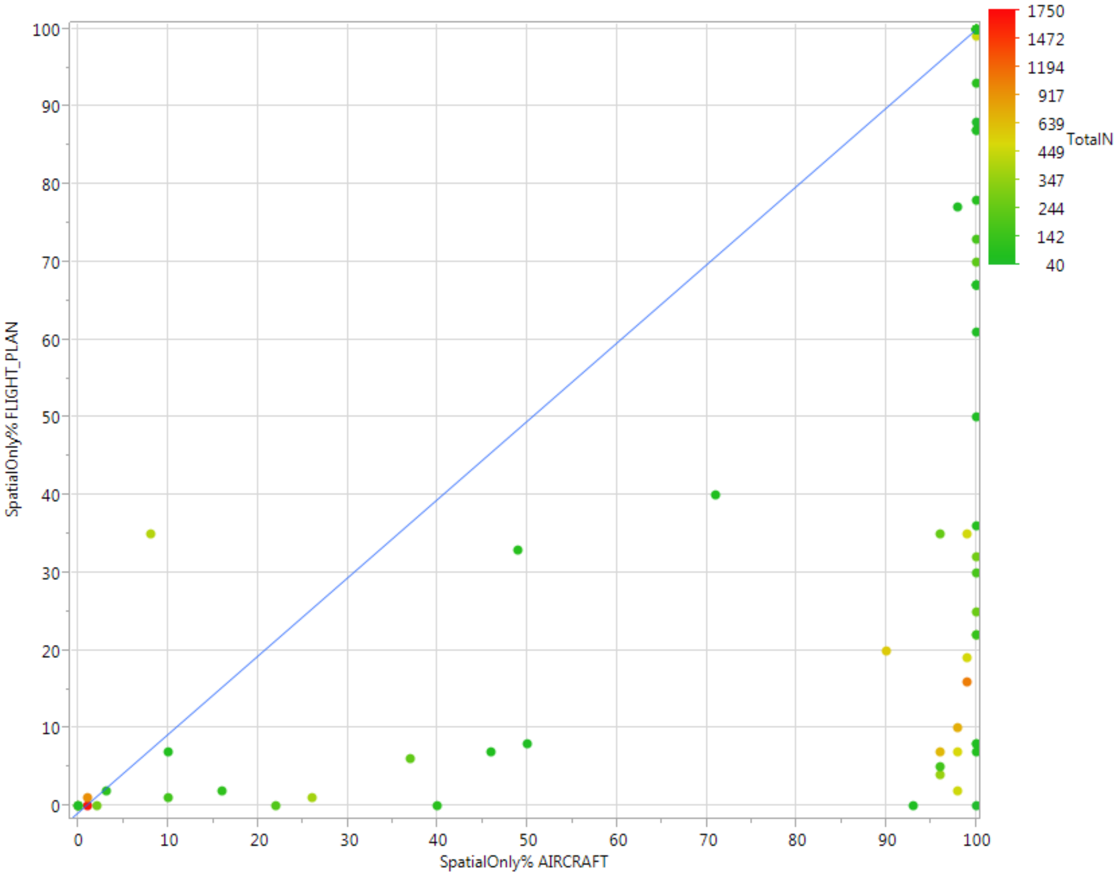

Figure 7. Spatial Only percentage for ZAU.

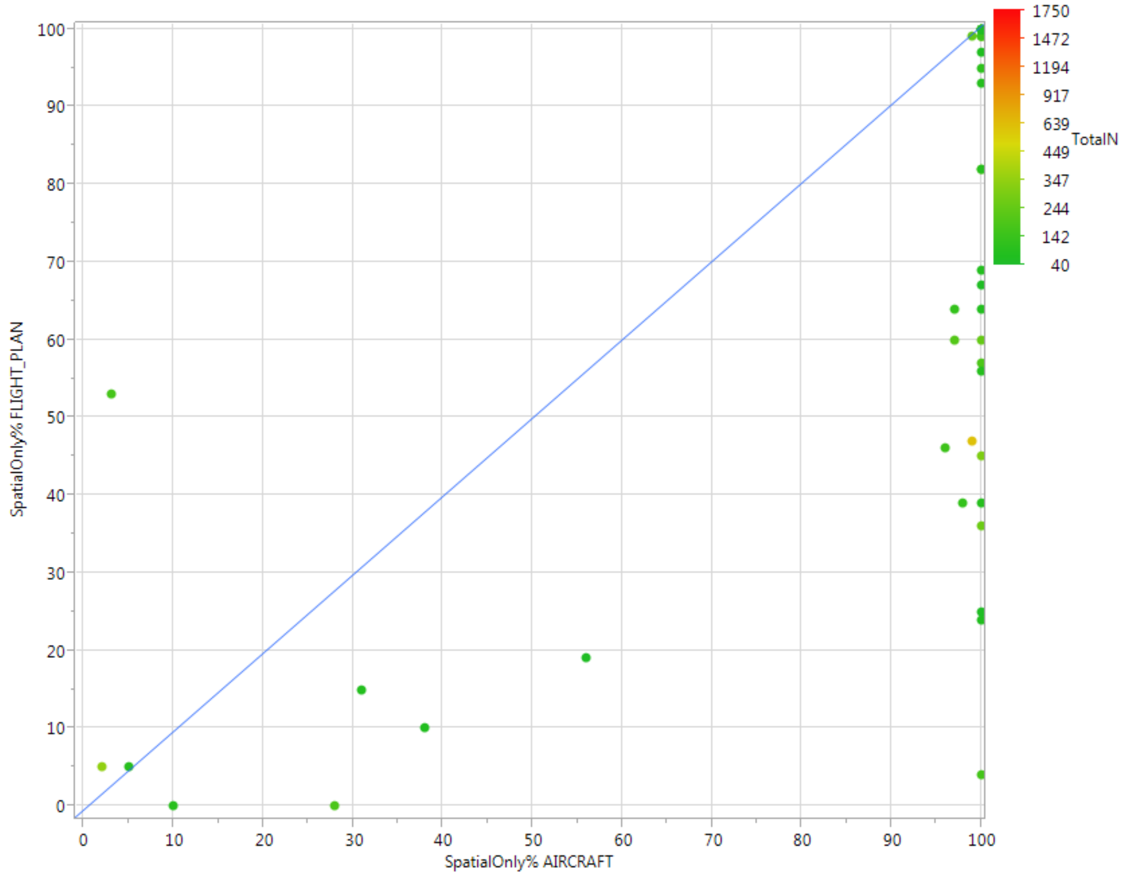

Figure 8. Spatial Only percentage for ZBW.

Of the 65 restrictions in ZAU for which significant data existed ($N \geq 30$), only three had no Spatial Hits in both the ACT and FPT data sets. Of the 43 restrictions in ZBW, only two had no Spatial Hits in both data sets. Most restrictions were met spatially in the ACT domain while being missed temporally, suggesting that the restrictions are positioned correctly. One common cause of temporal misses is the application of interim altitude clearances (LH) during arrival. Even though the clearance may be for the same altitude as the restriction, these clearances often force a trajectory rebuild for ACTs (FPTs are not affected by interim altitude messages) and the resultant trajectory will no longer model the restriction in question. This leads to Spatial Only hits (misses in the temporal dimension) though the controller's intention is to have the flights meet the restrictions, so it's debatable that this is even an issue, and perhaps this situation should be classified as a hit regardless of temporal distance. This issue will be left for future research.

The final metric, overall usage rate, considers all instances of restrictions being met out of all cases where the restriction was met or modeled in a trajectory (i.e., the grand total N for each restriction for the data presented here). Put simply, this metric represents the number of times the restriction was met spatially out of the total number of chances to meet the restriction spatially, and is a combination of the first two metrics considered. Usage rate is defined as the ratio (Hit + Spatial Only) : (Hit + Spatial Only + Miss), and is illustrated in Figure 9 and Figure 10 for ZAU and ZBW respectively.

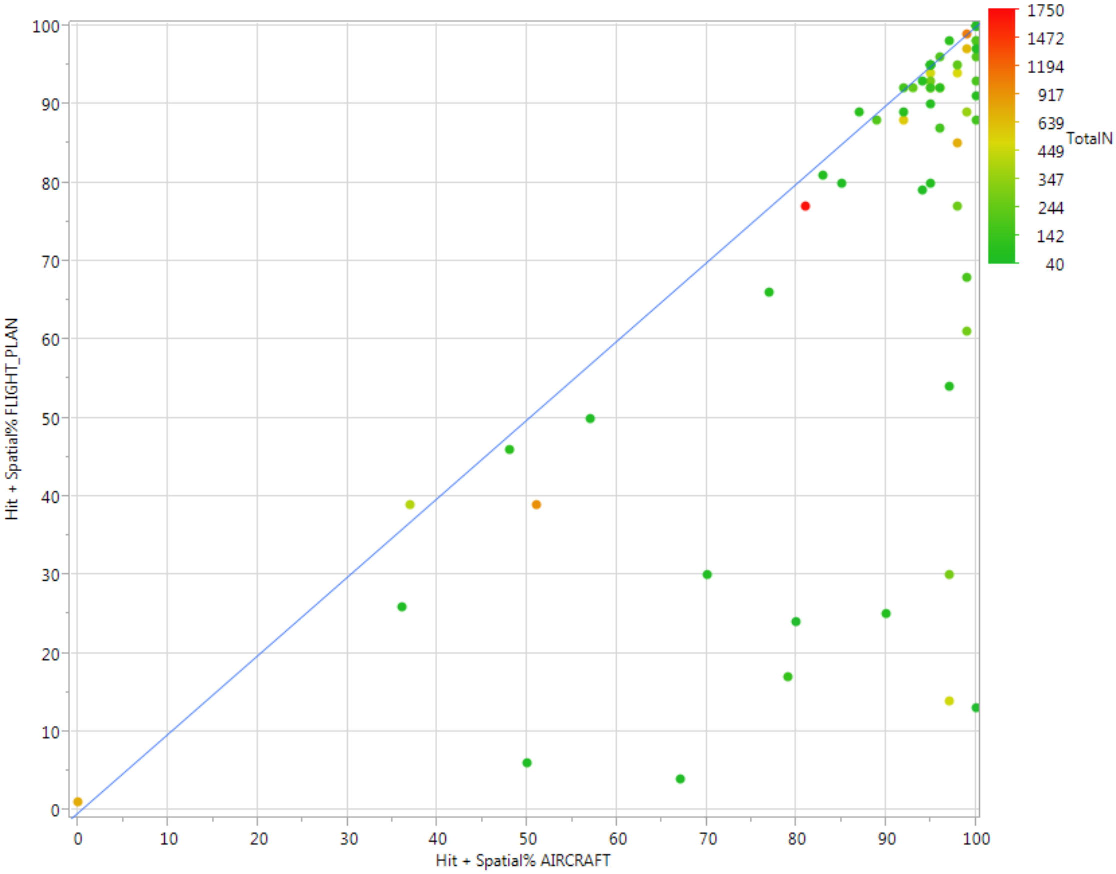

Figure 9. Hit plus Spatial Only percentage for ZAU.

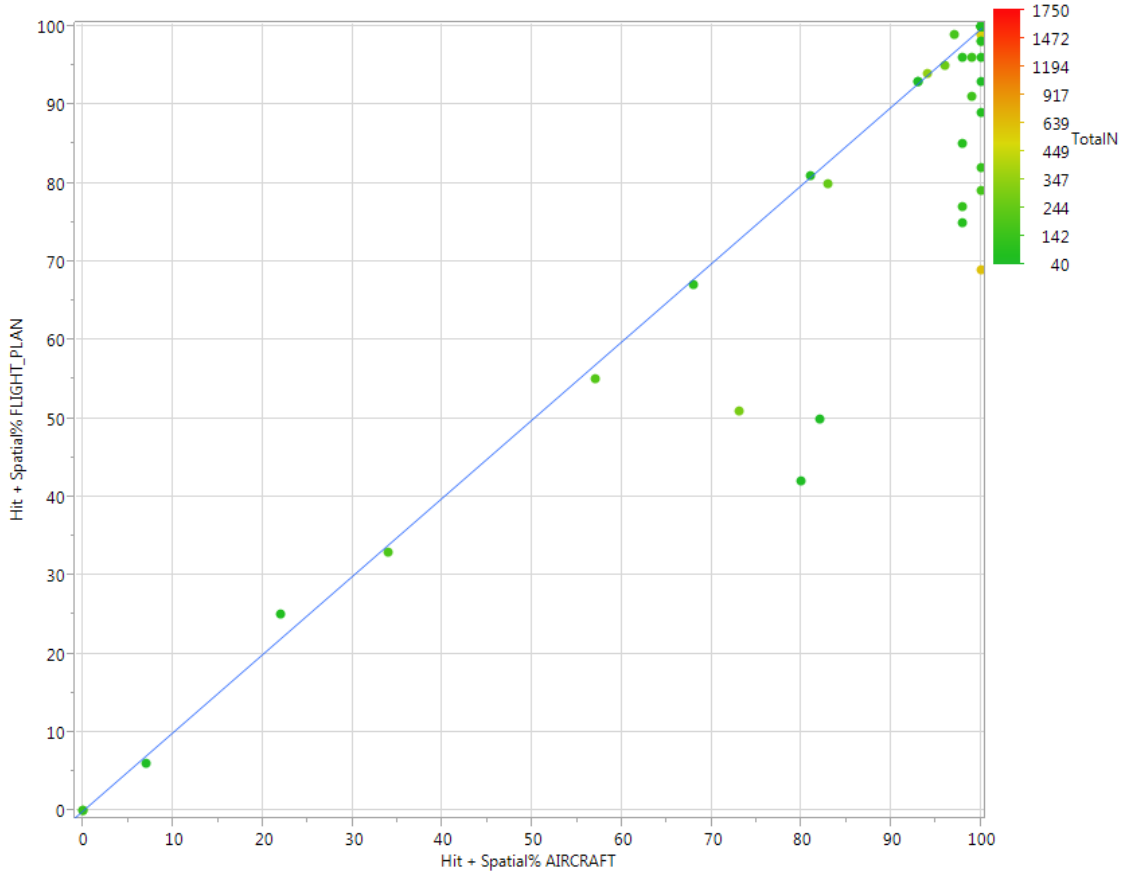

Figure 10. Hit plus Spatial Only percentage for ZBW.

Of the 65 restrictions with significant data (N ≥ 30) for ZAU, there was one case in which the hit rate percent rounded to zero in either the ACT or FPT data, and of the 43 restrictions in ZBW only one had a rounded hit rate of zero in either data set. Restrictions of note for this metric have a low usage rate, suggesting that the restriction was regularly being missed spatially. Restrictions that are missed spatially quite often – i.e. have a low usage rate - are problematic to ERAM's Conflict Probe (CP) in particular. The TM models restrictions with the assumption that the restriction will be met by an aircraft, and controller intent or improperly adapted restrictions would likely cause trajectory inaccuracies that could significantly degrade the CP's predictions. Resolving issues with these restrictions would likely have a positive impact on the CP.

3.2 Trajectory Accuracy

In addition to the above analysis and three metrics for understanding the usage of restrictions, the accuracy of related trajectories was analyzed to demonstrate how it is affected. For this analysis trajectory errors are calculated by considering the trajectory that is active 20 minutes prior to a modeled restriction, sampling predicted positions between +0 to +30 seconds from the time at restriction, and comparing them to the track data at the sampled times. In summary, the results indicate that for this method the average trajectory error for ZAU flights in the sample is 996 ft for Hits/4221 ft for Misses in ACTs and 948 ft. for Hits/2797 ft. for Misses in FPTs. In the ZBW scenarios, the average trajectory error is 1118 ft. for Hits/3095 ft. for Misses in ACTs and 1161 ft for Hits, 3117 ft for Misses in FPTs.

3.3 Flight Examples

In the following examples, the track of each flight is represented by thin black lines. For the purposes of illustrations, restrictions are depicted either as lines (thick, black) or polygons (thin black, shaded with blue).

3.3.1 Flight Example 1

Example 1 depicts a situation in one of the ZAU scenarios where a flight, traveling from the left of the figure to the right, meets a restriction spatially and the restriction is modeled at the time of the reported point. Therefore, this is classified as a Hit. The restriction shown here is C90_DEPT/SBN_T/P_AOB_100, an arc at FL 100 with a qualifier of 'at_or_below.' The vertical dimension, shown in the side view (Figure 11), is also met as the track passes right through the plane, though the track is artificially elevated just above the illustrated surface of the arc here in order to enhance visibility. In the top down view (Figure 12), it's evident that the track of the flight (thin black line) passes right through the center of the arc, so the horizontal criterion is met.

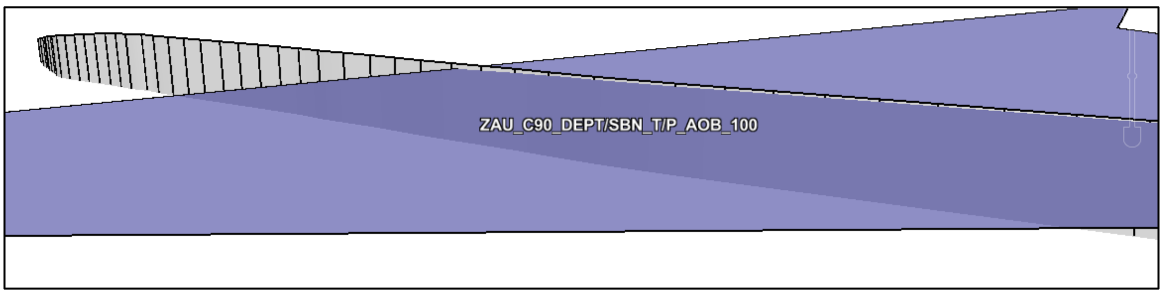

Figure 11. Example 1: hit, side view.

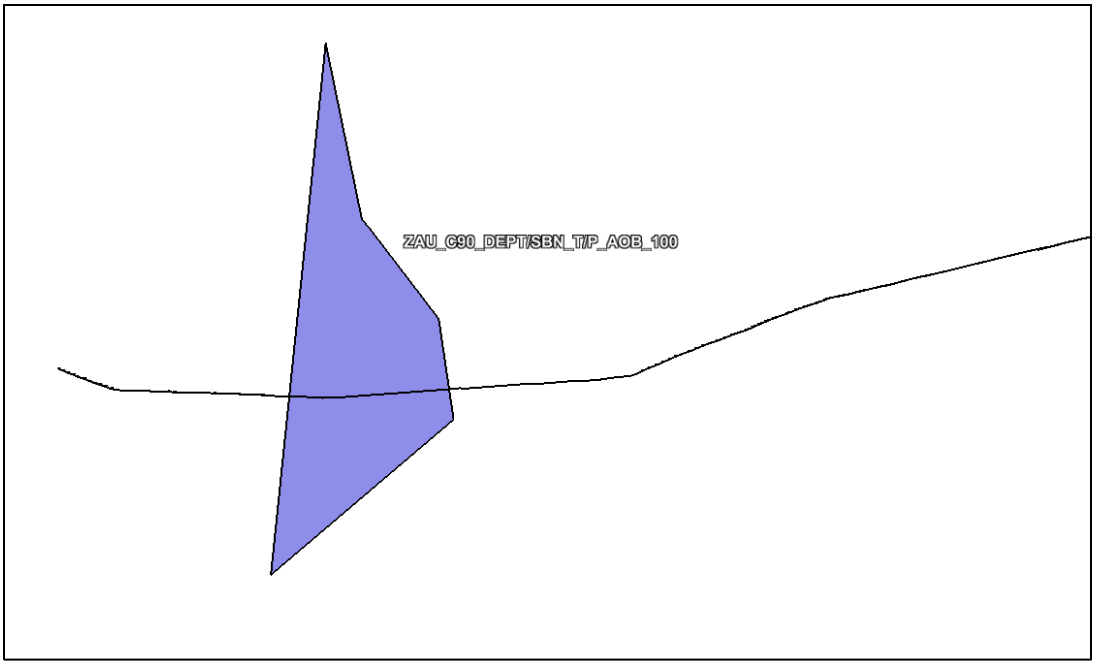

Figure 12. Example 1: hit, top down view.

3.3.2 Flight Example 2

Example 2 portrays a situation in a ZAU scenario where the restriction is hit spatially but the reported point occurs at a time when the restriction is no longer being modeled on the Aircraft Trajectory. SOP_ORD_74/74_A_TEDDY_A_110 is an arrival restriction at FL 110 with qualifier 'at_altitude.' In the side view (Figure 13), it's evident that the altitude of the track is within 300 ft. of the restriction, and the top down view (Figure 14) indicates that the horizontal position of the track passes within 2.5 NM of the restriction.

However, the red bracket drawn on the upper left region of the track represents the time that the restriction stops being modeled by the TM, which is about 6 minutes prior to when the flight reaches the restriction. 80% of the Spatial Only data for this restriction have a temporal distance between 2.5 minutes and 11 minutes.

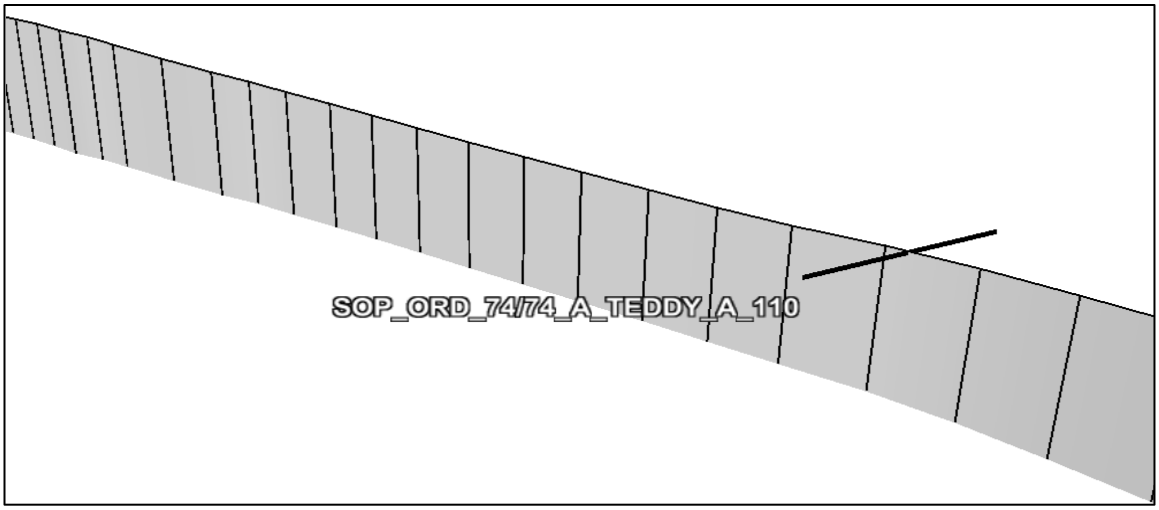

Figure 13. Example 2: spatial only, side view.

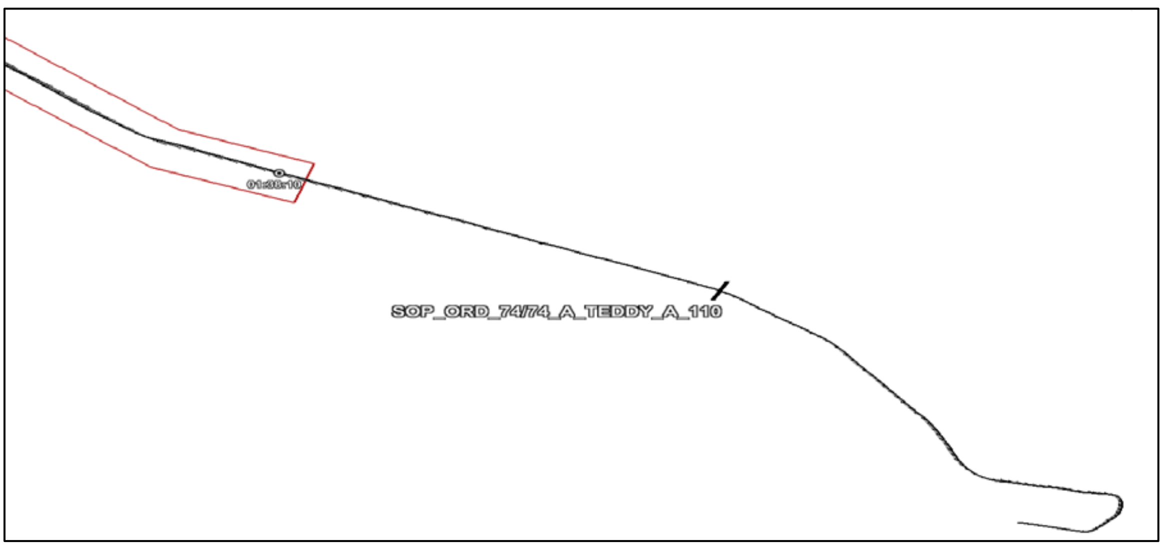

Figure 14. Example 2: spatial only, top down view.

3.3.3 Flight Example 3

In the third and final example, LOA_C90__ORD_74/ORD_J_VIA_KRENA_RWY14/09_090 is another restriction from ZAU at FL 090 with qualifier 'at_altitude'. Unlike previous examples, the top down view (Figure 15) shows 10 flights passing through the restriction in the horizontal dimension. Like example 1 the restriction is modeled at the reported point for each flight. However, none of the flights meet this restriction in the vertical dimension. This is evident in the side view (Figure 16), where the track of the flight is well over the restriction.

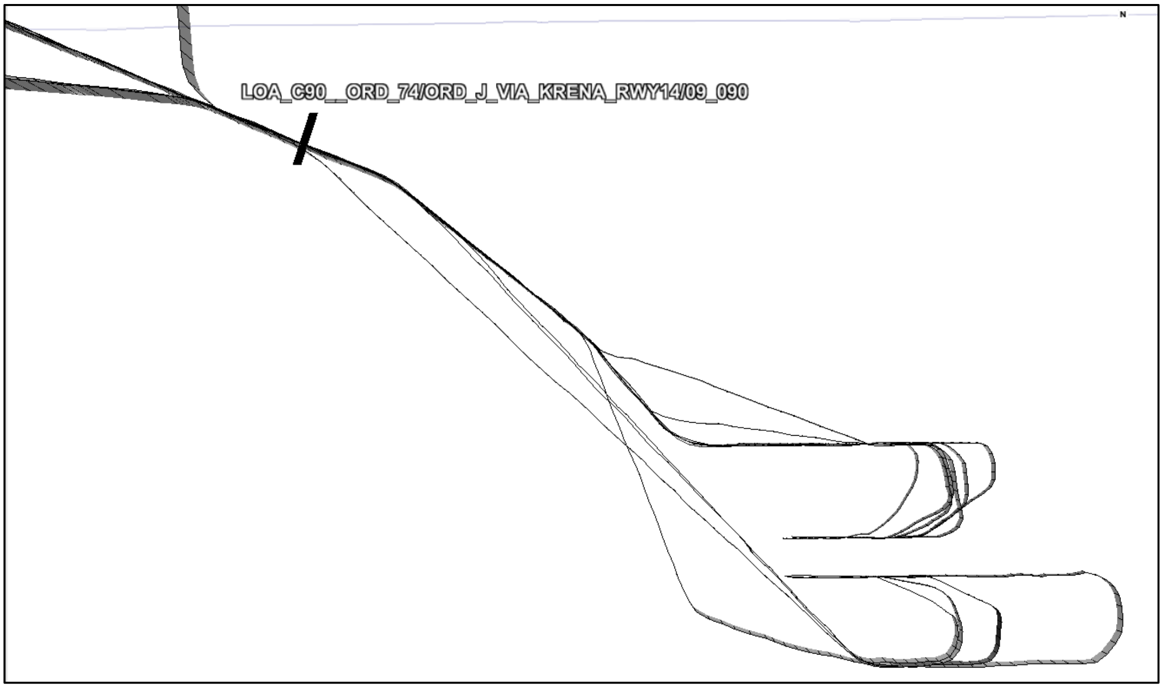

Figure 15. Example 3: miss (temporal only), top down view.

All of these flights were given interim altitude clearances for FL 110 prior to approaching the restriction, and thus the restriction stops being modeled well before the flights breach the 2.5 NM boundary. 80% of the Miss data for this restriction has a vertical distance between 1100 ft. and 2100 ft. The flights are all following their clearances, so it is possible that the restriction altitude (FL 090 to FL 110) or qualifier (‘at_altitude’ to ‘at_or_above’) need to be adjusted to reflect controller intent and improve ACT modeling/CP performance. This restriction appears in Figure 5, Figure 7, and Figure 9 with a rounded percentage of 0 in each case, suggesting that the utility of the metrics used is promising.

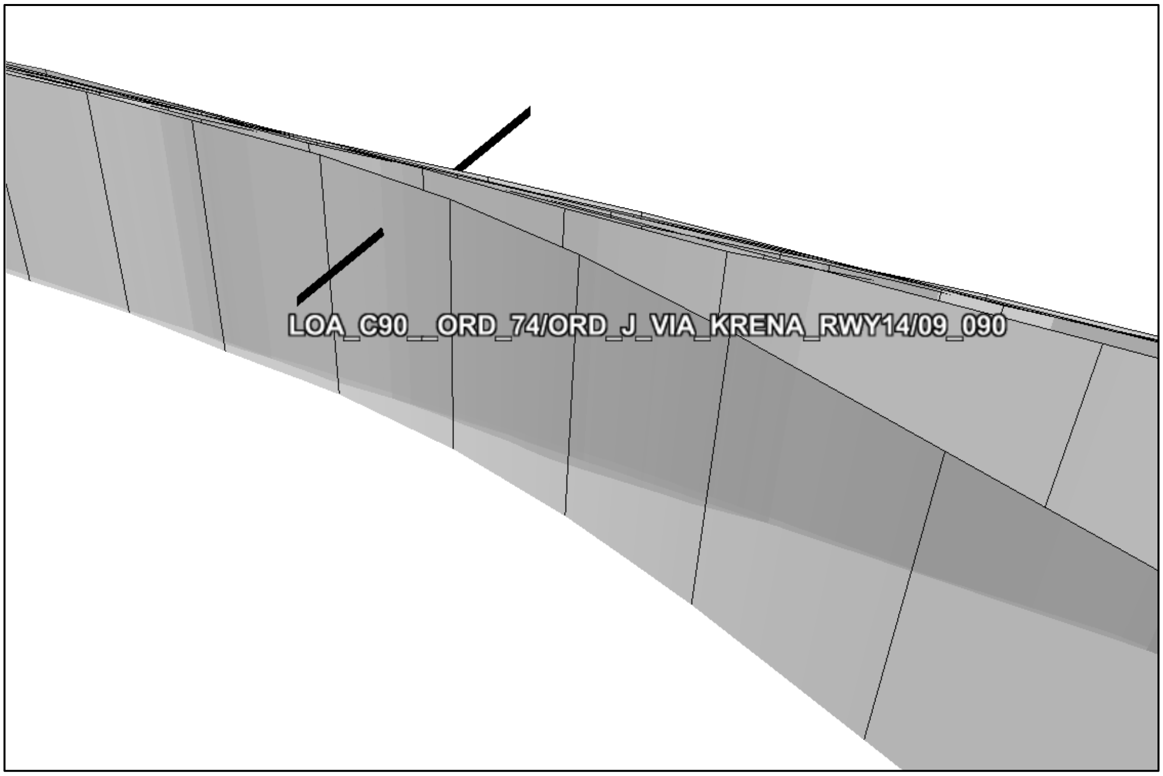

Figure 16. Example 3: miss (temporal only), side view.

4 Conclusions and Future Work

Restrictions are intended to support the controller by allowing the automation to capture behaviors specified in Letters of Agreement (LOAs), Standard Operating Procedures (SOPs), and other sources when building trajectories. They represent preliminary intent information that has not yet been entered by a controller and are not clearances. However, as part of the ERAM adaptation, restrictions serve an important function by directing trajectory modeling based on future controller intent that cannot be easily entered into the automation on a per flight basis. They can be useful if properly modeled, but if restrictions do not match the reality of where flights go, they can have a negative effect on the automation performance. When these airspace restrictions do not reflect controller and pilot intent, inaccurate predicted trajectories may result, particularly during the arrival phase of flights. Inaccurate trajectories can cause considerable degradation in the ERAM Conflict Probe, resulting in invalid or unwanted alerts.

This study provides a methodology that applies metrics to identify, through minimal effort, restrictions where the observed paths do not match the adaptation definition in either the Flight Plan Trajectory domain, the Aircraft Trajectory domain, or across both domains. Metrics based on horizontal, vertical, and temporal distances are defined in order to implement this categorization process, with details provided in Section 2.2. The empirical data for this study was collected from two ARTCCs, Chicago (ZAU) and Boston (ZBW). Two 24-hour periods of traffic for each center were collected and processed using the methodology detailed in this paper. A detailed analysis of this data was performed in order to make inferences about the restrictions modeled in ERAM.

The first metric presented is Hit percent which is defined in Section 3.1 and represents how often a restriction is met given that it is modeled in the trajectory of interest (i.e., the trajectory that is active when the reported point occurs). A restriction is considered to be met when the track passes through the restriction spatially (within defined thresholds) and the restriction is being modeled in the associated trajectory. Low hit percent values indicate that a restriction was often modeled but not flown. The results illustrated in Figure 5 and Figure 6 for the ZAU and ZBW scenarios show that Flight Plan trajectories tend to have a higher hit percent than Aircraft trajectories. This may be explained by the fact that Flight Plan trajectories tend to be more stable and are rebuilt less often; as a result a restriction is more likely to persist on a Flight Plan trajectory than an Aircraft trajectory.

The second metric presented is Spatial Only percent which represents the proportion of spatial hits that are not met temporally (i.e., that occur when the trajectory of interest does not model the restriction). High spatial only percentages indicate that at the time a restriction is hit it is often not being modeled in the active trajectory. Many of these cases could be due to interim altitude clearances or other reasons for removing or not modeling restrictions. The results illustrated in Figure 7 and Figure 8 for the ZAU and ZBW scenarios show that Aircraft trajectories tend to have a higher spatial only percent than Flight Plan trajectories. This may be explained by the fact that interim altitudes, which are common during departures and arrivals, may result in Aircraft trajectories being rebuilt but do not impact Flight Plan trajectories due to the current design and desire for stability.

The third metric combines these concepts to present the overall usage of a restriction by providing the proportion of instances where a restriction is met over all sampled data points. This metric indicates whether a restriction matches the behavior commonly observed in the track data. Significant discord between the observed behavior and the restriction definition points to possible TM and CP degradation, and these restrictions are good candidates for revision. For example, restriction LOA_C90__ORD_74/ORD_J_VIA_KRENA_RWY14/09_090 in ZAU, which is described in Flight Example 3, has an overall usage percent of zero in both Flight Plan and Aircraft trajectory domains and so is represented at the point (0, 0) in Figure 9. There are also several restrictions in ZBW with low overall usage percent, represented in the lower left corner of Figure 10.

Overall, the three metrics above provide quantitative evidence on the usage of the airspace restrictions for a particular ARTCC and adaptation chart cycle based on a data sample of traffic. These methods illustrate that the majority of the restrictions are modeled and flown. However, it also shows many instances where the restriction is infrequently or never flown as defined in the adaptation. These cases should be investigated further.

The metrics and methodology presented identifies these potentially problematic airspace restrictions. Since the *TBO Separation Standards Modern Procedures Project* is focused on improving the performance of ERAM's conflict probe, it is of particular importance to quantify the negative impact that any errors associated with airspace restrictions have on ERAM's trajectory and conflict predictions. The analysis in Section 3.2 compared the accuracy of aircraft and flight plan trajectories including restrictions that were met versus trajectories with restrictions that were not flown (i.e. missed). When airspace restrictions are not met as defined in the adaptation, the average vertical trajectory error near the restriction increases by 3,000 and 2,000 feet in ZAU and ZBW, respectively. These errors can cause multiple trajectory rebuilds when the radar surveillance track falls outside the standard adherence bounds. The work in Paglione and Oaks [2009] and subsequent studies have clearly shown that increases in trajectory accuracy will improve the accuracy of the Conflict Probe. Thus, identifying and then correcting these potentially problematic airspace restrictions will improve ERAM's performance. The methodology documented in this paper is designed to be extended to any ARTCC facility utilizing ERAM.

5 References

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Paglione, M. M. and Oak, R. D., “Effectiveness of Pairing Flights When Evaluating the Accuracy of a Conflict Probe” AIAA Guidance, Navigation, and Control Conference, Chicago IL, August 2009.

Schnitzer, B. S., Fabian, A., Young, C. M., Yao, C., “Evaluation of an ERAM Prototype to Improve Restriction Modeling by Refining Altitude Transition Rate Logic,” DOT FAA Technical Note DOT.FAA/TC-TN13/42, September 2013.

Appendix A: ZAU

RESTRICTION_NAME	TotalN	N Rows ACT	Hit% ACT	Miss% ACT	SpatialOnly% ACT	HitSpatial ACT%	N Rows FPT	Hit% FPT	Miss% FPT	SpatialOnly% FPT	HitSpatial% FPT%
ZAU_C90_DEPT/81_AOB_150	1711	877	80	20	1	81	834	77	23	0	77
LOA_C90_35/C90_J_HULLS_120	1078	564	50	50	99	99	514	99	1	16	99
ZAU_C90_DEPT_C90/44_D_150	967	431	51	49	1	51	536	39	61	1	39
LOA_C90__ORD_74/ORD_J_VIA_KRENA_RWY14/09_090	776	403	0	100	0	0	373	1	99	0	1
SOP_ORD_25/26_A_RHIVR_200	760	371	40	60	98	98	389	84	16	10	85
SOP_ORD_74/74_A_TEDDY_A_110	689	355	81	19	96	99	334	96	4	7	97
SOP_ORD_34/32_A_AOB_240	579	298	54	46	90	92	281	85	15	20	88
LOA_C90_ORD_51/ORT_J_VIA_TRTLL_AOB_110	514	262	40	60	98	98	252	94	6	7	94
LOA_C90_ORD_51/ORT_J_VIA_BENKY_AOB_120	494	260	100	0	99	100	234	99	1	19	100
LOA_C90_ORD_S_SAT_50/ORD_A_060	486	254	13	87	99	95	232	91	9	35	94
LOA_C90__ORD_26/ORD_J_VIA_WYNDE_100	475	63	33	67	98	97	412	13	87	2	14
LOA_ZID__ORD_ZID/34_J_VIA_MZZ_260	473	248	0	100	100	96	225	11	89	99	92
LOA_ZOB__ORD_ZOB/25_A_VIA_LTOUR_320	430	225	X	X	100	100	205	0	100	100	100
ZAU_C90_ZAU/ORD_VIA_WATSN_AOA_110	416	328	35	65	8	37	88	29	71	35	39
LOA_SBN_MDW_35/SBN_A_AWSUM_100	383	194	93	7	26	95	189	92	8	1	92
LOA_SBN_MDW_35/SBN_A_MEGGZ_110	361	176	78	22	96	99	185	89	11	4	89
SOP_ORD_74/74_A_BHAWK_AOB_230	291	73	0	100	100	97	218	25	75	22	30
SOP__ORD_52/51_A_240	282	120	0	100	100	99	162	52	48	32	61
ZAU_C90_S_SAT_DEPT_C90/77_D_150	280	147	94	6	2	95	133	93	7	0	93
SOP_DTW_34/36_A_VIA_FWA10DME_240	265	119	0	100	100	98	146	71	29	25	77
SOP_ORD_52/58_AOA_MAROC_240	253	155	100	0	96	100	98	97	3	35	98
ZAU_MKE_DEPT_C90/62_AOA_160	240	124	89	11	37	93	116	92	8	6	92
SOP_ORD_91/91_DRAMS_AOB_340	234	125	0	100	100	98	109	86	14	70	95
LOA_SBT_C90_MDW/32_AOB_100	205	112	87	13	22	89	93	88	12	0	88
LOA_SBN_MDW_32/SBN_A_FISSK_110	202	108	X	X	100	100	94	95	5	8	96
LOA_ZID__MDW_ZID/34_A_240	196	106	X	X	100	100	90	0	100	100	98
LOA_ZOB__MDW_ZOB/36_A_300	196	103	0	100	100	96	93	0	100	100	96
SOP__ORD_S_SAT_36/36_A_VIA_GSH25DME_240	182	78	0	100	100	99	104	60	40	30	68
SOP_ORD_91/91_VINCA_AOB_340	179	91	X	X	100	100	88	79	21	73	93
LOA_ZID__DTW_ZID/34_A_330	168	84	0	100	100	92	84	0	100	100	92
LOA_ZOB__DTW_DEPT_ZOB/25_A_EXC_CHI_MTA_VIA_J70_320	165	81	96	4	10	96	84	87	13	1	87
LOA_MKE_MKE_27/MKE_A_VIA_BAE55DME_140	164	79	100	0	96	100	85	88	12	5	88
LOA_ZKC_ORD_ZKC/91_AOB_370	136	73	0	100	100	95	63	0	100	100	92
SOP_ORD_SAT_55/51_J_VIA_BDF_150	134	29	0	100	100	79	105	14	86	22	17
LOA_ZID__ORD_ZID/36_J_VIA_FWA_340	120	61	0	100	100	95	59	0	100	100	95

RESTRICTION_NAME	TotalN	N Rows ACT	Hit% ACT	Miss% ACT	SpatialOnly% ACT	HitSpatial ACT%	N Rows FPT	Hit% FPT	Miss% FPT	SpatialOnly% FPT	HitSpatial% FPT%
ZAU_MKE_SAT_MSN/64_A_100	116	60	94	6	16	95	56	95	5	2	95
ZAU_C90_S_SAT_DEPT_C90/43_D_150	111	61	97	3	3	97	50	98	2	2	98
LOA_ZKC_ORD_SAT_ZKC/52_AOB_310	100	55	0	100	100	87	45	38	63	93	89
SOP_MDW_36/37_A_240	100	50	0	100	100	96	50	79	21	67	92
ZAU_GRT_MGT/22_AOB_100	100	52	36	64	40	48	48	46	54	0	46
ZAU_MST_64/74_AOA_110	95	50	89	11	49	94	45	90	10	33	93
SOP__DTW_60/23_A_330	92	48	0	100	100	92	44	0	100	100	89
LOA_MST_MKE/64_AOB_110	90	45	X	X	100	100	45	69	31	78	91
SOP_MKE_47/83_A_330	85	43	0	100	100	95	42	56	44	87	90
SOP_UGN_83/81_A_240	84	32	0	100	100	97	52	43	57	36	54
LOA_ZOB__ORD_ZOB/36_A_VIA_OXI_340	83	43	0	100	100	95	40	0	100	100	95
LOA_ZID_ORD_SAT_ZID/36_J_VIA_FWA_300	82	42	0	100	100	95	40	0	100	100	95
SOP_ORD_SAT_58/51_J_PIA25DME_170	81	20	0	100	100	90	61	23	77	7	25
LOA_C90_32_LOOTH_AT_110	80	39	0	100	100	95	41	58	42	67	80
ZAU_ORD_74/RFT_AOB_100	80	39	75	25	10	77	41	64	36	7	66
ZAU_ZOB_GRR_ZOB/GRR_J/T/P_AOB_100	78	42	73	27	46	83	36	79	21	7	81
ZAU_IND+_57/IND_AOB_130	73	38	100	0	71	100	35	100	0	40	100
ZAU_KCID_DEPT/55_AOB_100	68	35	100	0	0	100	33	100	0	0	100
LOA_MKE__MKE_74/MKE_J_VIA_VEENA_100	66	32	50	50	93	94	34	79	21	0	79
SOP_ORD_SAT_58/51_J_PNT10DME_170	66	23	0	100	100	70	43	29	71	8	30
ZAU_GRT_AZO/22/80_AOB_100	63	33	74	26	50	85	30	79	21	8	80
SOP__CMH_36/36_A_VIA_FWA_240	60	30	0	100	100	57	30	12	88	87	50
LOA_C90_35/ORD_J_ESSPO_AT_120	59	3	0	100	100	67	56	2	98	50	4
SOP_C90_52/55_58_A_VIA_BDF_MOTIF_STAR_50_WBDF_240	59	6	0	100	100	50	53	2	98	67	6
SOP_ORD_S_SAT_75/92_A_VIA_CVA_240	59	30	X	X	100	100	29	92	8	61	97
ZAU_PWK+_DEPT_C90/43_AOB_150	59	25	36	64	0	36	34	26	74	0	26
ZAU_MKE_SAT_C90_2/ZAU_AOA_160	58	45	100	0	98	100	13	100	0	77	100
SOP__ORD_SAT_52/52_A_BDF30DME_240	44	10	0	100	100	80	34	4	96	88	24
ZAU_MKE_SAT_C90/ZAU_AOA_160	36	4	X	X	100	100	32	13	88	0	13

Appendix B: ZBW

RESTRICTION_NAME	TotalN	N Rows ACT	Hit% ACT	Miss% ACT	SpatialOnly% ACT	HitSpatial ACT%	N Rows FPT	Hit% FPT	Miss% FPT	SpatialOnly% FPT	HitSpatial FPT%
BOS_34/BOS_J_KRANN_110	625	254	100	0	99	100	371	54	46	47	69
BOS_19/34_J_230	610	304	X	X	100	100	306	60	40	99	99
BOS_ZNY/19_J_VIA_ORW_270	543	270	0	100	100	100	273	0	100	100	99
CYUL_DEPTS_TO_52	348	172	94	6	2	94	176	93	7	5	94
JFK_46/32_J_VIA_TRAIT_240	308	154	X	X	100	100	154	100	0	45	100
EWR_05/N90_J_070	294	119	0	100	100	73	175	16	84	82	51
BDL_19/BDL_A_MAD_110	268	133	0	100	100	96	135	92	8	36	95
EWR/SATS_V489_A_070	253	124	0	100	100	83	129	61	39	60	80
BDL_ZNY/19_A_VIA_DPK_190	245	122	100	0	99	100	123	100	0	99	100
HPN_BOUNO_ZNY/32_J_DPK_AT_150	234	115	0	100	X	0	119	0	100	X	0
EWR_21/05_A_160	216	101	X	X	100	100	115	33	67	99	98
EWR_39/22_A_ALB25DME_240	212	102	4	96	97	57	110	32	68	60	55
BDL_21/07_A_140	194	97	X	X	100	100	97	100	0	57	100
LGA_24/06_J_190	193	97	X	X	100	100	96	100	0	99	100
HPN_BOUNO_ZNY/32_J_GWENY_AT_100	192	95	27	73	28	34	97	33	67	0	33
BDL_ZNY/19_A_BDL_AOA_070	178	100	97	3	3	97	78	97	3	53	99
PVD_32/PVD_A_110	175	77	X	X	100	100	98	78	22	4	79
MHT_36/MHT_J_VIA_MHT25DME_090	156	75	75	25	96	99	81	85	15	46	91
EWR/LGA_47/07_A_BDL_160	150	67	0	100	100	99	83	25	75	99	96
INTERIM_DEPT_PVD_OVER_PUT_100	136	62	0	100	X	0	74	0	100	X	0
BDL_07/BDL_A_VIA_BDL30DME_110	131	59	100	0	97	100	72	62	38	64	82
PWM_16/PWM_A_VIA_NEETS_110	130	57	50	50	98	98	73	67	33	39	77
ISP_ZNY/32_A_090	114	57	X	X	100	100	57	X	X	100	100
LGA_21/06_J_180	113	56	0	100	100	68	57	10	90	95	67
BOS_NSAT_47/BDL_A_VIA_GASSE_050	101	50	98	2	10	98	51	96	4	0	96
JFK_ZNY/19_A_DEPT_270	94	47	80	20	5	81	47	80	20	5	81
LGA_SAT_HPN_ZOB/10_A_330	94	47	X	X	100	100	47	X	X	100	100
BOS_16/BOS_J_CROSS_BOS37DME_110	92	45	X	X	100	100	47	80	20	82	96
BOS_NSAT_47/BDL_A_VIA_DVANY_110	92	40	0	100	100	98	52	57	43	56	75

RESTRICTION_NAME	TotalN	N Rows ACT	Hit% ACT	Miss% ACT	SpatialOnly% ACT	HitSpatial ACT%	N Rows FPT	Hit% FPT	Miss% FPT	SpatialOnly% FPT	HitSpatial FPT%
EWR_17/46_A_280	91	45	X	X	100	100	46	100	0	93	100
ALB_22/ALB_A_ALB30DME_110	90	42	0	100	100	98	48	78	22	39	85
BOS_SAT_19/47_A_VIA_HFD_150	85	42	X	X	100	100	43	93	7	69	98
ALB_D_S22_SOUTHBOUND_ABOVE_170	84	42	90	10	31	93	42	92	8	15	93
ISP_N90/32_RICED_070	83	39	X	X	100	100	44	74	26	64	89
ALB_06/21_A_150	76	38	X	X	100	100	38	100	0	24	100
N90_DEPTS_TO_ZDC_ABOVE_240	76	36	15	85	38	22	40	23	77	10	25
JFK_10/20_J_290	74	37	X	X	100	100	37	X	X	100	100
ALB_ZNY/19_J_VIA_V487_240	70	36	X	X	100	100	34	100	0	97	100
PVD_ZNY/31_A_VIA_J62_270	60	30	0	100	100	93	30	0	100	100	93
EWR_23/05_T/P_150	59	28	0	100	100	7	31	0	100	100	6
ALB_21/ALB_A_ALB30DME_110	58	20	64	36	56	80	38	37	63	19	42
MHT_38/22_J_EEN55DME_240	58	22	0	100	100	82	36	25	75	67	50
PVD/ISP_47/34_A_WIPOR_11	58	28	X	X	100	100	30	91	9	25	93