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Measuring Performance of Initial Ground-based Interval Management – Spacing (GIM-S) Operations

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***Abstract*— The Time-Based Flow Management (TBFM) automation system provides scheduling and scheduling-management tools to Air Traffic Control (ATC) to support time-based metering operations. Time-based metering is used to develop an orderly and efficient flow of traffic in en route airspace to coordinate delivery to the terminal. Recent enhancements to TBFM include the introduction of Ground-based Interval Management–Spacing (GIM-S). GIM-S introduces three new functions to improve time-based metering operations: extended metering, coupled scheduling, and speed advisories. The expected benefits of GIM-S include increased meter point delivery accuracy, reduced vectoring, and increased use of Performance Based Navigation (PBN) procedures. These benefits are expected to translate into more consistent and predictable arrival operations for air carriers. This paper presents a methodology for assessing the impact of GIM-S operations relative to the aforementioned benefits. Results indicate that time-based metering operations are improved with the use of GIM-S; however, the varied and inconsistent use of GIM-S between en route facilities reduces the data available for review and reflects operational models that are not necessarily consistent with the envisioned use to maximize benefits.**

Keywords-GIM-S; Interval Management; time-based metering; delivery accuracy; Performance Based Navigation, RNAV procedure conformance; operational performance measurement, schedule predictability

Introduction

The Federal Aviation Administration's (FAA) Time-Based Flow Management (TBFM) system provides scheduling and decision support tool functionality for Air Traffic Control (ATC) to perform time-based metering operations, which aid ATC in managing air traffic into congested airspace. TBFM integrates departure and arrival traffic demand to provide unified and efficient flows of traffic into and out of the terminal during high-density operations. The TBFM system uses trajectory modeling functions to build a sequence and schedule of aircraft joining an arrival flow and provides a time schedule at meter reference points (MRPs). The sequence is generated on a first-come, first-served basis and an aircraft's schedule at an MRP is frozen when the aircraft crosses the freeze horizon, usually specified as an arc located an adapted distance upstream of an MRP. In high-density operations, some aircraft may need to be "delayed," where their nominal flight times are increased through speed changes or vectoring (i.e., path length changes), to ensure adequate spacing with other aircraft at merge points. TBFM sends the necessary display elements to the En Route Automation Modernization (ERAM) platform which manages the display to ATC.

Recent enhancements to TBFM include the introduction of Ground-based Interval Management-Spacing (GIM-S), which provides three additional functions to enhance time-based metering operations and more efficiently pre-condition arrival flows to enable the more consistent use of Performance-based Navigation (PBN) arrival procedures. The first two functions, extended metering and coupled scheduling, enable the adaptation of multiple MRPs upstream of an arrival meter fix at the en route/terminal boundary. These MRPs, referred to as Extended Meter Points (XMP) and Coupled Meter Points (CMP), allow delay absorption and sequencing to begin earlier in the arrival flow and prior to top of descent. The XMP and CMP are optional points within an arrival flow metering design and enable different design characteristics. For example, the sequence at the CMP is designed to match the sequence at the meter fix, however the sequence at the XMP may not match the sequence at the CMP or meter fix. These MRPs can be strategically placed to break out delay allocation into numerous airspace regions and shorten freeze horizons to help reduce uncertainties in an aircraft's estimated time of arrival (ETA) at an MRP.

The third function, speed advisories, suggests airspeeds that ATC can provide to an aircraft to help meet its frozen scheduled time of arrival (STA) at an MRP. Spacing intervention through speed changes in the cruise phase of flight can be more fuel efficient than vectoring an aircraft off its charted route during the descent phase of flight. The TBFM-computed speed advisories are designed to deliver aircraft more consistently to the MRP at their scheduled times and reduce vectoring.

Figure 1 shows a generic depiction of arrival operations with and without GIM-S functionality. Prior to GIM-S, Miles-in-Trail restrictions may be used to restrict the flow rate of aircraft. Controllers would use standard control procedures such as vectors, holding, or speed instructions to ensure aircraft were at least the specified number of miles behind preceding aircraft. With GIM-S, multiple MRPs can be adapted and allocated delay, and speed advisories can be used to meet the STA at each MRP. For example, during a busy traffic push, an aircraft may need to be delayed five minutes in order to meet the sequence and schedule of an arrival flow. GIM-S could be adapted to allocate two minutes of delay to be absorbed between the XMP freeze horizon and the XMP, two minutes between the CMP freeze horizon and the CMP, and the remaining one minute between the meter fix freeze horizon and the meter fix. The freeze horizon defines the location at which the schedule for a particular MRP is frozen. The TBFM schedule is designed to always add delay when needed to meet the spacing constraints at an MRP. This effectively freezes aircraft ahead of schedule such that it is easier to absorb delay through speed or vectors rather than putting some aircraft behind schedule in a position where they would have to increase their speed to meet the schedule.

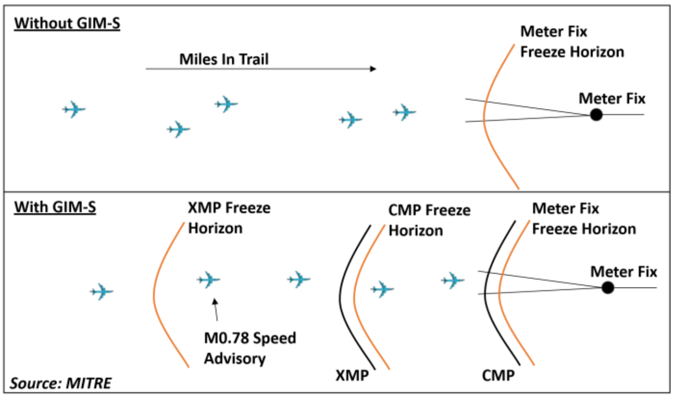

Figure 1. Generic depiction of arrival operations with and without GIM-S functionality.

The GIM-S Initial Operating Capability (IOC) was achieved on September 22, 2014. Albuquerque Center (ZAB) was selected as the GIM-S key site for arrival metering into Phoenix Sky Harbor International Airport (KPHX) via the EAGUL6 Area Navigation (RNAV) Standard Terminal Arrival (STAR). In March 2015, GIM-S was expanded to support arrivals into KPHX via the PINNG1 RNAV STAR. In August 2015, Denver Center (ZDV) begin supporting adjacent center metering (ACM) using the GIM-S extended metering functionality to support the EAGUL6 arrival flow. GIM-S has also been deployed for arrival flows into KDEN and KSEA as shown in Figure 2. Efforts are on-going to fully transition use of GIM-S at those sites.

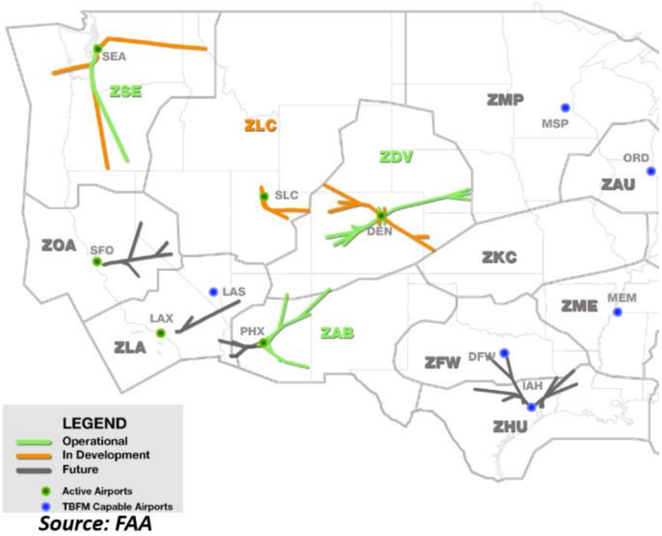

Figure 2. GIM-S arrival flow implementation map.

EXPECTED IMPACTS OF GIM-S

The GIM-S functions are intended to increase adherence to PBN arrival procedures, allowing aircraft to fly more efficient trajectories into the terminal area without requiring costly vectoring. At low traffic densities, GIM-S helps ATC pre-condition traffic prior to top of descent, clear the aircraft for the PBN arrival procedure, and allow the aircraft to continue without intervention into the terminal [1]. As traffic density increases, automation tools are needed to assist the controller in identifying a sequence and schedule for the arrival flow and to assist in managing the aircraft to their STAs. Reference [2] presented a model to determine the delivery accuracy needed at MRPs to enable aircraft to remain on their PBN procedures. Applying it to operations at KPHX showed that a 15-second standard deviation in the delivery accuracy would be needed. Reference [3] explored the benefits of time-based metering to improve aircraft delivery to the meter fix and how that delivery accuracy relates to trajectory management in the terminal. Using a model of Atlanta's Hartsfield-Jackson International Airport, they showed that aircraft must be delivered to the meter fix with a standard deviation of 10 seconds to avoid vectoring in the terminal and to maintain the maximum throughput. Several other references on earlier, but similar, time-based metering concepts also show the relationship between accurately pre-conditioning arrival flows and the ability to allow aircraft to remain on their planned routes [4-8].

GIM-S speed advisories and the Delay Countdown Timer (DCT), which displays the difference in an aircraft's ETA and its STA at an MRP, help controllers manage aircraft to their STAs. The delivery accuracy is a function of the ETA accuracy [9], and the frequency with which ATC issues corrective actions. For example, issuing a single speed advisory when the aircraft is 400 NM from the MRP may lead to poor schedule conformance due to the errors in the ETA at the time the speed advisory was calculated. As previously mentioned, extended metering breaks the longer arrival metering operation into smaller distances to limit ETA errors that result in inefficient operations. Coupled scheduling enables the distribution of schedule delays across MRPs [10].

While the performance of the GIM-S functions within TBFM are important to yield the anticipated benefits, the delivery performance at the meter fix is also important for ensuring the success of future operational concepts like Terminal Sequencing and Spacing (TSAS) and Interval Management (IM). TSAS enables metering operations to continue into terminal airspace. Arrival flows across the meter fixes need to meet their STAs within 30 seconds, 95% of the time (i.e., a 15-second standard deviation), to support the merging of flows within the terminal. Without precise delivery to the meter fix, terminal controllers may need to take action, including vectoring aircraft off of their planned arrival routes, to manage merging flows [11, 12]. IM, a future concept enabled by flight-deck avionics that provide speed guidance to help a flight crew in achieving and maintaining a relative spacing interval from another aircraft, also relies on flows being pre-conditioned prior to initiating IM Operations [13].

Improved delivery accuracy to MRPs as enabled by GIM-S is also expected to lead to more consistent and predictable flight operations. When aircraft consistently arrive close to their STAs, their flight times in the airspace become more predictable. Reference [14] suggests that improved schedule predictability can enable a reduction in airline resources needed to meet flight schedules and a reduction in passenger travel time scheduled to accommodate delays. Reference [15] also suggests increased flight time predictability can aid airlines in improving scheduling and making more accurate fuel loading decisions. Their work used an empirical model to estimate how predictability impacts air transportation service providers operational scheduling decisions. Results suggest that airlines are willing to accept outlier delays in order to realize the efficiency benefits of shorter scheduled flight times. In other words, reducing the variance in the distribution of flight times is more important than reducing the average of flight times.

DEVELOPING A METHODOLOGY TO MEASURE GIM-S IMPACTS

Measuring the impact of initial GIM-S operations will help inform the continued deployment of GIM-S and other time-based metering applications. This analysis focuses on measuring operational performance against the expected benefits of GIM-S operations. Lessons learned from these results may help adjust or optimize GIM-S designs at existing sites. The results may also help focus operational design and local adaptation priorities at future implementation sites. Results can also inform whether pre-conditioning of an arrival flow is sufficient to support terminal metering applications.

Initial Considerations for Measuring Performance

The GIM-S adaptation design reflects a facility's operational objectives within the framework of the TBFM system's functional constraints. For example, the distance between freeze horizons and MRPs, or the use of extended metering may be different across sites or may even change over time at the same site. To ensure analysis extensibility across sites, an individual site's adaptation variables should be separated from how performance is quantified. In other words, site-specific adaptation parameters should be inputs to generic functions from which a set of common metrics may be quantified. As GIM-S is deployed to additional arrival flows, the same functionality used to measure GIM-S performance can be applied in the context of a given GIM-S design. In this way, the core metrics and the means to assess those metrics remain the same in order to track changes and trends over time. As new sites are deployed or existing sites are updated, the adaptation variables can be updated without modifying the metrics to enable consistent measurement across sites. Additionally, these metrics may remain applicable as future metering operations evolve to include the use of TSAS and IM.

Discussions with ATC at a GIM-S site can provide insight into site-specific operational objectives and their use of time-based metering and GIM-S functionality, which can aid in determining any unique performance metrics that should be quantified, and aid in interpreting the findings.

Data Sources Used to Measure Performance

Two sources of data are used to measure GIM-S performance. Track data from individual flights is used to measure flight behavior in order to obtain metrics such as procedure conformance and vectoring. Track data was obtained from MITRE's Threaded Track database, which is a data integration project that fuses surveillance sources into a synthetic time referenced, three-dimensional track. The Threaded Track data is composed of position reports for each flight. In most airspace, the Threaded Track data has position updates once every 4-5 seconds, based on updates from multiple radars. Each report contains data on the aircraft ID (e.g., American Airlines 1255 [AAL1255]), aircraft type (e.g., Boeing 737), latitude, longitude, altitude, and track heading. Due to the large size of this position-time data, the source data is stored in the Hadoop computing architecture. Structured Query Language (SQL)-like queries were developed to access the track data relevant to GIM-S operations.

The other source of data is TBFM data, which can be used to indicate which flights are associated with GIM-S operations. TBFM data was obtained from TBFM Inter-process Communication messages. These messages log TBFM-generated data elements such as STAs and observed crossing times, or Actual Times of Arrival (ATAs), at meter points. This data is then used to evaluate the delivery accuracy, which is the difference in an aircraft's ATA and its STA, at an MRP. The messages also log TBFM-proposed speed advisory messages and log when a controller accepts a speed advisory.

Proposed speed advisory data is grouped into one of four possible states:

- "A" Available: Indicates TBFM has calculated a speed that will solve the current meet-time error (i.e., the difference in the ETA and STA). This is the proposed speed that can be displayed to the controller.
- "N" No Speed Advisory Available: Indicates TBFM cannot find speeds that will successfully solve the current meet-time error, or when TBFM detects the aircraft is in a vertical transition.
- "T" No Speed Advisory Required: Indicates the aircraft does not have a meet-time error that exceeds an adapted threshold (e.g., if the adapted threshold is 30 seconds, meet-time errors less than 30 seconds will not generate speed advisories).
- "D" Delete: This message is typically generated when the aircraft crosses the MRP.

An ACCEPT message is logged only when the controller presses the accept button through the controller's display menu to accept an Available speed advisory. This does not necessarily mean the speed was communicated to and implemented by the flight crew. Audio tapes of the controller-pilot communications would be needed to verify a speed was implemented.

GIM-S Performance Metrics

Based on research into expected performance impacts, four metrics were developed to assess changes to operations and benefits that may be observed with the use of GIM-S functionality. These metrics include:

I. rate of vectoring in the en route airspace prior to top of descent,

II. rate of lateral conformance to arrival procedure routes,

III. delivery accuracy relative to the frozen scheduled time of arrival at the MRPs, and

IV. flight time between XMP freeze horizon and arrival meter fix.

En Route Vectoring Metric

The vectoring metric is used to identify flights that have deviated from their intended flight paths. Most aircraft flying through the airspace between the extended meter arc freeze horizon and extended meter arc will fly a straight path. Some aircraft make a single turn, likely indicating the aircraft is flying to a defined waypoint and making an intended course change along their flight path. Other aircraft make multiple turns, commonly indicative of a deviation from their intended flight path, and often termed an "ATC vector." During a vector, the first turn is away from the intended flight path and the second turn is back towards the intended flight path. This series of turns is often used by ATC to lengthen the flight path of the aircraft as a way to slow the aircraft down in relation to its STA or to help deconflict with another aircraft to meet a miles-in-trail restriction or time-based metering scheduling objective.

Originally, an algorithm was developed to look for these vectors by comparing the straight-line distance between the freeze horizon and meter arcs to the actual distance flown by aircraft. When this difference exceeded 3 NM, the flight was categorized as vectored. However, this method did not account for single turns or changes in headings towards waypoints. Therefore, flights following their navigation path and making intentional course changes at a waypoint were classified as vectors. Flight plan information could be used to identify intentional course changes; however, due to the dynamic nature of a flight plan and the extensive logic that would be required to map a flight plan to a track, a simpler solution was used. An algorithm was developed to detect turns based on changes to the aircraft's ground track. In this way, flights could be classified as straight flights, flights with a heading change, or flights with multiple turns (i.e., vectored flights). Example tracks are shown in Figure 3.

The vectoring algorithm utilizes a series of steps to determine a flight's vectoring status. Specifically, the algorithm looks for changes in the aircraft's ground track relative to its most recent ground track. To do this, the last 15 ground tracks are averaged on a moving basis and compared to its most recent track. This series of differences is saved and if the local minima or maxima exceeds a certain threshold, that point in the track is considered a turn. Next, the algorithm counts the number of turns between the freeze horizon and MRP. If there are no turns, the flight is considered a straight flight. If there is only one turn, the flight is classified as having a heading change. If there are two or more turns, an extra step is necessary to look for changes in turn direction. A flight that turns consecutively in the same direction is still classified as a heading change. Flights that have consecutive turns in opposing directions, indicative of a turn away from the path and then a turn back to the original path, will be classified as vectored.

The GIM-S functions enable speed advisories to be provided in the en route airspace to help pre-condition the sequence and spacing of aircraft prior to top of descent. These speed advisories are expected to be used in place of vectoring when speed changes alone are sufficient to meet STAs. The results will quantify the rate at which aircraft are vectored in the en route airspace prior to joining their arrival procedure. It is expected that the introduction of GIM-S will reduce the rate of vectoring.

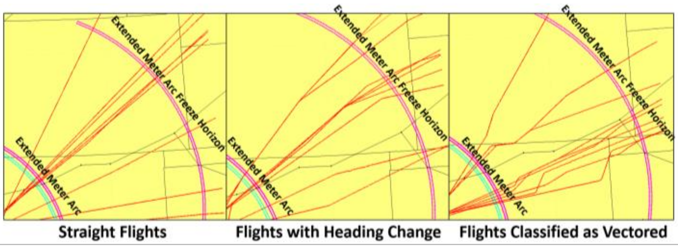

Figure 3. Example flight paths, in red, as categorized by the vectoring algorithm.

RNAV STAR Lateral Conformance Metric

The RNAV STAR lateral conformance metric attempts to identify the rate at which aircraft conform (in the horizontal plane only) to the defined arrival route. Aircraft descending from cruise down to their final approach will typically descend along an RNAV STAR while adhering to speed, altitude, and navigation constraints. Typically, the location of the meter fix or mile-in-trail restriction (prior to metering) is placed at some point along the RNAV STAR. Aircraft that have not been effectively pre-conditioned to meet scheduling and spacing constraints at the meter fix may need to be maneuvered off of the defined RNAV route. This can create extra workload for controllers and flight crews and may result in a less efficient descent trajectory.

To evaluate the RNAV STAR lateral conformance, an aircraft's reported track positions are compared to a 2-NM bound on either side of a straight-line route as defined by the RNAV procedure's waypoint (depicted by the red boundary in Figure 4). If an aircraft's track position exceeded the boundary for at least 10 consecutive positions, then that flight was characterized as deviating from the lateral boundary of the RNAV STAR. The EAGUL procedure is an RNAV1 procedure, so any navigational deviations are expected to be within 1 NM of the geodesic path through the waypoints. Any deviations beyond 2 NM are expected to be the result of vectoring the aircraft for scheduling and spacing constraints.

The radar-based track positions used in this analysis typically have an update rate of 4-5 seconds. To ensure a flight was not classified as a deviation due to a few outlier position reports, a flight had to deviate for at least 10 consecutive position reports to be considered out of conformance.

The GIM-S functions pre-condition the sequence and spacing of traffic prior to joining the RNAV STAR. This is expected to increase the rate at which aircraft will initiate and maintain the STAR without ATC intervention to account for sequencing or spacing problems at the meter fix.

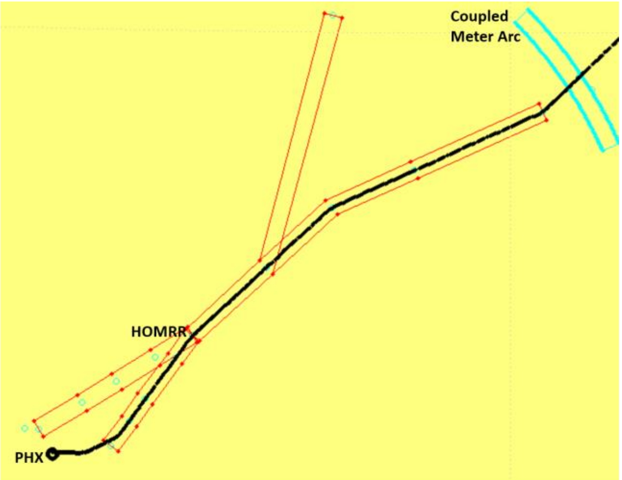

Figure 4. Example flight path, in black, staying within the 2-NM conformance bounds, in red, along the EAGUL RNAV STAR with meter fix HOMRR.

Meter Point Delivery Accuracy Metric

The introduction of GIM-S is expected to improve the precision that aircraft are delivered to the meter fix or an upstream MRP. The meter point delivery accuracy metric quantifies the delivery accuracy at an MRP relative to the TBFM-defined frozen STA. This is computed by subtracting the reported meter fix crossing time from the frozen meter fix STA. Negative times indicate the aircraft arrived late compared to the schedule and positive times indicate the aircraft arrived early compared to the schedule.

Flight Time Metric

The flight time metric simply measures the flight time between two points along the flight path. For the GIM-S analysis, these points are determined when the flight path crosses each GIM-S adapted meter arc and meter fix. For example, the flight time between the XMP and the meter fix is calculated as the difference between the first track point in time that crosses through the XMP and the closest track point in time that flies by the meter fix, as depicted in Figure 5. Due to radar update rates, the first measured track point within the XMP polygon may differ from flight to flight. The measured point is not interpolated to when the nose of the aircraft actually crossed the meter arc.

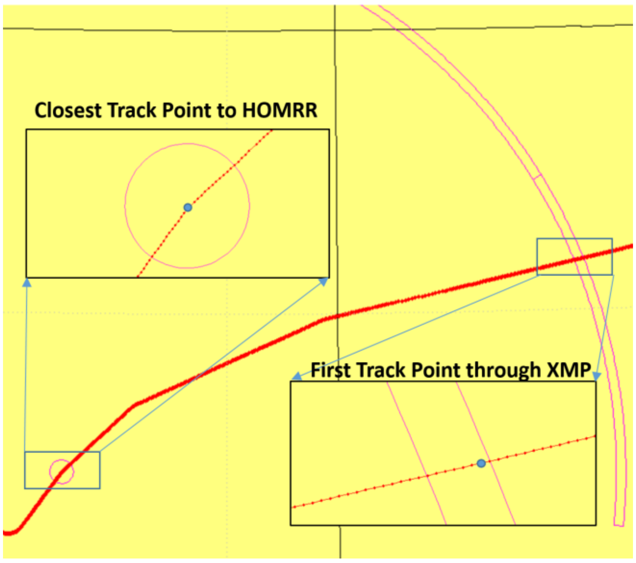

Figure 5. Example flight path, in red, and the associated measurement point for the flight time metric.

Interpreting Findings

Since the metrics are implemented on all flight operations, the results are categorized to enable interpretation.

Each flight will fall into one of the following five groups:

I. Pre-IOC, indicating the set of flights prior to the initial use of GIM-S functionality on an arrival flow.

II. Post-IOC, indicating the set of flights after the initial use of GIM-S functionality on an arrival flow.

III. Post-IOC and GIM-S Off, indicating the set of flights after GIM-S IOC for which speed advisories were not generated.

IV. Post-IOC and GIM-S Available, indicating the set of flights after GIM-S IOC for which speed advisories were available (this includes the states “A” Available, “N” Not Available, “T” Not Required, “D” Deleted, and the Accepted indication as described previously).

V. Post-IOC and GIM-S Accepted, indicating the set of flights after GIM-S IOC for which a speed advisory was generated and accepted by the controller.

This categorization is useful for understanding the impact of GIM-S functionality, the impact of speed advisories, and the impact of accepted speed advisories. It should be noted that categories III, IV, and V are sub-sets of the flights in category II.

Another grouping is based on flights occurring during 1) peak hours, or 2) non-peak hours. An arrival flow typically has multiple distinct ‘rush hour’ time periods each day. For example, at KPHX the facility indicates the peak hours are 7-9am, 11am-1pm, and 530-730pm local time. At KPHX, GIM-S is typically used during these time periods. This categorization enables analysis of similar time periods before and after GIM-S IOC that may have had similar traffic rates.

Flights can also be grouped based on the traffic density of the airspace. In this case, traffic density is measured as the number of aircraft crossing the meter fix in a one-hour time period, starting at the bottom of each hour. Flights are grouped based on the traffic density in the hour of their meter fix arrival. For example, 40-70% traffic density at meter fix HOMRR corresponds to 13-23 arrival aircraft/hour. These groupings enable analysis of time periods before and after GIM-S IOC that may have had similar traffic density.

RESULTS

This section summarizes some of the key findings based on an analysis of the first three arrival flows implemented with GIM-S functionality.

Two arrival flows into KPHX through the HOMRR and BRDEY meter fix have been adapted with GIM-S functionality as shown in Figure 6. Both arrival flows were adapted with an XMP and CMP with speed advisories for those points. Metering is rarely used to either the HOMRR or BRDEY meter fix and GIM-S is not adapted to provide speed advisories when metering is used to these meter fixes. The GIM-S solution into KPHX focuses on pre-conditioning the arrival flow prior to top of descent and puts less emphasis on delivery accuracy into the Terminal airspace.

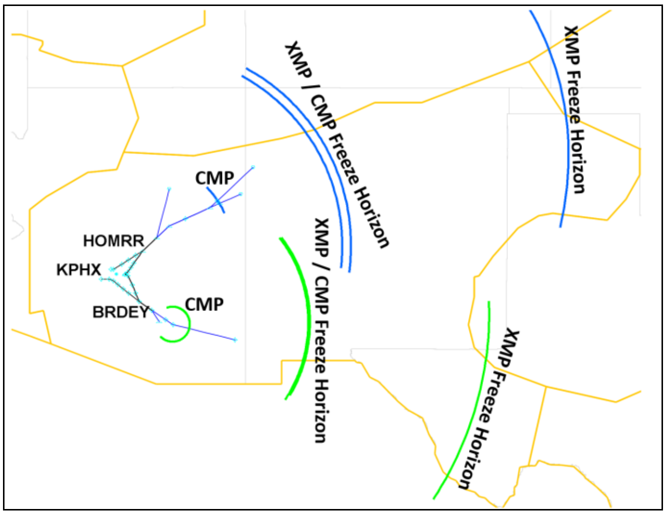

Figure 6. Location of MRPs, arrival procedures, and meter fixes for the two GIM-S adapted flows into KPHX.

The northeast arrival flows into KDEN through the LANDR and SAYGE meter fixes have also been adapted with GIM-S functionality, as shown in Figure 7. Unlike KPHX, this adaptation does not utilize any upstream meter points. A freeze horizon is placed 230 NM upstream of the meter fix, and speed solutions are generated to meet the STA at the meter fix. The GIM-S solution into KDEN focuses on enabling the use of the arrival procedure without vectoring and improving meter fix delivery accuracy.

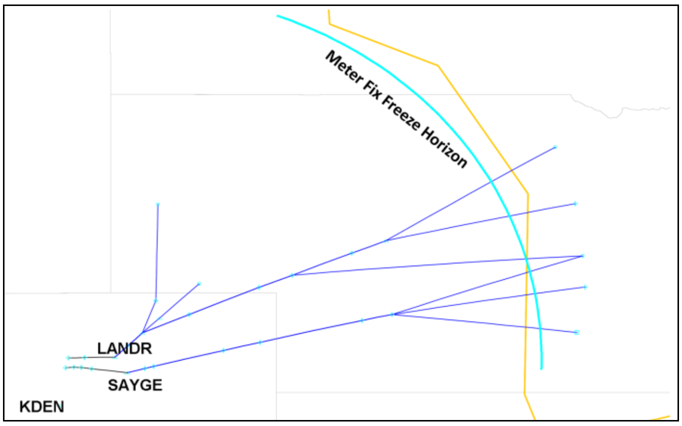

Figure 7. Location of the MRPs, arrival procedures, and meter fixes for the GIM-S adapted flow into KDEN.

Rate of Vectoring Prior to Top of Descent

At KPHX, the rate of vectoring between the XMP FH and XMP appears to be seasonally driven and traffic dependent. Summer months have a higher rate of vectoring largely due to convective weather. As would be expected, busier time periods also translate into increased vectoring because of the need to maneuver aircraft in high-density airspace.

The use of GIM-S reduces the rate of vectoring. Figure 8 shows the vectoring rate trend over time and Table 1 shows the cumulative results by various categories (the values in parentheses specify the number of flights evaluated in each category). Results are shown for flights before and after the GIM-S initial operating capability (IOC). The post-IOC results are also broken down into times when no speed advisories were generated (GIM-S Off), times when speed advisories were made available (GIM-S On), and specifically for the aircraft who accepted a speed advisory (GIM-S On and speed accepted). The data in Figure 8 is limited to peak traffic times at KPHX where traffic density at the MRP was 50-100% of maximum and excluded summer when thunderstorms impact the results.

TABLE 1. RATE OF VECTORING BETWEEN THE XMP FREEZE HORIZON AND XMP FOR FLIGHTS ARRIVING INTO KPHX (NUMBER OF TOTAL FLIGHTS)

	Before GIM-S IOC	*After GIM-S IOC*	*After GIM-S IOC Off*	*After GIM-S IOC On*	*Accepted Speed Advisory*
All Hours	13.8% (45210)	13.3% (72481)	14.1% (48189)	11.6% (24292)	10.0% (5919)
Peak Hours, 50-100% Traffic Rates	18.4% (12088)	17.9% (18842)	21.8% (8522)	14.6% (10320)	11.0% (3323)
Peak, 50-100% Rates, Excluding Summer Months	15.3% (8327)	14.8% (14124)	16.3% (6060)	13.7% (8064)	10.6% (2802)

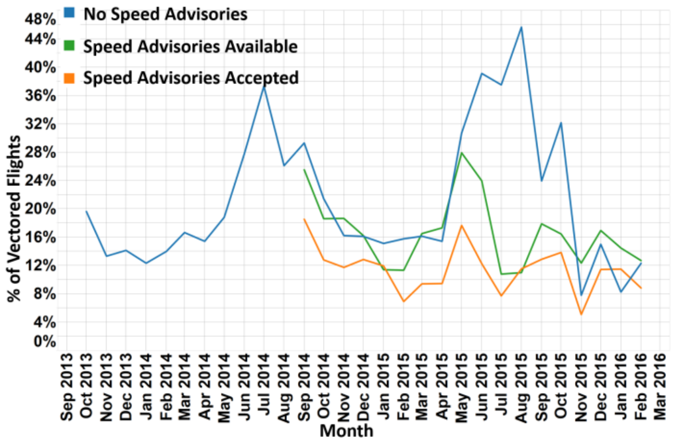

Figure 8. Rate of vectoring between the XMP freeze horizon and XMP for flights arriving into KPHX, filtered to the peak hours and 50-100% traffic density at the CMP.

The results suggest that the use of speed advisories is often a viable alternative to issuing vector instructions, a result consistent with feedback received during discussions with the ATC facility. The reduced vectoring can lead to more consistent and predictable flight operations in ZAB airspace.

About 10% of the aircraft for which a speed advisory was accepted still appeared to receive a vector. This reinforces the idea that speed advisories are just one means in which ATC achieves the objectives in time-based metering operations. For example, an aircraft may still need to be vectored to account for an internal departure that may not have been scheduled in TBFM. If a speed advisory is accepted early in the airspace, any uncertainties that accumulate during the flight to the XMP may lead to additional delay being required. In some cases, it was reported that a speed solution was outside the range that a controller was comfortable assigning. In these cases, the controller may first vector the aircraft, and then assign a speed solution once the aircraft's flight time has been adjusted to absorb some initial delay. These situations highlight the importance of correctly adapting the GIM-S system to a given airspace.

Arrival Procedure Conformance

At KPHX, higher traffic rates generally resulted in increased conformance to the arrival procedure. When the traffic flow is light, aircraft may be instructed to fly directly to the meter fix, which effectively short-cuts the aircraft. This can result in decreased flight time for an individual aircraft. During higher traffic rates, a short-cut for a single aircraft may be detrimental to the broader arrival flow. Table 2 shows the arrival procedure conformance at three different traffic rates.

TABLE 2. RATE OF LATERAL CONFORMANCE TO EAGUL ARRIVAL PROCEDURE (NUMBER OF TOTAL FLIGHTS)

Traffic Rate	*Before GIM-S IOC*	*After GIM-S IOC*	*After IOC GIM-S - Off*	*After IOC GIM-S - On*	*Accepted Speed Advisory*
EAGUL 0-40%	80.9% (26729)	78.1% (49403)	77.0% (40394)	83.2% (8469)	84.9% (1158)
EAGUL 40-70%	86.4% (26781)	84.3% (40199)	83.1% (28566)	87.2% (11633)	87.9% (3428)
EAGUL 70-100%	91.6% (5648)	88.0% (10722)	86.7% (5079)	89.1% (5643)	89.8% (1824)

Figure 9 focuses on arrival procedure conformance during the medium traffic rates. Results indicate the rate of lateral conformance to the EAGUL arrival procedure increased when GIM-S speed advisories were being generated and accepted to the upstream meter points. This suggests the use of GIM-S tools prior to top of descent provides some benefit in pre-conditioning the flow such that aircraft can remain on the procedure to the meter fix.

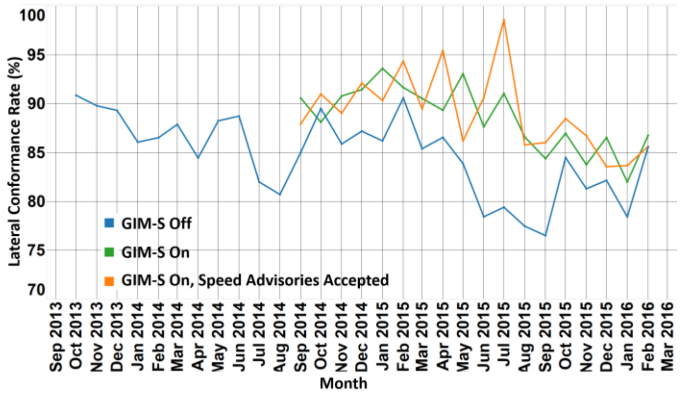

Figure 9. Rate of lateral conformance to EAGUL arrival procedure, filtered to the peak hours and 40-70% traffic density at the meter fix.

Arrivals on the PINNG arrival procedure into KPHX are typically not provided with a short-cut even during lower traffic rates. When GIM-S was used in the upstream airspace, the rate of arrival procedure conformance increased across all traffic rates as shown in Table 3. A simple comparison of conformance rates before and after GIM-S indicates the rate of arrival procedure conformance decreased after GIM-S was introduced. One possible explanation is that the pre-GIM-S data does not include data from summer months, which typically generate lower rates of procedure conformance. The PINNG arrival procedure was published in September 2014 so procedure conformance data is not available for the summer of 2014 to confirm this hypothesis.

TABLE 3. RATE OF LATERAL CONFORMANCE TO PINNG ARRIVAL PROCEDURE (NUMBER OF TOTAL FLIGHTS)

	Before GIM-S IOC	*After GIM-S IOC*	*After IOC GIM-S - Off*	*After IOC GIM-S - On*	*Accepted Speed Advisory*
PINNG 0-40%	91.9% (7977)	90.8% (16148)	90.4% (14592)	94.9% (1556)	99.1% (115)
PINNG 40-70%	92.6% (5557)	90.1% (11059)	88.8% (8561)	94.6% (2498)	96.9% (350)
PINNG 70-100%	90.8% (978)	89.2% (1555)	85.3% (802)	93.4% (753)	90.8% (153)

Table 4 summarizes the arrival procedure conformance for KDEN arrivals to the LANDR and SAYGE meter fixes at various traffic rates. At KDEN, descent speed advisories are provided to help meet the STA at the meter fix; however, there are no upstream MRPs to help precondition the arrival flow. One factor contributing to lower procedure conformance rates at KDEN compared to KPHX could be the lack of pre-conditioning prior to top of descent. A direct comparison of all flights before and after GIM-S IOC indicates the conformance rate increases a few percent after GIM-S IOC across all traffic rates. In addition, the rate of conformance increases after GIM-S IOC when speed advisories are available and in particular when speed advisories are accepted. The rate of conformance increased about 10-15 percent for the set of flights that accepted speed advisories, as compared to the set of flights prior to GIM-S IOC. Therefore, issuing a descent speed advisory to help meet the STA at the meter fix appears to be a useful mechanism to meet the STA while still allowing the aircraft to remain on the arrival procedure.

TABLE 4. RATE OF LATERAL CONFORMANCE TO KDEN NORTHEAST ARRIVAL PROCEDURES (NUMBER OF TOTAL FLIGHTS)

	Before GIM-S IOC	*After GIM-S IOC*	*After GIM-S IOC - Off*	*After GIM-S IOC - On*	*Accepted Speed Advisory*
KDEN NE 0-40%	59.7% (2119)	60.4% (2547)	59.1% (2030)	65.4% (517)	75.6% (41)
KDEN NE 40-70%	57.8% (2431)	60.1% (2895)	57.0% (1983)	66.8% (912)	70.4% (71)
KDEN NE 70-100%	57.0% (1071)	63.4% (1164)	61.3% 604)	65.7% (560)	70.2% (47)

Meter Point Delivery Accuracy for KPHX Arrival Flow

Since the GIM-S adapted arrival flow into KPHX did not perform time-based metering operations prior to GIM-S deployment, the change in delivery accuracy at meter reference points cannot be observed. However, the results can highlight how different types of speed advisories impact the delivery accuracy.

Delivery accuracy to the XMP on the KPHX arrival flow improved for the set of flights in which a speed advisory was accepted, as shown in Table 5. At the XMP, 80.1% of flights that had an accepted speed advisory were delivered within ±30 seconds of the STA, versus 57.4% of flights that had an available speed advisory but were not accepted. In the current implementation at KPHX, the DCT displays times rounded to the nearest minute. Federal Aviation Administration (FAA) Notice 7110.612 requires controllers to comply with metering times within plus or minus one minute. For the data analyzed, 98.6% of flights with accepted speed advisories were delivered within ±1.5 minutes of the STA. Similar results are observed at the CMP.

TABLE 5. DELIVERY ACCURACY RATES TO XMP ON KPHX ARRIVAL FLOW BY GIM-S SPEED ADVISORY FROM JANUARY 2015 – JUNE 2016

	± 0.5 minutes	*± 1 minute*	*± 1.5 minutes*
Accepted Speed	80.1%	95.2%	98.6%
Available but not Accepted Speed	57.5%	84.2%	94.9%
Not Required	77.5%	93.5%	97.8%
Not Available	0.6%	27.0%	63.9%

Metering is rarely used to the HOMRR meter fix and GIM-S is not adapted to provide speed advisories when metering is used. Therefore, meter fix delivery accuracy was not evaluated for that MRP.

Meter Point Delivery Accuracy for KDEN Arrival Flow

Denver Center was operating with time-based metering prior to implementation of GIM-S, allowing for a comparison of delivery accuracy before and after GIM-S. Delivery accuracy at the meter fix did improve slightly after GIM-S implementation, as shown in Table 6 and Figure 10. In the current implementation at KDEN, the DCT displays times rounded to the nearest 10 seconds. For the set of flights in which a GIM-S speed advisory was accepted, meter fix delivery accuracy within ±30 seconds improved by nearly 5 percent.

TABLE 6. DELIVERY ACCURACY RATES TO METER FIXES ON KDEN ARRIVAL FLOW BY GIM-S SPEED ADVISORY FROM JANUARY 2015 – JUNE 2016

	± 0.5 minutes	*± 1 minute*	*± 1.5 minutes*
No Speed Advisory (Before GIM-S)	53.9%	88.4%	91.4%
Accepted Speed	58.8%	93.5%	97.7%
Available but not Accepted Speed	53.3%	89.4%	92.6%
Not Required	54.6%	90.5%	94.2%
Not Available	23.1%	55.4%	58.5%

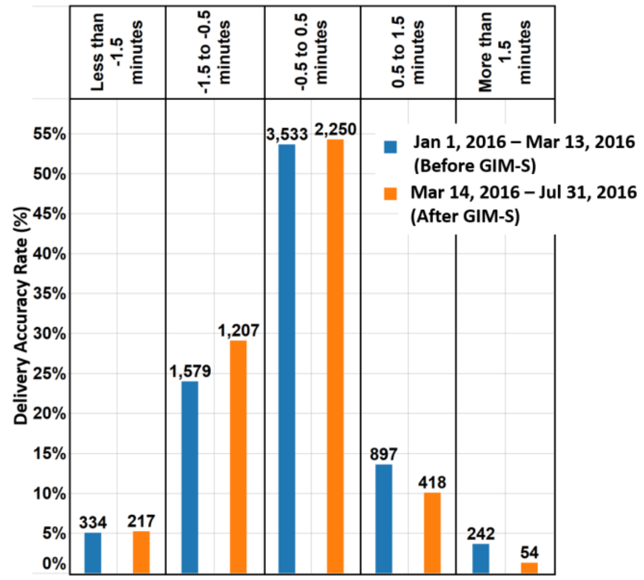

Figure 10. Delivery accuracy before and after GIM-S at meter fixes LANDR and SAYGE on the KDEN northeast arrival flow from January 2016 – July 2016.

Flight Time Variations

Flight times between the XMP freeze horizon and meter fix HOMRR depend on a variety of factors such as wind magnitude and direction, cruise altitudes and speeds, and aircraft types. Results are limited to jets; however, the specific type of jet is not distinguished as the range of jet types is expected to be randomly distributed throughout the data over time. The average flight time is approximately 3-4 minutes less in summer months than winter months. This difference can be attributed to predominant wind conditions during different seasons. During summer months, aircraft typically experience tailwinds, and during the winter months, aircraft will experience headwinds when cruising towards meter fix HOMRR. Aircraft are able to absorb more delay when experiencing a headwind because they will spend more time in a given airspace when they are flying slower.

Numerous methods have been developed to quantify flight time variability [15, 16]. For this work, the standard deviation, and upper percentiles of the flight time distribution are scrutinized. Figure 11 shows the cumulative distribution of the flight time between the XMP freeze horizon and meter fix HOMRR during peak hours from November-March, 2013-2016. The three distributions represent when metering was not used, when GIM-S metering was being used, and the set of flights for which a GIM-S speed advisory was accepted. The dark gray shading shows ± 1 standard deviation around the mean, and the light gray shading shows ± 2 standard deviations around the mean. Results indicate the distribution in flights times is narrowed when GIM-S functionality is used. Similar results were observed when analyzing the summer months. Future research may attempt to quantify how much reduced variation is necessary to enable reduced scheduled block times.

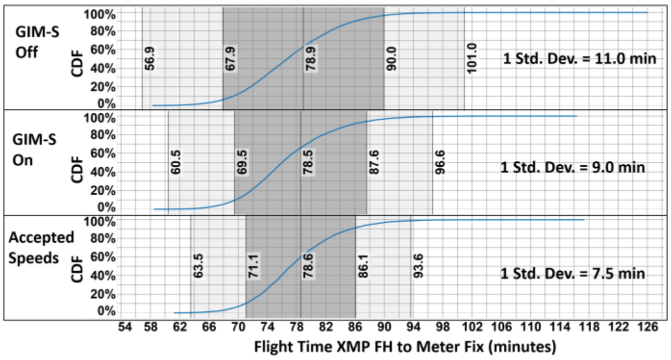

Figure 11. Distribution of flight time between XMP freeze horizon and meter fix HOMRR.

Aircraft are not being metered to the HOMRR meter fix or in the terminal. Flight times in the terminal may still be impacted by procedural conformance. Figure 12 shows the distribution of flight time between the meter fix, HOMRR, and arrival time at KPHX, when landing on the DERVL transition, during peak hours of the winter months. When aircraft adhered to the arrival procedure, per the previously described definition of procedure conformance, the distribution of flight times was reduced compared to aircraft that were vectored off the procedure. Therefore, effective pre-conditioning of an arrival flow that results in increased arrival procedure conformance can also contribute to the potential to reduce scheduled block times.

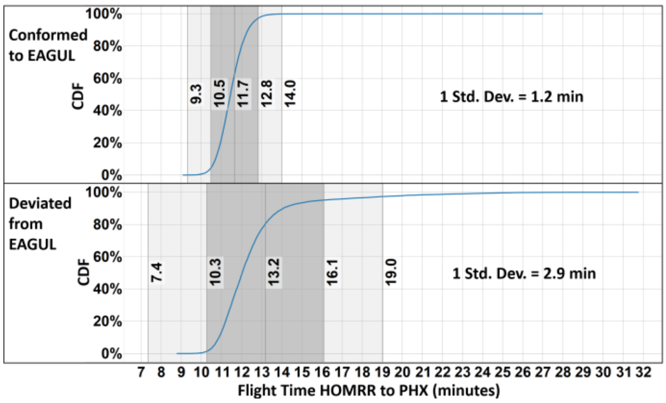

Figure 12. Distribution of flight time between HOMRR meter fix and wheels down at PHX using the DERVL arrival transition.

SUMMARY

This paper described the GIM-S capabilities for enhanced time-based operations and demonstrated a methodology for measuring GIM-S impacts. Additionally, this paper provided a summary of the expected impacts of GIM-S functionality and observations of flight operations at the first two sites operating with GIM-S.

The GIM-S solution into KPHX focuses on pre-conditioning the arrival flow prior to top of descent. This did appear to translate into a reduction in the rate of vectoring and variation in flight times for aircraft during the use of GIM-S functionality. A slight increase in the rate of arrival procedure conformance was also observed when GIM-S was used in the upstream airspace. However, the prevalence of short-cuts on the EAGUL arrival flow obscures a firm conclusion.

The GIM-S solution into KDEN focuses on enabling use of the arrival procedure without vectoring and improving meter fix delivery accuracy. Again some positive results were observed. The rate of arrival procedure conformance increased by 10-15% for the arrivals that were issued a speed advisory to meet the STA at the meter fix. A 5% increase in meter fix delivery accuracy was also observed. Nearly 60% of aircraft were delivered within 30 seconds of the STA.

While some positive impacts were observed, neither KPHX nor KDEN currently use a GIM-S operational metering design that would enable the full set of theoretical benefits (i.e., KPHX does not use speed advisories to the meter fix and KDEN does not use the extended metering and coupled scheduling functionality to enable metering operations over longer distances). The initial designs focused on tailoring metering operations to support the way flights were managed before GIM-S tools were available. Future implementations and adaptation updates should strive to balance site-specific considerations with the fundamental changes that enable the full benefits of a time-based metering environment that includes the GIM-S functionality.

Future work could involve continuous monitoring of the impacts of GIM-S as new sites are deployed and current sites evolve. Data-driven insights from current operations may be useful in identifying beneficial or detrimental impacts to support future implementation decisions. Additional metrics such as total fuel burn may inform the impacts and possibly incentivize the use of GIM-S functionality.

Future work could also leverage modeling capabilities or operational data to identify how adaptation parameters impact operational performance. It is expected that adaptation parameters could be tuned in certain environmental conditions to increase operational performance.

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