Estimation of airline benefits from avionics upgrade under preferential merge re-sequence scheduling

Tatsuya Kotegawa[1]
NASA Ames Research Center, Moffett Field, CA, 94035 USA

and

Charlene Cayabyab[2]
University of California Santa Cruz, Moffett Field, CA 94035 USA

and

Noam Almog[3]
Aerospace Computing Inc., Moffett Field, CA 94035 USA

Modernization of the airline fleet avionics is essential to fully enable future technologies and procedures for increasing national airspace system capacity. However in the current national airspace system, system-wide benefits gained by avionics upgrade are not fully directed to aircraft/airlines that upgrade, resulting in slow fleet modernization rate. Preferential merge re-sequence scheduling is a best-equipped-best-served concept designed to incentivize avionics upgrade among airlines by allowing aircraft with new avionics (high-equipped) to be re-sequenced ahead of aircraft without the upgrades (low-equipped) at en-route merge waypoints. The goal of this study is to investigate the potential benefits gained or lost by airlines under a high or low-equipped fleet scenario if preferential merge re-sequence scheduling is implemented.

I. Introduction

MODERNIZTION of the airline fleet avionics is one of the essential factors to fully enable Next Generation Air Transportation System (NextGen) technologies and procedures for increasing National Airspace System (NAS) capacity. For example, onboard Automatic Dependent Surveillance-Broadcast (ADS-B) "Out" units provide significantly higher surveillance and control precision than is possible with conventional radars. With increased aircraft tracking precision, the minimum separation constraints between flights can be lowered, allowing air traffic controllers (ATC) to fit more aircraft in the airspace. ADS-B "In" provides even more capacity to the NAS by allowing equipped aircraft to hear position reports from other nearby aircraft without going through ATC, further lowering the minimum separation constraints[1]. The Federal Aviation Administration (FAA) mandated that all aircraft equip with ADS-B "Out" by 2020[2]. However, despite the mandate, avionics upgrade rate has been slow and airlines have requested additional incentives to help bear the cost of equipping[3].

Accelerating the airline fleet avionics upgrade rate will hasten the delivery of NextGen benefits. Several studies have already investigated ADS-B benefits and facilitation strategies. Many of these studies quantify the operational benefits of ADS-B for the NAS under nominal Air Traffic Management (ATM) procedures[4-7], or focus on the qualitative assessment of ADS-B benefits across various NAS stakeholder perspectives (e.g. passengers, airlines, airports, ATC, military, etc.)[8-11]. Fewer studies that investigate operational incentives or utilize the nature of airline competition in favor of NAS-wide benefits, have been proposed[12-13].

Preferential Merge Re-sequence Scheduling (PMRS) is a best-equipped-best-served, operational incentive concept designed to facilitate the avionics transition process by taking advantage of the airline industry's

---

[1] Research Aerospace Engineer, Systems Modeling and Optimization Branch, M/S-210-8, AIAA Member.
[2] Programmer Analyst, U.C. Santa Cruz, M/S 210-8.
[3] Programmer Analyst, Aerospace Computing Inc., M/S 210-8, AIAA member.

competitive nature. As a modification to air traffic schedulers like the Traffic Management Advisor (TMA)[14], PMRS rewards aircraft with upgraded avionics (high-equipped) by re-sequencing them ahead of aircraft that are not (low-equipped) at merge waypoints, decreasing the high-equipped aircraft's air time and delay risks. In competition with high-equipped flights, low-equipped flights are re-sequenced lower in the queue leading to longer airtime and higher delay risks. Figure 1 illustrates this concept. PMRS is simply a motivation strategy to accelerate the avionics transition process through opportunities for airlines to gain an operational advantage over its competitors by upgrading its fleet avionics sooner. It is not designed to achieve any airspace capacity optimality.

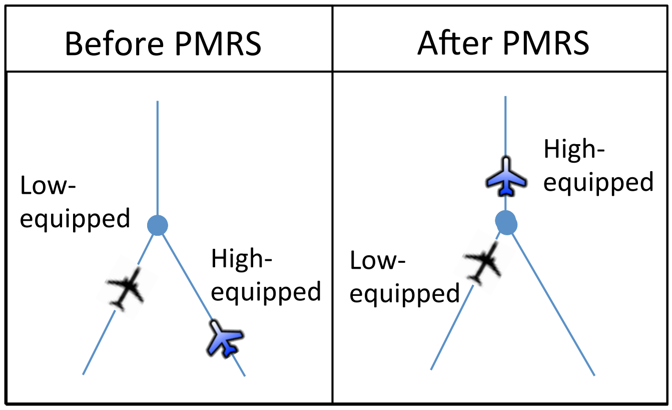

Figure 1: Illustration of PMRS impact on aircraft sequence

The main objective of research presented in this paper is to investigate the nation-wide operational impact and corresponding monetary incentives of PMRS on airlines if they chose to upgrade their fleet avionics. The research also searches for sections of the NAS that will have high PMRS impact due to fleet allocation patterns across multiple airlines. A companion paper[15] describes the mock scheduler used to test the PMRS concept as well as the detailed implication of PMRS for arrival flights to Phoenix Sky Harbor International Airport (PHX) in the Albuquerque Air Route Traffic Control Center (ZAB) airspace. In the future, PMRS can be applied to provide incentives to aircraft not only based on its avionics equipage but also other airline investments that benefit the NAS as a whole, such as increased utilization of greener aircraft with lower emissions and noise. The remainder of this paper is organized as follows. Section II further discusses some of the reasons for low fleet avionics upgrade rate. Section III provides the technical approach taken to quantify potential airline benefits through PMRS. A description of the simulation tools and data utilized for this study is also listed. Benefits analyses at both the NAS and airport level (focused on PHX arrival flights in ZAB airspace) across multiple airlines are shown in Section IV. Conclusions and future work based on the presented research are discussed in Section V.

II. Background: ADS-B benefits for the NAS vs. Airline

Airspace capacity increases attained through ADS-B "In" and "Out" benefit the airlines by reducing delays originating from airspace capacity constraints, leading to lower operations costs and increased profit margins[16]. However, under a mixed equipage environment during the earlier fleet avionics transition phase, these benefits may actually steered away from high-equipped to low-equipped aircraft in order to maximize airspace capacity. Figure 2 illustrates this phenomenon. Arrival sequence A is the baseline case where the high-equipped aircraft avionics capability is disabled. Arrival sequence B has the high-equipped aircraft avionics enabled, and arrival sequence C shuffles the sequence of the high- and low-equipped aircraft to maximize airspace capacity. In sequence B, the low-equipped aircraft are receiving the benefits of airspace capacity increase without investing on avionics upgrade, becoming "free-riders". In sequence C, the high-equipped aircraft is actually placed later in the queue to maximize airspace capacity. This is a penalty for the operating airline because it implies longer air time and higher delay risks. Thus, airlines can achieve "free-rider" benefits without equipping, which reduces the incentive to equip before a mandate is issued.

Also, the cost to upgrade avionics on commercial aircraft is extremely high. The FAA Advisory and Rulemaking Committee (ARC) estimated that for ADS-B "In" equipage, airlines will need to spend between $130,000 – $290,000 to forward-fit aircraft; $270,000 – $425,000 to retrofit in-production aircraft; and $490,000 – $700,000 to retrofit out-of-production aircraft[17]. This is a significant investment especially for the legacy airlines that operate a large fleet of older aircraft. The combination of high avionics cost and unclear ROI is resulting in slow fleet upgrade rates among the airlines especially for non-mandated ADS-B "In", standing in the way of NextGen implementation.

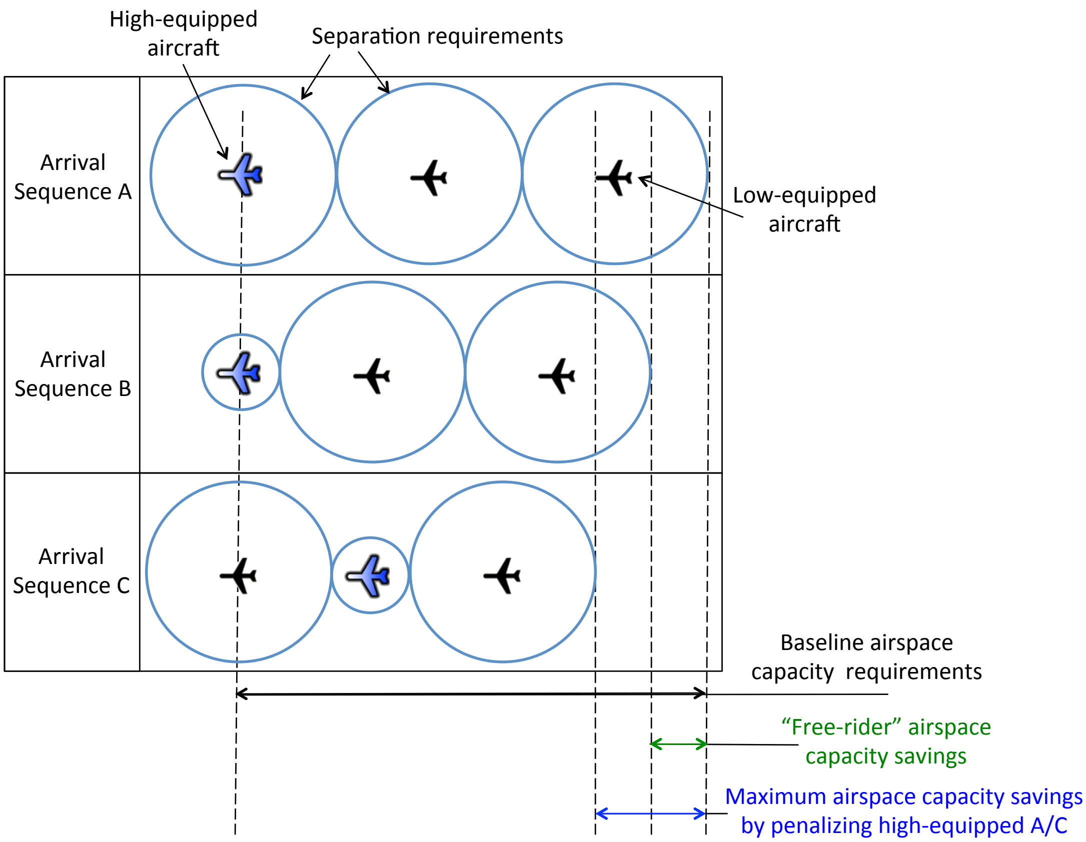

Figure 2: Airspace capacity savings under a mixed equipment scenario

III. Technical Approach

PMRS benefits will be investigated from a both a bottoms-up and a top-down approach. The bottoms-up approach quantifies the PMRS benefits to airlines under various equipage rate scenarios for arrival flights to PHX merging at waypoints within the ZAB airspace. The top-down approach uses the impact of PRMS implementation at PHX/ZAB to estimate its extended impact on other NAS regions. PHX/ZAB is used as an anchor point to analyze fleet utilization patterns of multiple airlines and identify other NAS regions with high PRMS implications. Research reported in this paper mainly focuses on the top-down approach, and further details on the bottoms-up approach are described in the companion paper[15].

Section III.A provides a summary of the two simulation tools applied for the PMRS analyses. First is the Airspace Concept Evaluation System (ACES)[18], which generates the baseline, unimpeded aircraft trajectories using historical flight waypoints extracted from Airline Situation Display to Industry (ASDI) data. The Preferential Merge Re-sequence Scheduler System (PMRSS) imports the ACES trajectories and calculates the number of re-sequence opportunities achievable through speed control for aircraft that are selected by the user to be high-equipped. It also calculates the corresponding estimates on operational benefits such as airtime reduction. Airframe specific benefits calculated via PMRSS are fused with airline fleet utilization data across the NAS available from the Bureau of Transportation Statistics (BTS)[19]. The coupling of the PMRSS results and BTS data can reveal other airspaces with high PMRS benefits extended from PHX. Figure 3 summarizes the approach mentioned above into a flowchart.

Section III.B lists out the criterion required for a flight pair to be PMRS-eligible and Section III.C defines the metrics used for the airport-level PMRS benefits evaluation.

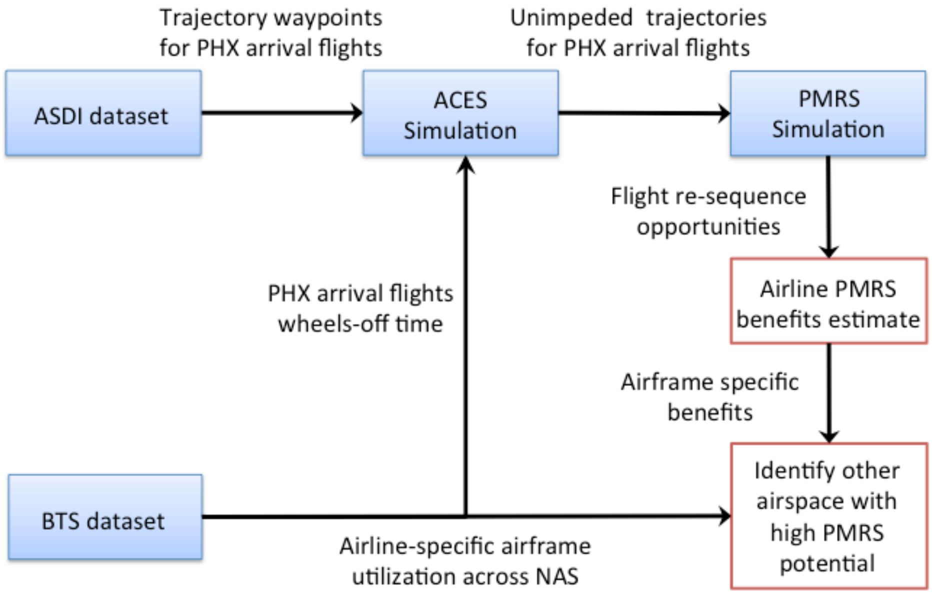

Figure 3: PMRS analysis flowchart

A. Simulation Tools

1. Airspace Concept Evaluation System (ACES)

The Airspace Concept Evaluation System (ACES) is a fast-time air traffic simulation tool developed at NASA Ames Research Center. Air traffic data is modeled in ACES by simulating trajectories according to aircraft models from the Base of Aircraft Data (BADA)[20] and historical flight track data obtained from ASDI. Current and advanced air traffic management technologies and concepts are implemented in ACES using an agent-based High Level Architecture (HLA) modeling framework that is capable of interacting all of the key components of the NAS for a comprehensive gate-to-gate simulation. The simulated output data provides metrics that allow for a full assessment of the impacts of proposed concepts on the NAS.

In this study, ACES is utilized to simulate air traffic without air traffic controller influence on the arrival sequence. This was accomplished by configuring the simulation without airspace and airport capacity constraints and with Traffic Flow Management (TFM) disabled to allow aircraft to fly at cruise speed across the entire recorded flight track from ASDI. The resulting unimpeded trajectories are then used to determine which merge waypoints are crossed by each flight and the corresponding cross times. The simulated waypoint crossing data was verified and validated against historical data for accuracy. In addition to waypoint crossing times, wheels-on time were determined in the ACES output data for inputs to the PMRSS, discussed next.

2. Preferential Merge Re-sequence Scheduler System (PMRSS)

The Preferential Merge Re-sequencing Scheduler System (PMRSS) is a queue-based, first-come-first-served scheduler based on the flight's merge waypoint arrival time simulated from ACES. For each merge waypoint, the scheduler first sequences the flight by their waypoint cross-times calculated from the unimpeded ACES trajectories. If the flight being scheduled has been designated as high-equipped by the user, the scheduler attempts to re-sequence it ahead of any low-equipped aircraft, provided the aircraft pair fulfills the PMRS criteria discussed in Section III.B. Re-sequencing is accomplished by first allowing high-equipped flights to speed up, and then, if necessary, slowing down the low-equipped flights within the passing window. For this paper, the passing window was set to ±10% of the flight time required between merge waypoints, departure and arrival airports at cruise speed. Further details on the PMRSS logic are described in the companion paper[15].

B. PMRS Eligibility Criterion

In this paper, PMRS is allowed only between aircraft pairs that satisfies the following conditions:

1) The aircraft pair is merging from different tracks. A pair of tracks is considered separate if the heading angle difference at the merge waypoint is larger than 7 degrees, or the average distance between the tracks is greater than 5 nmi.
2) The aircraft in the pair are operated by different airlines.
3) Difference in merge waypoint arrival time between the aircraft pair is less than 10 minutes (For results using historical and ACES trajectories only)
4) Aircraft re-sequencing is possible with ±10% cruise speed change. (For results using PMRSS only)

The ±10% cruise speed constraint under criteria #4 is extracted from the commonly expected range of speed reduction for research related to Flight Deck Interval Management and Controller Managed Spacing[21]. The 10 minutes time window under criteria #3 was approximated by taking ~10% of the average airtime for PHX arrival flights, which was 128 minutes.

C. Benefits Metric and Equipage Assumptions

Airline PMRS benefits in this paper centers on the number of re-sequence opportunities that occur at the merge waypoints. K_{ahead} is the number of competitor aircraft that can be skipped by the airline of focus at merge waypoints by being high-equipped, assuming the competitor fleets are completely low-equipped. In other words, K_{ahead} measures the PMRS advantages if the focus airline upgrades its fleet before the competitors. K_{behind} is the inverse concept of K_{ahead}, which is the number of competitor aircraft that will skip ahead at merge waypoints assuming the focus airline is entirely low-equipped and the competitor fleets are completely high-equipped. K_{behind} represents the disadvantages, or benefits lost by an airline if the competitors upgrade their fleets first. Corresponding operational benefit estimates, such as airtime savings or change in fuel requirements, are also investigated. These metrics are used for the bottoms-up approach.

For the top-down approach, a metric referred to as the Propagation Factor (PF) is formulated to quantify airframe sharing between PHX and other airports β served by airline α:

$$PF_{PHX(\alpha,\beta)} = \frac{w_{PHX(\alpha,\beta)}}{w_{non-PHX(\alpha,\beta)}} \tag{1}$$

$PF_{PHX(\alpha,\beta)}$ is simply a ratio between the average arrival operations to airport β with airframes that were used for at least one PHX arrival ($w_{PHX(\alpha,\beta)}$) and average arrival operations to airport β with airframes that were never used for PHX arrivals ($w_{non\text{-}PHX(\alpha,\beta)}$). High $PF_{PHX(A,\beta)}$ implies high airframe sharing between airport β and PHX by the focus airline α. High airframe sharing implies that aircraft will not only receive re-sequencing benefits in PHX/ZAB if high-equipped, but also at those other airspaces when PMRS is implemented across the NAS.

Both the top-bottom and bottoms-up approach assumes an extreme scenario in which the focus airline fleet is 100% and its competitors are 0% high-equipped for K_{ahead} analysis (vice versa for K_{behind}). Such an extreme scenario is unrealistic, but a useful assumption to simplify and reduce the volume of analyses required to quantify PMRS benefits. The final paper may also include further analysis varying the equipage rates among the fleet.

IV. Results and Discussion

The analysis methods described in the previous section is applied to investigate PMRS benefits for four airlines; two nation-wide and two regional. The PHX case study discussed in Section IV investigate flights bound to PHX between 4:00 AM and 11:00 PM MST on April 19th, 2011 over a total of eight merge waypoints inside the Albuquerque Air Route Traffic Control Center (ZAB), displayed in Figure 4 (tracks shown are for one nation-wide airline). Section IV.B further investigates a nation-wide carrier to identify any high airframe sharing between PHX arrival operations and arrival operations to other airports. The final paper will expand on these results by coupling findings from both the top-down and bottoms-up approach to comprehensively quantify avionics upgrade benefits under PRMS at the PHX and NAS level.

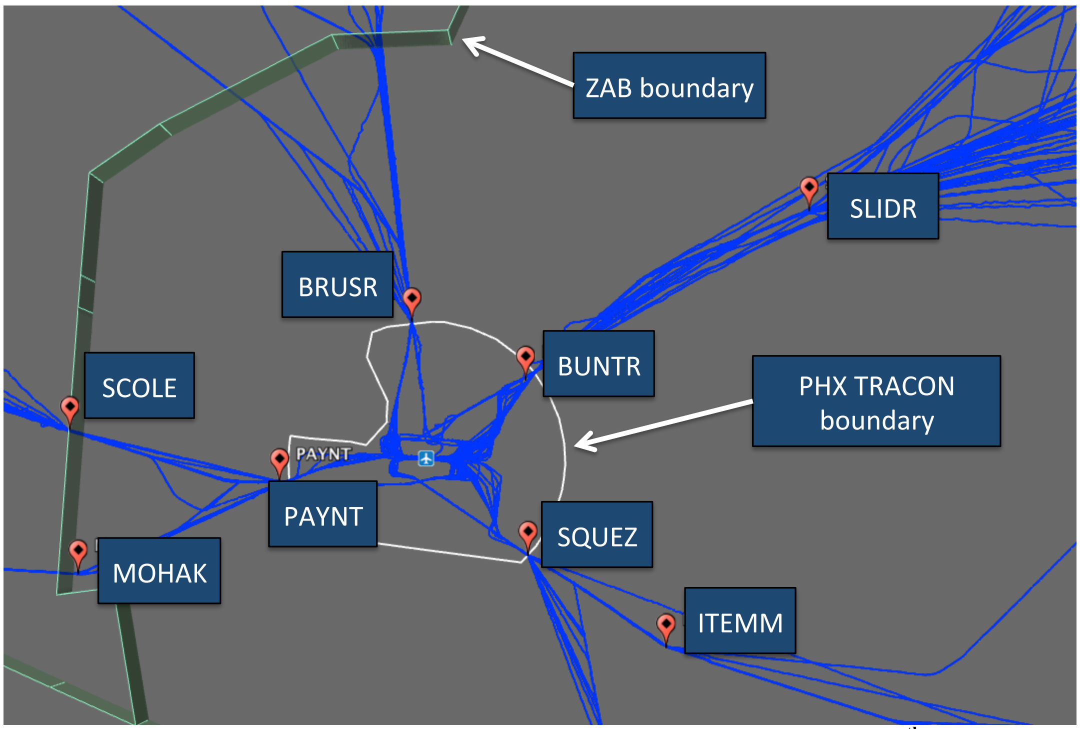

Figure 4: ZAB merge waypoints and PHX arrival flight tracks for April 19th, 2012

A. PHX case study results

At PHX, more than 600 flight operated by 25+ different airlines arrive daily; approximately 80% of those flights are operated by airlines A, B, C and D. Airlines A and B are nationwide carriers, whereas C and D are regional. Figure 5 breaks down the volume of air traffic that passes through each merge waypoint from Figure 4 by its operating airline. Some flights in Figure 5 are counted for multiple merge waypoints depending on the arrival procedure structures.

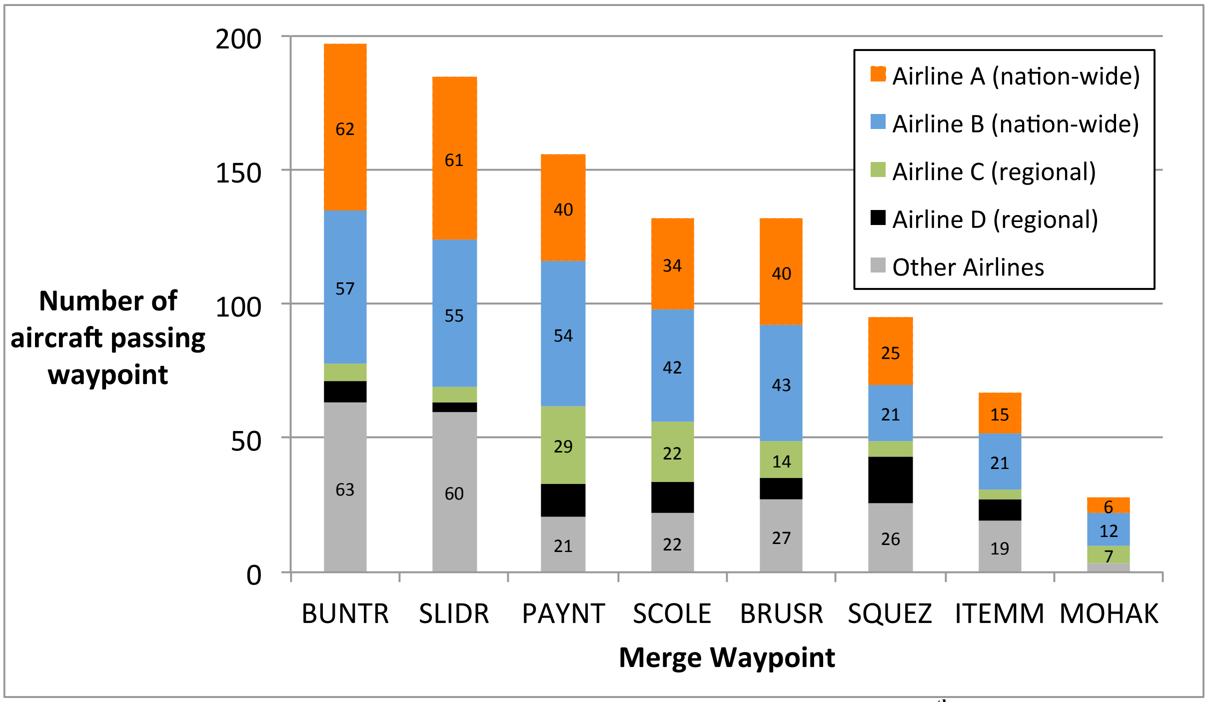

Figure 5: Air traffic through merge waypoint by airlines for April 19th, 2012

Figures 6 through 9 show the PHX PMRS airline benefit estimates using a cumulative fleet K_{ahead} and K_{behind} probability distribution. The y-axis represents the ratio of the focus airline fleet that had at least K_{ahead} opportunities to pass or K_{behind} opportunities to get passed by a competitor airline, shown on the x-axis. The cumulative probability distribution provides a uniform view on the likelihood of re-sequencing opportunities at each of the merge waypoint regardless of the airline fleet size. In Figure 8 for example, approximately 67% of the airline C fleet had the opportunity to pass at least one competitor aircraft merging at the SLIDR fix based on historical trajectories (distribution curve noted as "Historical").

There are three curves in the cumulative K_{ahead} and K_{behind} probability distribution. The "Historical" and "ACES" curve provides K_{ahead} and K_{behind} estimates based on the recorded and simulated merge waypoint pass times. Aircraft pairs that cross through merge waypoints in close proximity within each other (see Section III.B) are estimated to be PMRS capable. These results do not incorporate any re-sequencing and simply used for validating the PMRS distribution.

The smaller, regional airlines typically have higher K_{ahead} and K_{behind} primarily due to their lower number of operations. With lower number of operations, the probability of a regional airline's flight being sequenced near the competitor's flight is much higher compared to the larger, nation-wide airlines with higher operations. Also, Figures 6 through 9 all display a significant gap between the estimated (Historical/ACES) and final (PMRSS) distribution for both K_{ahead} and K_{behind}. For example, the airline A fleet ratio with $K_{ahead} \geq 1$ (Figure 5) is estimated to be approximately 50% (under historical/ACES curve) but drops to 10% in the PMRSS. This behavior is expected because the historical/ACES distribution curve is the "upper-bound" on PMRS potential and should not be exceeded. Again, the historical/ACES curve is used only for PMRS validation purposes, and the three curves should not overlap.

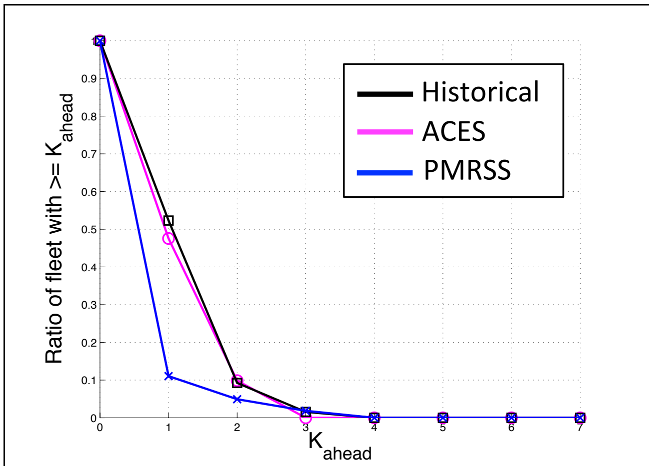

Figure 6: Airline A fleet cumulative K_{ahead} probability distribution at SLIDR

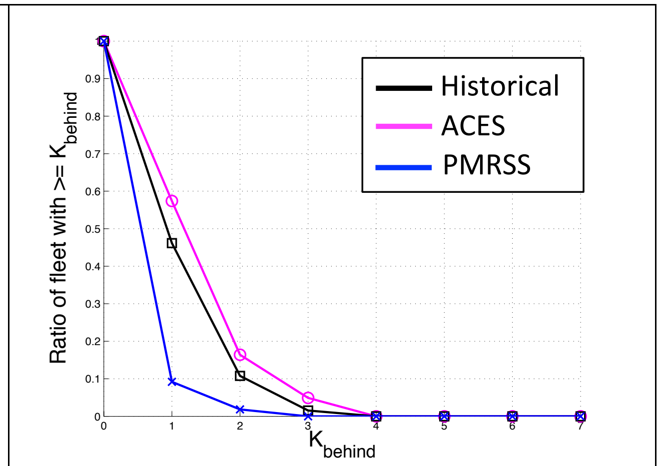

Figure 7: Airline A fleet cumulative K_{behind} probability distribution at SLIDR

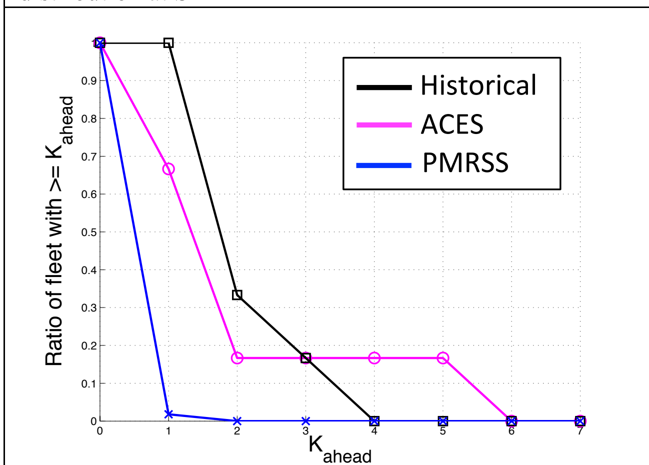

Figure 8: Airline C fleet cumulative K_{ahead} probability distribution at SLIDR

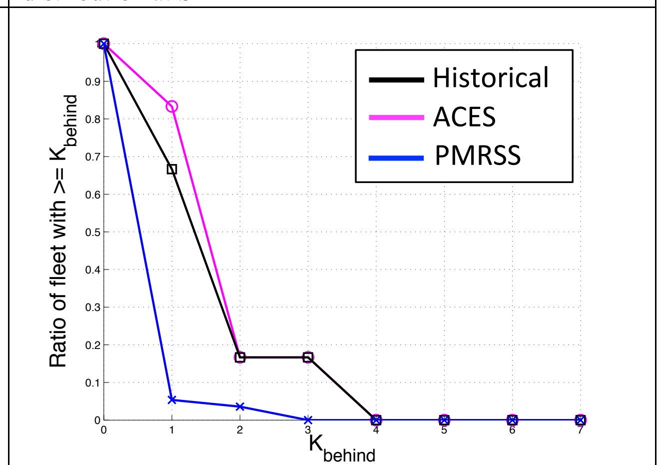

Figure 9: Airline C fleet cumulative K_{behind} probability distribution at SLIDR

B. PMRS potential for other US airspaces

This section examines Airline A fleet utilization patterns across the NAS to identify any high airframe sharing between arrival operations to PHX and to other airports. Table 1 lists the top 10 airports serviced by airline A with the highest $PF_{PHX(A\ \beta)}$, based on 2010 fleet utilization data from the BTS. Figure 10 further visualizes the *PF* data with airline A's operational market share at the corresponding airports. MIA has the highest *PF* value followed by CLT and SAN. From the *PF* perspective, CLT seems to be an attractive market for PMRS. However, PMRS is designed to be most effective at markets with high airline competition (low market share). Thus airline A will receive the most extension of PHX-based benefits at airports located in the low market share / high *PF* sections of Figure 10, such as MIA, SAN and GEG instead of high market share airports like PHL and CLT.

Figure 11 examines the 2010 airframe utilization ratio between PHX and non-PHX arrival operations for the airline A fleet, categorized by aircraft type. Understanding the fleet composition is important because the manufacturing status of the aircraft primarily determines the cost for the avionics upgrade, as discussed in Section II. Each marker in Figure 11 represents a single airframe within the fleet, and its size is inversely proportional to the total number of unique airports it serviced. A blue line with a slope and y-intercept equal to 1 and 0, respectively, is also displayed in Figure 11. Aircraft that reside around this blue line are aircraft regularly used to fly into PHX and have high PMRS ROI potential within the fleet if high-equipped at PHX/ZAB airspace. For the PHX/ZAB area, A320-100/200, B737-300 and A319 airframes clustering around the 500-600 ranges on the x-axis should be prioritized to be high-equipped. The final paper will investigate PMRS ROI estimates by correlating the equipage cost (by aircraft type) with the operational benefits (e.g., change in fuel requirements, airtime) of PMRS investigated from the *PF* (top-down approach) and bottoms-up analysis in the companion paper. The final paper may also look into the fleet utilization patterns of other airlines and develop an avionics upgrade prioritization scheme to maximize the expected airline benefits from PMRS.

Table 1: Airline A airframe propagation factor rankings using PHX as anchor airport

Airport	Total arrival PAX	Total arrival Ops	Total airframes	Total arrival ops using PHX involved airframes	Total PHX involved airframes used	Total arrival ops using non-PHX involved airframes	Total non-PHX involved airframes used	Propogation Factor
MIA	377,419	3,258	150	3,255	147	3	3	22.1
CLT	10,005,305	81,305	368	80,534	322	771	46	14.9
SAN	497,296	3,661	205	3,656	201	5	4	14.6
GEG	77,083	740	28	736	26	4	2	14.2
LGA	982,106	12,502	160	12,454	152	48	8	13.7
ORD	868,726	6,916	296	6,879	278	37	18	12.0
PBI	410,490	3,775	157	3,766	153	9	4	10.9
RDU	443,493	4,064	223	4,037	208	27	15	10.8
MHT	57,616	708	72	707	71	1	1	10.0
TPA	843,767	6,998	284	6,967	272	31	12	9.9

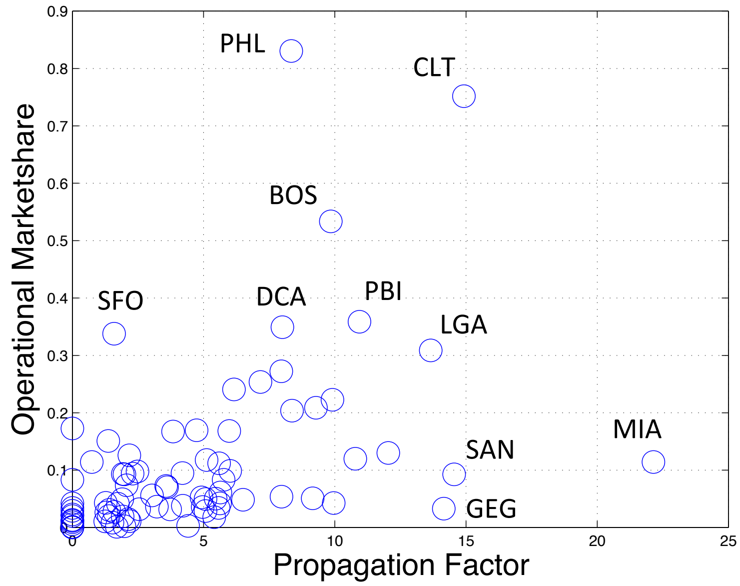

Figure 10: Airline A airframe propagation factor using PHX as anchor airport

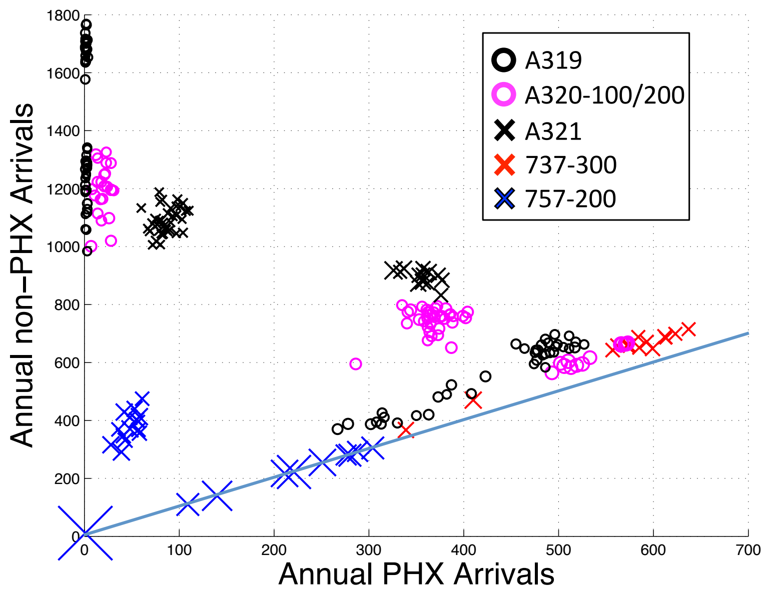

Figure 1: Airline A airframe propagation factor using PHX as anchor airport

V. Conclusion and Future Work

In Section IV, Figures 6 through 9 illustrated that approximately 10% of airline A flights inbound for PHX going through SLIDR are capable of receiving some PMRS benefits if high-equipped. Figure 10 and Table 11 revealed that PMRS benefits gained in PHX/ZAB would have the highest propagation effect on CLT, but MIA, SAN and GEG may have more PHX-extended PMRS benefits based on the airline A market share. Figure 11 displayed that high-equipping selected A320-100/200, B737-300 and A319 airframes will most likely provide the highest PMRS ROIs to airline A for the PHX/ZAB region. For the final paper, further analyses that fuse together the top-down and bottoms-up approach is required to provide in-depth PMRS ROI estimates for airlines. Besides the K_{ahead} and K_{behind}, PMRS benefits will also be investigated from the standpoint of fuel consumption and air time. PMRS benefits also need to be translated into some monetary form to align with equipage cost.

Acknowledgments

The authors thanks John Robinson and Michael Bloem for many useful discussions and the anonymous reviewers for their careful and helpful comments.

References

[1]Huerta, M., "NextGen Implementation Plan March 2012," Federal Aviation Administration, http://www.faa.gov/nextgen/implementation/media/NextGen_Implementation_Plan_2012.pdf [cited 12 February 2013]

[2] "Automatic Dependent Surveillance-Broadcast (ADS–B) Out Performance Requirements To Support Air Traffic Control (ATC) Service; Final Rule," Federal Register, Vol. 75, No. 103, Rules and Regulations, 14 CFR Part 91, Docket No. FAA–2007–29305, Amdt. No. 91–314, RIN 2120–AI92, May 2010.

[3] "Report From the ADS-B Aviation Rulemaking Committee to the Federal Aviation Administration: Recommendations on Federal Aviation Administration Notice No. 7–15, Automatic Dependent Surveillance—Broadcast (ADS–B) Out Performance Requirements to Support Air Traffic Control (ATC) Service; Notice of Proposed Rulemaking September 26, 2008," Federal Aviation Administration, pp. 46-47.

[4] Post, J., Wells, M., Bonn, J. and Ramsey, P., "Financial Incentives for NextGen Avionics: ADS-B Case Study". 8th USA/Europe Air Traffic Management Research and Development Seminar, May 2012.

[5] Barmore, B., Abbott, T., Capron, W., "Evaluation of Airborne Precision Spacing in a Human-in-the-Loop Experiment", AIAA 5th Aviation Technology, Integration and Operations Conference, September 2005.

[6] Grimaud, I., Hoffman, E., Rognin, L., Zeghal, K., "Spacing Instructions in Approach: Benefits and Limits from an Air Traffic Controller Perspective", 6th USA/Europe Air Traffic Management Research and Development Seminar, June 2005.

[7] Sweet, D., Manikonda, V., Aronson, J., and Roth K., "Fast-time Simulation System for Analysis of Advanced Air Transportation Concepts", AIAA Modeling and Simulation Technologies Conference and Exhibit. August 2002.

[8] Marais, K. and Weigel, A., "Encouraging and Ensuring Successful Technology Transition in Civil Aviation", 25th Digital Avionics System Conference, Portland, OR, October 2006.

[9] Eguchi, M., "System Dynamics Analysis of Incentives for ADS-B Equipage", Ph.D Dissertation, Technology and Policy Program Engineering Systems Division, Massachusetts Institute of Technology, Boston, MA, 2008.

[10] Kirkman, W., Pyburn, J., and Swensson, R., "Accomplishing Equipage for NextGen", 28th Digital Avionics Conference, Orlando, FL, 2009.

[11] Lester, E., "Benefits and Incentives for ADS-B Equipage in the National Airspace System," Ph.D Dissertation, Aeronautics and Astronautics, Massachusetts Institute of Technology, Boston, MA, 2007.

[12] AhmadBeygi, S., Bromberg, E., Elliott, M., Krishna, S., Lewis, T., Schultz, L., Sud, V., Wetherly, J., "Operational incentives in Traffic Flow Management," Integrated Communications, Navigation and Surveillance Conference, 2012, pp. C1-1-C1-13, 24-26 April 2012.

[13] AhmadBeygi, S., Bromberg, E.,, Elliot, M., Krishna, S., Lewis, and Sud, V.,"Analysis of Operational Incentives for NextGen Equipage in Traffic Flow Management" 12th AIAA Aviation Technology, Integration, and Operations Conference, September 2012.

[14] Nedell, W., Erzberger, H. and Neuman, F., "The Traffic Management Advisor", Proceedings of the American Control Conference, San Diego, CA, May 1990.

[15] Almog, N., Kotegawa, T., "Incentivizing Aircraft Equipage Upgrade Through Preferential Merging: A Phoenix Case Study", Aviation 2013, American Institute of Aeronautics and Astronautics, Reston VA (submitted for publication)

[16] Bennett, M., Knorr, D., and Rakas, J., "Economic benefits of an increase in en route sector capacity from controller-pilot data link communications," Transportation Research Record, Vol. 1888, 2004.

[17] Carey, B. (2011, November 21). Committee: ADS-B 'In' Not Currently Justified. *AINonline News*. Retrieved from http://www.ainonline.com/aviation-news/ain-air-transport-perspective/2011-11-21/committee-ads-b-not-currently-justified

[18] Meyn, L., Windhorst, R., Roth, K., Drei, D. V., Kubat, G., Manikonda, V., Roney, S., Hunter, G., Huang, A., and Couluris, G., "Build 4 of the Airspace Concept Evaluation System," AIAA Modeling and Simulation Technologies Conference and Exhibit, Keystone, Colorado, 21-24 Aug. 2006.

[19] Bureau of Transportation Statistics. Database name: Air Carrier Statistics (Form 41 Traffic) - U.S. Carriers. http://transtats.bts.gov/. [Accessed December 20, 2012].

[20] "User Manual for the Base of Aircraft Data (BADA) Revision 3.6," Eec note no. 10/04, Eurocontrol Experimental Centre, July 2004.

[21] Prinzel, L. J., Shelton, K. J., Kramer L. J., Arthur, J. J., Bailey, R. E., Norman, R. M., Ellis K., and Barmore, B. E., "FlightDeck-Based Delegated Separation: Evaluation of an On-board Interval Management System with Synthetic and Enhanced VisionTechnology," *IEEE 30th Digital Avionics Systems Conference (DASC)*, Online Proceedings, IEEE, Washington, DC, 2011.