

Incentivizing Aircraft Equipment Upgrade Through Preferential Merging: A Phoenix Case Study

Noam Almog¹

Aerospace Computing Inc., Moffett Field, CA 94035 USA

and

Tatsuya Kotegawa²

NASA Ames Research Center, Moffett Field, CA, 94035 USA

Preferential Merging is a best-equipped best-served air traffic management concept meant to accelerate the adoption of Automatic Dependent Surveillance-Broadcast Out (ADS-B Out) in the national airspace by giving an operational incentive to airlines who invest in upgrading their fleet. The concept relies on re-sequencing aircraft arrival order at en-route arrival merge-fixes favoring high-equipped aircraft (such as ADS-B Out) over low-equipped aircraft. This in turn reduces flight-time for high-equipped aircraft and moves them ahead in the arrival queue. In this study Preferential Merging was simulated using historical flight traffic into Phoenix Sky Harbor International Airport, focusing on a benefit analysis from an airline's perspective. A second set of Monte Carlo simulations randomizing aircraft equipage were run to determine the effectiveness of Preferential Merging as the percent of ADS-B Out equipped Aircraft increases. Results show that the policy creates a 4.5 minute reduction in total flight time for aircraft equipped with ADS-B Out, and that the incentive provided by the policy remains effective over a broad range of ratios of high- to low-equipped aircraft in the US airspace.

I. Introduction

IN order to meet the increasing traffic demand on the U.S. National Airspace System (NAS), the Federal Aviation Administration (FAA) has outlined the Next Generation Air Transportation System (NextGen). Part of this effort requires equipping aircraft with Automatic Dependent Surveillance-Broadcast Out technology (ADS-B Out).¹ However, despite a mandate for aircraft to be ADS-B Out equipped by 2020, the adoption rate of the technology has been slow, and airlines have requested additional incentives to help bear the cost of upgrading.^{2,3} One way to incentivize airlines to upgrade their avionics is through Operational Incentives (OPI), which are created with best-served, best-equipped Air Traffic Management (ATM) policies. These policies favor high-equipped aircraft over low-equipped aircraft when allocating resources in the NAS.⁴ Some research has been done on creating operational incentives pre-departure, with best-served best-equipped procedures integrated into the Ground Delay Program (GDP). Comparatively, little research has been done on airborne, best-served best-equipped ATM policies.^{5,6}

Preferential Merging (PM) is an air traffic control concept being investigated that gives an operational advantage to ADS-B Out equipped aircraft in the airborne phase. Essentially, PM is a logic modification to air traffic schedulers, such as the Traffic Management Advisor (TMA),⁷ which re-sequences high-equipped aircraft ahead of low-equipped aircraft at arrival merge-fixes. By re-sequencing the crossings at the arrival fixes to favor high-equipped aircraft, airlines with high-equipped fleets (ADS-B Out equipped) see a reduction in total flight time. PM is designed for incentivizing ADS-B Out equipage, however the algorithm itself is agnostic. The PM algorithm does not take into account any physical properties of ADS-B Out, beyond that having this feature flags an aircraft to receive preferential treatment. Consequently, PM can be generalized for any aircraft feature the FAA wants to incentivize, such as lower-emission, or lower-noise aircraft, or any other airline investment that benefits the NAS as a whole. Figure 1 illustrates the effect of preferential merging at the merge-fix, with a high-equipped aircraft skipping ahead of a low-equipped aircraft in the arrival stream.

¹ Programmer Analyst, Aerospace Computing Inc., M/S-210-8, AIAA member.

² Aerospace Engineer, Systems Modeling and Optimization Branch, M/S-210-8, AIAA Senior Member.

The goal of the research presented in this paper is to implement Preferential Merging in an air traffic simulation and investigate the magnitude of benefits gained by upgrading, or lost by not upgrading to ADS-B Out from an operational point of view. The effect of PM is quantified in terms of time savings and delays, as well as passing behavior. This is done for both an individual airline, as well as over a broad range of high- to low-equipage aircraft ratios for all arrival traffic merging into a single airport. To accomplish this, one day of historical flight data was used in an unconstrained air traffic simulation with a queue-based scheduling algorithm implementing the PM logic for all arrival traffic into Phoenix International Airport (PHX). A companion paper to this study investigates the same question, but from an economic perspective, performing a financial analysis on the operational benefits created by Preferential Merging.⁸

The remainder of this paper is organized as follows. Section II describes the approach to simulating Preferential Merging in the airspace including the data and methods used. Section III presents the results of the simulation and provides a benefits analysis at both the airline and airspace scale. Section IV outlines the conclusions from this study and a description of future work based on the results of this research.

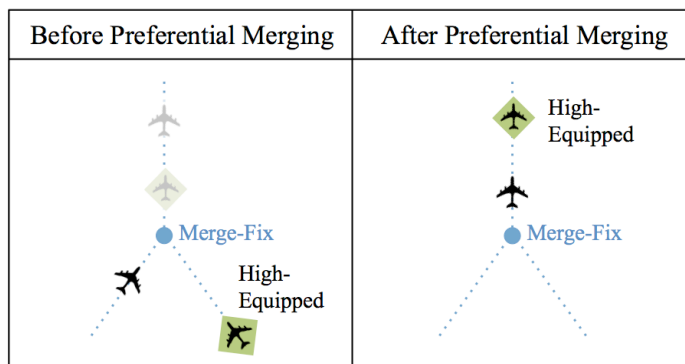


Figure 1. Preferential Merging affects the arrival sequence into the merge-fix.

II. Approach

The following section describes the procedure used to simulate Preferential Merging for flights arriving into PHX. The procedure involves three main steps: collecting historical data for PHX-bound flights, using this historical flight data as input into an unconstrained, high-fidelity air traffic simulation, and lastly imposing PM logic to re-sequence the arrival queue at each of the merge-fixes going into PHX. Each of these steps will be explained in the following subsections with emphasis on the PM scheduling algorithm. A flowchart of the experiment is shown in Fig. 2.

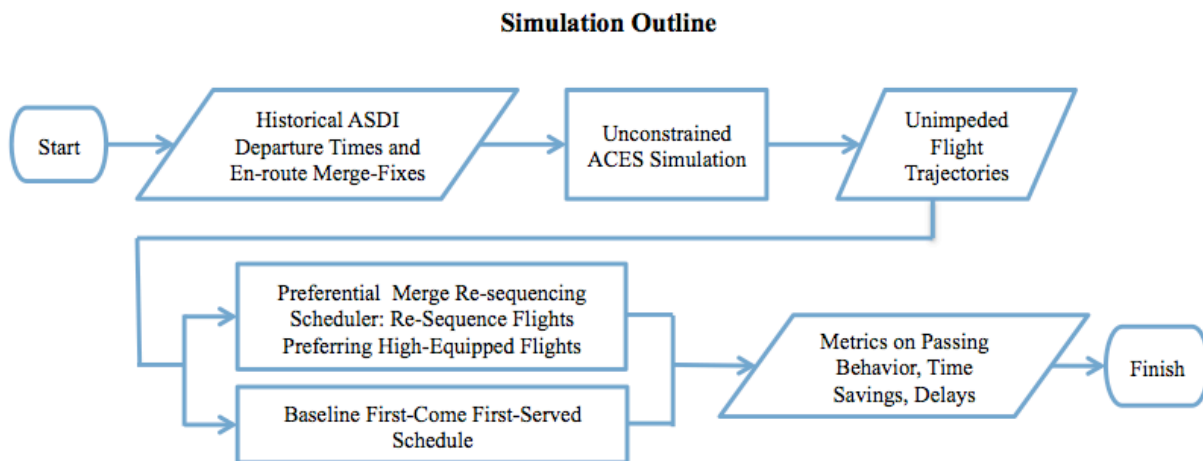


Figure 2. Flowchart of Preferential Merging Simulation.

A. Scenario

The traffic scenario used in this study consisted of all PHX arrivals in a single day's traffic between 4:00 AM and 11:00 PM MST on April 19th, 2012. This day was used because of its high traffic and minimal weather impacts. In total there were 559 flights merging through eight different fixes: SCOPE, MOHAK, PAYNT, SQUEZ, SLIDR, BUNTR, BRUSR, and ITEM. Figure 3 is a visual representation of the scenario. The blue lines are tracks of the aircraft into PHX, while the red dots show the 8 merge-fixes at which PM was implemented. To minimize the amount of variables in the experiment, wind was not included in the simulation.

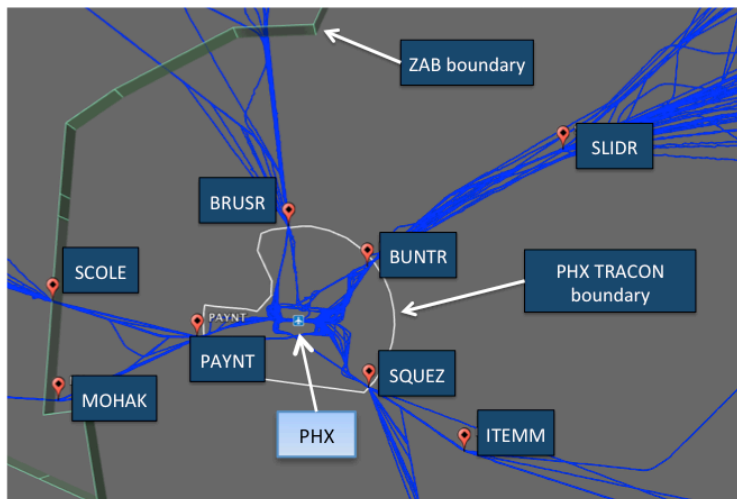


Figure 3. Aircraft Flight Paths for Preferential Merging Simulation Scenario.

B. Real-World Air Traffic Data

Real-world flight-track data was used as the input for the simulation. The data were derived from Aircraft Situation Display to Industry (ASDI) logs, which are collected by the FAA.⁹ These logs contain flight plans, radar positions and aircraft headings for daily traffic in the NAS. Among the flights for 4/19/2012, only flights passing through at least one of the eight merge-fixes into PHX were of interest. To determine this, a flight was identified to have passed through a particular merge-fix if at any point its recorded position was within 3.5 miles of the merge-fix location. Since very few flights actually passed through the exact location of the merge fix, the value of 3.5 miles was determined by visual inspection of the flight paths.⁸ Determining whether two flights were on the same horizontal track was also necessary. To determine this, flights with heading differences of less than 7 degrees or more were considered to be on the same track.⁸ For scheduling arrivals to meet airport arrival constraints, real-world airport capacities were collected from Aviation System Performance Metrics (ASPM) data, which contain hourly departure and arrival rates for 77 of the major U.S. airports.¹⁰

C. Unconstrained Air Traffic Simulation

Using the flight-track data collected from ASDI as input, a set of PHX arrival aircraft trajectories were created using the Airspace Concepts Evaluation System (ACES).¹¹ Developed at the NASA Ames Research Center, ACES is a gate-to-gate simulation of air traffic at local, regional, and national levels. ACES simulates flight trajectories using a high-fidelity flight-physics engine and aircraft models derived from the Base of Aircraft Data (BADA).¹² Numerous studies have validated ACES, showing it produces flight metrics comparable to those observed in the actual NAS.^{13,14} In this study ACES was used with all airport and airspace capacity constraints turned off in order to produce unconstrained trajectories for the flights of interest in the ASDI dataset. The resulting output included wheels-off, top-of-climb, merge-fix crossing, top-of-descent, and wheels-on times, as well as cruise speed for each flight. This was used as input into the merge scheduler.

D. Preferential Merge Re-sequencing Scheduler (PMRS)

The Preferential Merge logic was implemented as a queue-based scheduler, which creates a schedule of cross-times for all flights going through a given merge-fix. PMRS operates on a first-come first-served basis based on a flight's unconstrained arrival time at the merge-fix. The caveat being, that high-equipped flights can attempt to pass low-equipped flights in the arrival sequence. Passing is governed by rules regarding which track the aircraft is on, vortex separation, and max cruise speed constraints. Additionally, PMRS computes airport arrival times for each aircraft adhering to airport arrival capacity constraints. Figure 4 outlines the PMRS algorithm, without restrictions on same-track passing.

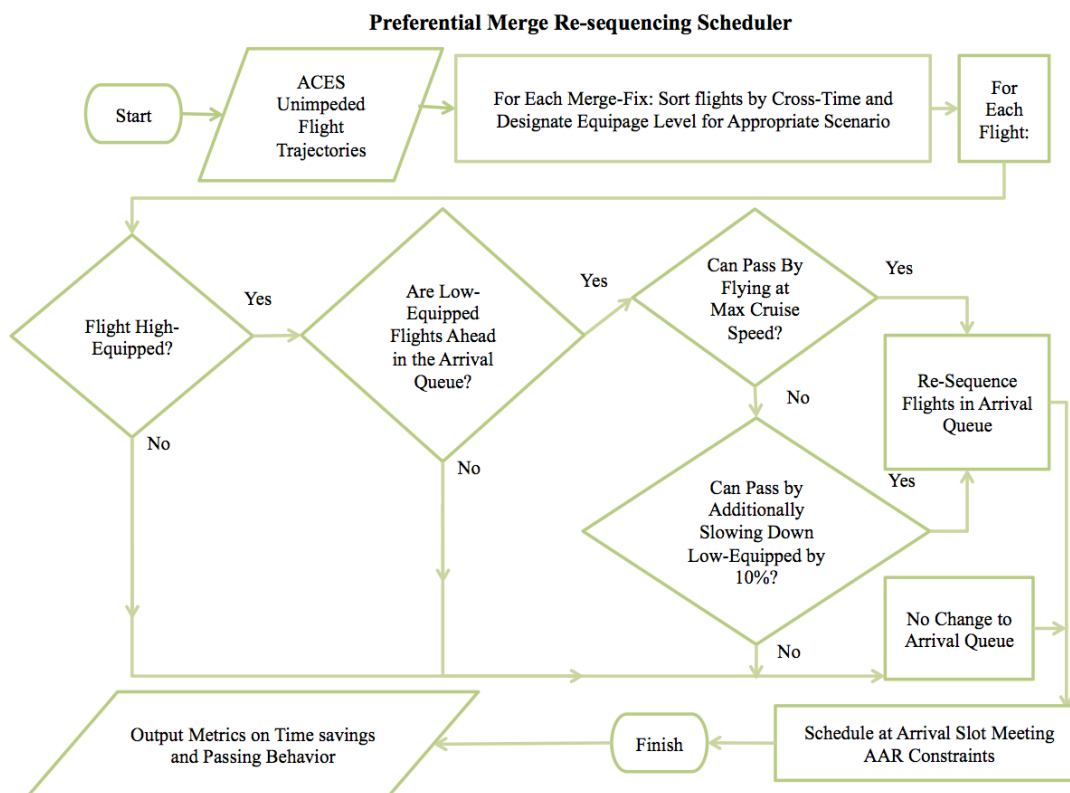


Figure 4. The Preferential Merge Re-sequencing Scheduler Algorithm.

Depending on the parameters of the experiment, a subset of the flights are designated as high-equipped. This is either based on airline membership, or in the case of Monte Carlo simulation, a randomized percentage of the total aircraft. For each merge-fix, the scheduler orders the flights by their unconstrained merge-fix cross-times, and begins adding each flight to the tail of the arrival queue. In this process, the scheduler accounts for minimum vortex separation constraints, which are on the order of 50 to 140 seconds depending on the size and ordering of the two aircraft.⁸ If the current flight being scheduled has been designated as high-equipped, the scheduler attempts to let it pass any previously scheduled low-equipped aircraft in the arrival queue.

PMRS has a built-in toggle for allowing flights on the same horizontal track to pass each other, which is allowed by default. However, in some scenarios passing is restricted to only aircraft on differing tracks. Figure 5 illustrates the difference between same-track passing enabled and disabled. The figure shows a high-equipped aircraft, *H-E*, as it attempts to pass two low-equipped aircraft *a* and *b*. With same-track passing disabled, the high-equipped aircraft can only pass aircraft *a*, which is on a different track. With same-track passing enabled, the high-equipped aircraft can also pass aircraft *b*, which is on the same track. Because allowing same-track passing creates a significantly higher number of passing opportunities, it is enabled by default.

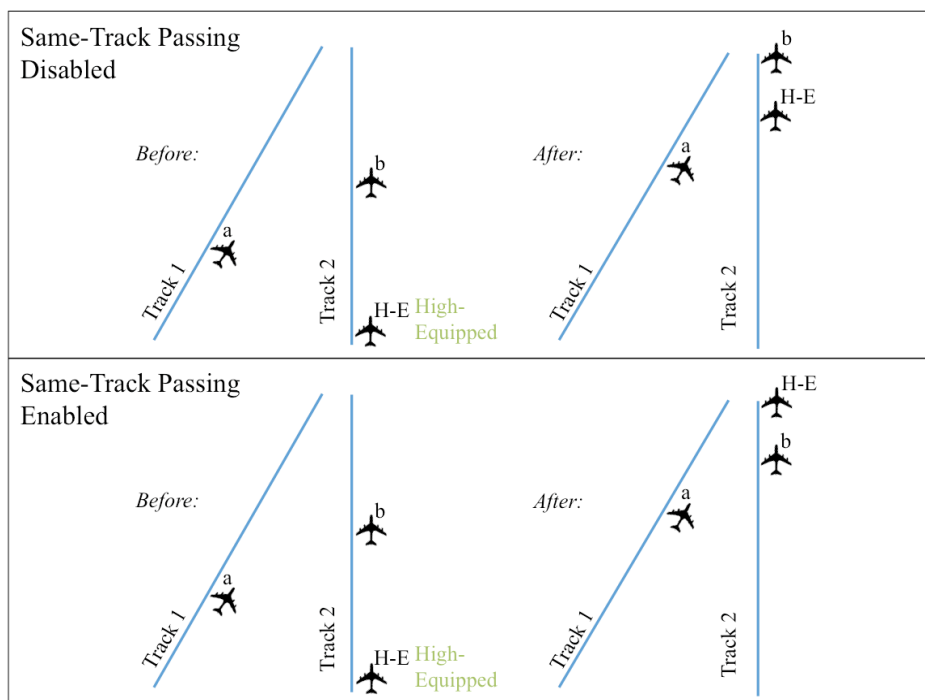


Figure 5. The Effect of Enabling Same-Track Passing in Preferential Merging.

Passing is accomplished by speeding up high-equipped flights, and then, if necessary, slowing down low-equipped flights in the high-equipped flight's passing window. The passing window is defined as the amount of time which can be added or subtracted to the nominal crossing time by adjusting the aircraft's cruise speed during its cruise phase. The cruise phase is defined as the time between top-of-climb and top-of-descent. Slowing down of low-equipped aircraft is limited to 10% less than the nominal cruise speed from the unconstrained ACES simulation. Speeding up of high-equipped aircraft is limited to the max cruise speed obtained from the aircraft manufacturer's specifications.⁸

For flights passing through a single merge fix, the period for which the speed is adjusted begins at top-of-climb and ends at the target merge-fix or at top-of-descent depending on which occurs first. Flights passing through multiple merge-fixes follow the same procedure except that the previous merge-fix is the starting point of the speed adjustment period. If after accounting for minimum vortex separation, the time margin provided by the flights' speed adjustment is large enough such that the high-equipped aircraft can pass the low-equipped aircraft, the arrival queue is re-sequenced. The re-sequencing results with the high-equipped flight moving ahead of the low-equipped in the arrival queue. Under conditions where these constraints are satisfied for multiple low-equipped aircraft, a high-equipped aircraft can pass multiple low-equipped aircraft at once.

After all the merge-fixes have been sequenced, aircraft are scheduled to the arrival airport. Arrival slots are scheduled to meet the airport's hourly arrival rate (AAR), which is specified in the ASPM data. For the day of the traffic scenario, the AAR at PHX ranges from 74 to 78 arrivals per hour. To meet this constraint, arrivals are separated by a $[1 \text{ hour}/\text{AAR}]$ time interval. For example for an AAR of 30, aircraft are separated by $1/30^{\text{th}}$ of an hour (2 minutes). Spacing the flights using this method ensures that the number of arrivals never exceeds the airport arrival constraint.

When the process is completed, PMRS outputs a schedule of aircraft crossing times for each merge-fix and arrival times at PHX, in which the crossing and arrival ordering has been modified according to the Preferential Merging logic (see Fig. 1). This schedule is only computed once unlike most tactical schedulers such as the Traffic Management Advisor (TMA), which are scheduled periodically. Future research will include investigation into how often PMRS should be re-computed. The output includes metrics on the number of passes made by high-equipped aircraft, as well as the number of times low-equipped aircraft are passed. This preferential schedule is compared to the baseline schedule, which is simply first-come-first-served schedule with the same vortex and arrival rate constraints enforced. Comparison with the baseline schedule shows the arrival time decrease or increases compared to nominal arrival times due to preferential merge scheduling. The following results are based on this output.

III. Results

Using the approach described in the previous section, different preferential merging scenarios were evaluated. The first set of scenarios, presented in Section A, focus on the effect of preferential merging on the airline scale. In these scenarios only one airline fleet is high-equipped or low-equipped with respect to the rest of the traffic. This section includes comparisons between PMRS performance with same-track passing enabled and disabled, a national and regional airline, and an early-adopter and late-adopter airline. Each of these includes an analysis of time savings and delays, as well as passing behavior.

The second set of scenarios, presented in Section B, investigate the behavior of PM across the entire traffic dataset as the total percentage of high-equipped aircraft in the airspace increases. This was done using Monte Carlo simulation, by iteratively equipping random aircraft at each percentage point. These results are described in detail in the following subsections. Note that in both Sections A and B, same-track passing is allowed unless otherwise noted.

A. The Effect of Preferential Merging on a Single Airline

This section comprises of different scenarios used to investigate the effectiveness of preferential merging for a single airline. In these scenarios an airline's fleet is high- or low-equipped with respect to the rest of traffic. The first scenario compares the effect of allowing and disallowing same-track passing in PMRS for a high-equipped national airline. In the second scenario the effect of being an early-adopter, high-equipped airline is contrasted between a national and regional airline. An inverse scenario for a late-adopter, low-equipped national airline is then analyzed. Each of these scenarios includes a benefits analysis in terms of flight time, and passing behavior. Lastly the passing behavior for an early-adopter, high-equipped national airline is looked at in more detail.

Table 1 shows the benefits for a high-equipped airline under varying scenarios. The first two columns demonstrate the difference between allowing and not allowing same-track passing in PMRS. The first and third column contrast the operational advantage for a national versus a regional airline when high-equipped. This table is referenced in subsections 1 and 2. The [max] for total number of passes shows the maximum number of low-equipped aircraft passed by a single high-equipped aircraft. It is worth noting the higher values of standard deviation in this and the following tables. This is due to the relatively smaller sample size 559 flights compared to the relatively high variance in the passing behavior among the flights in this dataset. Future work would include a larger sample size to obtain a better quantization of average aircraft behavior under PMRS.

Table 1. Benefits for an Airline With a High-Equipped Fleet.

Same-Track Passing Enabled?	Yes	No	Yes
Type of Airline	National	National	Regional
Airline's Flights Into PHX [Percent of Total Day's Traffic]	174 [31%]	174 [31%]	56 [10%]
<i>Passing Behavior</i>			
Number of Passes Per Flight with Standard Deviation	1.5 ± 2.6	0.4 ± 0.8	2.4 ± 2.6
Total Number of Passes [Max]	252 [17]	63 [6]	133 [11]
<i>Time Metrics for Total Fleet</i>			
Time Savings Per Flight (Minutes) with Standard Deviation	2.7 ± 3.8	1.1 ± 2.6	4.4 ± 4.9
Total Time Savings (Hours)	7.9	3.2	4.1
Total Airtime for Fleet (Hours)	322.3	327.0	62.5
Time Savings as Percentage of Total Airtime	2.4%	1.0%	6.2%

1. The Effect of Same-Track Passing in PMRS

PMRS is designed to both allow and restrict passing of aircraft on the same horizontal track (see Fig. 5). The reasoning behind limiting same-track passing is that the extra fuel-cost of dropping altitude, or performing a path-stretch maneuver could outweigh the time-savings benefit of the passing. Since the fuel burn of these modified trajectories was not simulated in this study, it was not included in the benefits analysis. However, since it is suspected that same-track passing could lead to high fuel, or air-traffic-management overhead, a scenario with same-track passing disabled is included here.

The effect of enabling same-track passing in PMRS for a high-equipped national airline can be seen by comparing the first and second columns in Table 1. Allowing same-track passing more than tripled the number of passes per flight for a high-equipped national airline from 0.4 to 1.5 and quadrupled the total number of passes from 63 to 252. The change in policy more than doubled the time savings per flight from an average of 1.1 minutes to 2.7

minutes. The total time savings across the fleet also doubled from 3.2 hours to 7.9 hours. In terms of percentage relative to total flight time, flight time savings for the fleet increased from 1.0% to 2.4%. From these results it is clear that allowing same-track passing creates a higher operational incentive than when it is disabled, with respect to time-savings. However, since fuel burn was not taken into account in this study it is possible that future iterations of PMRS will restrict same-track passing producing time-savings more akin to the results seen here.

2. Comparison of PMRS for National and Regional Airline

To compare the effect of preferential merging for both a small and large early-adopter carrier, PM scenarios were run for a national as well as a regional airline. As seen in the first and third columns of Table 1, PMRS created a higher operational incentive for the regional airline. Regional flights passed an average of 2.4 other flights as opposed to 1.5 for the national airline. On average these flights arrived earlier by 4.4 minutes as opposed to 2.7 minutes, and the savings as a percent of total flight time were also larger at 6.2% compared to 2.4%. This effect is due to the airline size. The regional airline fleet consisted of 56 flights (10% of total traffic) compared to the larger national airline fleet consisting of 174 flights (31% of total traffic). This means that the regional airline's flights could pass up to 90% of the remaining flights, while the national airline could pass only 69%. Overall, the higher benefit for the regional airline is due to more opportunities to pass other flights. Those benefits would decrease if the regional airline increased the size of its fleet.

3. The Cost of Being Low-Equipped

Table 2 demonstrates the disadvantage of having a low-equipped fleet compared the rest of the traffic. In this scenario the national airline has a low-equipped fleet with the rest of the aircraft in the airspace being high-equipped.

Table 2. Losses for a National Airline When the Rest of the Traffic is High-Equipped

<i>Passing Behavior</i>	
Number of Times Flight is Passed with Standard Deviation	0.9 ± 1.4
Total [Max]	161 [8]
<i>Time Metrics for Airline</i>	
Delay Per Flight (Minutes) with Standard Deviation	2.5 ± 5.1
Total Delay for Fleet (Hours)	7.1
Total Airtime for Fleet (Hours)	337.3
Airline Losses as Percentage of Total Airtime	2.2%

The loss of being the only fleet unequipped is significant. On average 90% of low-equipped flights got passed, with a maximum of a single flight getting passed 8 times. On average low-equipped aircraft arrived 2.5 minutes later, and had total delays of 7.1 hours for the day. This represented a total increase of 2.2% in total airtime for the low-equipped fleet.

4. A Closer Look at Flight Passing Behavior

The following takes a closer look at passing behavior for a national airline's fleet. Figure 6 shows the cumulative distribution of minimum number of passes made for high-equipped flights for a national airline.

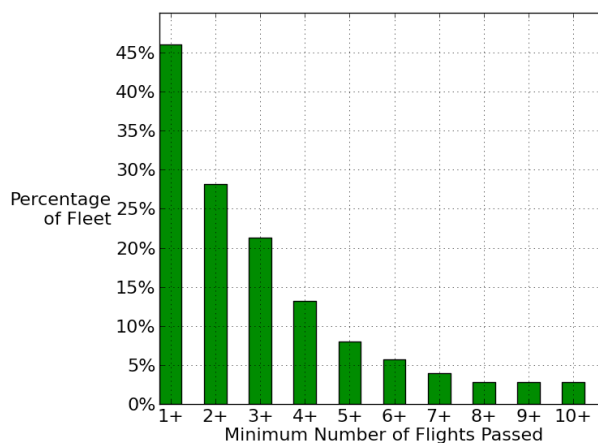


Figure 6. The Cumulative Distribution of Minimum Number of Passes Made Per Flight for a High-Equipped National Airline.

Figure 6 shows that close to 43% of high-equipped flights passed at least one low-equipped flight. 27% passed at least 2, 21% passed at least 3. 3% of flights passed 10 or more other aircraft. This type of information can be useful for an airline in trying to optimize its equipment investment strategy, but would vary according to the airline's relative schedule and airport.

Of the total 174 high-equipped national airline flights, there were 5 flights (3%), which passed 10 or more aircraft. These 3% accounted for 10% of the total time saved across the fleet. Included in this set, is one flight that made 17 passes. This particular flight was relatively long flight (the second longest of the entire fleet), giving it a large speed-adjustment/passing window. It also passed through the two busiest merge-fixes at one of the most congested times of the day. It is possible that this high number of passes for a single aircraft is not realistic for a real-world implementation of Preferential Merging. This implementation of PMRS is unrestricted in the number of passes per aircraft, but future revisions of the policy could include limits to the number of passes per flight, as well as the number of times a flight can be passed. This would be determined with input from the FAA and air traffic controllers and would have an effect on the amount of time savings allotted by PMRS. If for instance passes were limited to no more than 10 per aircraft, an approximate drop of 10% of total savings could be expected.

Table 3 shows an extension of this analysis. It compares the total metrics of flights in the high-equipped national airline's fleet to only the flights within that fleet that successfully made passes. Again this information could be useful for an airline trying to optimize its equipment investment strategy.

Table 3. National Airline's Total High-Equipped Fleet vs. Only High-Equipped Flights That Made Passes.

<i>Metrics for Total Fleet</i>	
Number of High-Equipped Flights	174
Time Savings (Minutes)	2.7 ± 3.8
<i>Metrics for Only Flights That Made Passes</i>	
Number of High-Equipped Flights That Made Passes	80
Time Savings (Minutes)	5.9 ± 3.7

The above mentioned table represents the subset of high-equipped flights that had an opportunity to utilize their passing advantage. Of the 174 flights for the national airline, 80 made passes. The average time savings for those flights was 5.9 minutes per flight, more than double the average over the entire fleet, which was 2.7 minutes.

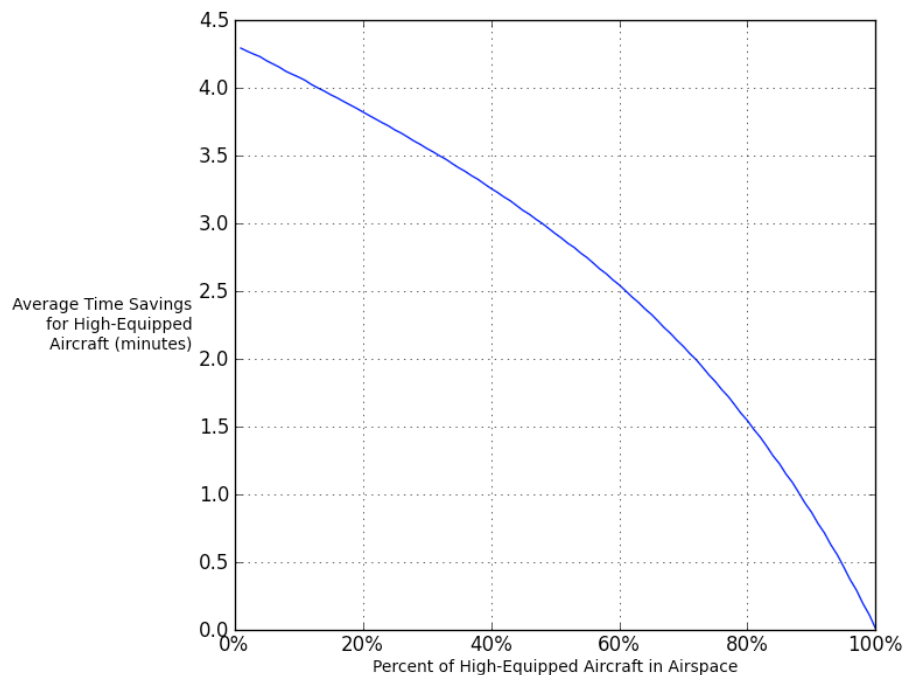
It is important to note that all flights that made passes arrived earlier than in the baseline schedule. However, flights that were equipped, but did not make passes, arrived both earlier and later. This is caused by the chaotic effect that reordering the arrival queue has on arrival time. PMRS takes into account vortex constraints, spacing arrivals by an amount of time based on aircraft type. In general a larger aircraft in front of a smaller aircraft requires more spacing than a smaller aircraft in front of a larger one. Consequently, if two flights are scheduled for the same arrival slot, but one is larger, the order they are scheduled changes the delay needed to meet the vortex constraints. Thus, a byproduct of re-sequencing the arrival queue is that in some rare cases low-equipped flights arrive earlier and high-equipped flights arrive later than their nominal arrival times.

B. Testing the Effectiveness of Preferential Merging as More Aircraft Become High-Equipped.

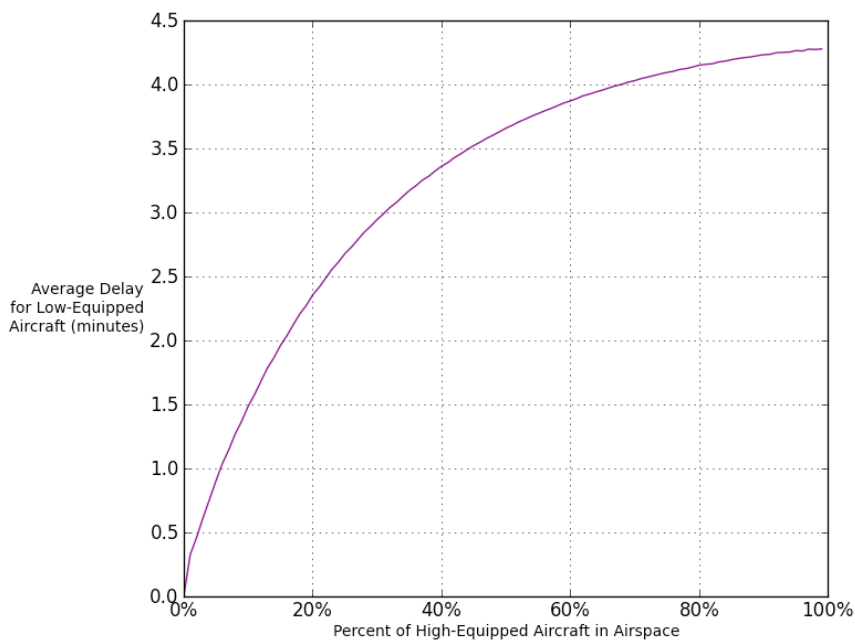
The purpose of these simulations was to measure the operational incentives provided by PMRS as the ratio of high- to low-equipped aircraft in the airspace increases. This analysis is important in order to ensure that PMRS is effective over a broad range of equipage scenarios. Using a Monte Carlo simulation, aircraft were designated as high-equipped at random, while incrementally increasing the total percentage of high-equipped aircraft flying into PHX. 100,000 Monte-Carlo simulations were conducted for each percentage point. From these, time savings and number of passes were calculated for high-equipped aircraft. Arrival delay and number of times passed were calculated for low-equipped aircraft. Note that in this set of simulations, equipage is not associated with any particular airline. Also, equipping is done randomly over many iterations, future work may include a more sophisticated method of determining which aircraft are equipped according to economic principles, or some other heuristic.

1. The Change in Time Savings for High-equipped, and Delay for Low-Equipped Aircraft as the Percentage of High-Equipped Aircraft in the Airspace Increases.

Figure 7 shows the decrease in flight-time savings for high-equipped aircraft (a), and increase in delay for low-equipped aircraft (b) as the total percent of high-equipped aircraft in the airspace increases.



(a)



(b)

Figure 7. Decrease in Time Savings for High-Equipped Aircraft and Increase in Delay for Low-Equipped Aircraft as Total Percentage of High-Equipped Aircraft Increases.

As demonstrated in Fig. 7a, when only a small percentage of aircraft are high-equipped, there is a significant advantage to being high-equipped. These earliest adopters receive on average around 4 minutes in time savings per flight. This advantage drops slowly at first and then accelerates as high-equipped aircraft saturate the airspace. The early-adopter advantage halves at around 70%, and then disappears entirely at 100%.

Conversely, as the time savings drop for high-equipped flights, the penalty for being low-equipped increases. This is seen in Fig. 7b. As the number of high-equipped aircraft increases, the average delay for low-equipped flights increases rapidly, reaching half the maximum delay at less than 20%, and finalizing at the maximum of 4.3 minutes average delay when 99% of the airspace is high-equipped.

To summarize, while the incentive of time savings decreases as more aircraft become high-equipped, the disincentive of added delay for being low-equipped increases. In this way Preferential Merging, while initially

compensatory, shifts to being punitive. The combined effect is that preferential merging remains effective over a broad range of equipage scenarios.

It is worth noting that PMRS has an effect on the total traffic delay ranging from an average of +3.4 additional hours of delay to -1.6 hours less delay, compared to the nominal amount of delay. The maximum amount of delay occurs at around 10% high-equipage and the minimum at 80%. Future work on PMRS will include optimization to minimize the impact of additional delay on the rest of the airspace.

2. *Passing Behavior as the Percentage of High-Equipped Aircraft in the Airspace Increases.*

Figure 8 shows the trend in number of passes for high-equipped flights (a) and the number of times low-equipped flights get passed (b) as the number of high-equipped aircraft in the airspace increases.

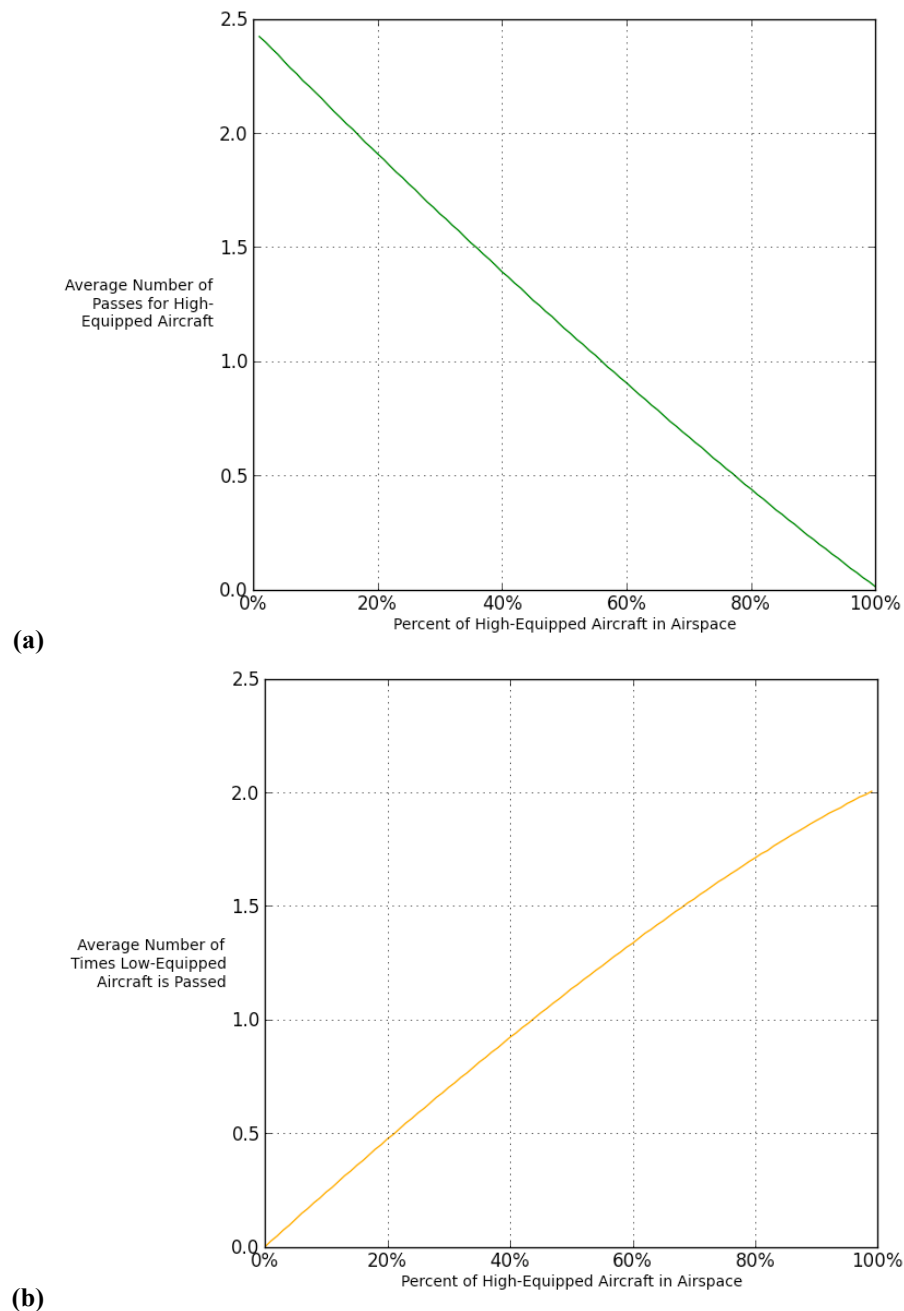


Figure 8. The Decline in Passing Ability for High-Equipped Aircraft, and Increase In Number of Times Low-Equipped Aircraft Are Passed, as the Total Percent of High-Equipped Aircraft Increases.

Similar to the trends in airtime savings and delay, as the average number of passes for high-equipped aircrafts decreases, the average number of times low-equipped aircraft get passed increases. As seen in Fig. 8a, the earliest adopters get the highest passing advantage at an average of 2.5 passes per flight. The final set of flights that remain low-equipped get passed an average of 2 times per flight as seen in Fig. 8b.

Unlike the flight time savings and delay trends, which changed at a logarithmic rate, the passing behavior changes at a nearly linear rate. Similarly to time savings and delay, however, as the passing incentive of being high-equipped decreases, the disincentive of being low-equipped and being passed increases. Again, with the initial effect of PM is compensatory and the final effect is punitive, PM remains effective over the range of high- to low-equipage scenarios.

In the companion paper based on this study by Kotegawa et al., which included fuel burn and direct operating cost (DOC), the operational advantages for high-equipped flights over an 18 month period translated into cost savings equivalent to 1-19% of the avionics cost depending on the airline and scheduler variant explored.⁸ Analysis concluded that PM benefits in the PHX airspace alone are most likely not capable of paying off the entire equipage cost within an acceptable timeframe, suggesting implementation of PM in other airspaces to extend its financial benefits.

IV. Conclusion

In this study, Preferential Merging, a best-served, best-equipped Air Traffic Management policy was simulated, allowing higher-equipped flights to pass lower-equipped flights at merge-fixes. The intention of this research was to design a policy that would create an incentive for airlines to upgrade to ADS-B Out.

Preferential Merging was modeled using real-world traffic data as input into a high fidelity air traffic simulator. The output trajectories were then run through a queue-based scheduler implementing the Preferential Merging policy. Different scenarios were run analyzing the operational benefits provided by PM for a typical airline. These scenarios included enabling and disabling same-track passing, and national and regional airline types. Another set of scenarios used randomized Monte Carlo simulations to study the performance of PM in mixed high- to low-equipage scenarios.

In the set of scenarios focusing on the effect of PM on a typical airline, three primary conclusions were drawn. It was found that allowing same-track passing greatly increased the operational benefit provided by Preferential Merging. This change in PMRS logic more than doubled the total flight time savings for the airline and quadrupled the total number of passes. It was also found that a regional airline will see nearly double the flight time savings and number of passes than a larger national airline. Lastly, it was found that there is a definite disadvantage to being low-equipped when PM is implemented, in which airlines that were last to equip saw an increased delay average of 2.5 minutes per flight.

The Monte-Carlo simulation showed that as the percentage of high-equipped aircraft in the airspace increases, the incentives of being high-equipped decreased. When the airspace is mostly low-equipped, a high-equipped aircraft can see average time savings of 4.5 minutes and 2.5 passes per flight. This advantage eventually drops to 0 as the airspace becomes fully high-equipped. At the same time the disincentive of being low-equipped increases as there are more high-equipped aircraft in the airspace. While low-equipped aircraft initially see no additional delays, as high-equipped aircraft saturate the airspace, low-equipped aircraft are delayed up to 4.2 minutes and passed over 2 times per flight. Overall it was seen that while being a compensatory policy at first, Preferential Merging eventually becomes punitive. The result is that Preferential Merging remains an effective means to incentivize over a broad range of high- to low-equipage scenarios.

From the financial analysis described in the companion paper to this study by Kotegawa et al.,⁸ it would appear that while preferential merging could help incentivize ADS-B Out equipage, it does not create an operational advantage large enough for an airline to totally recoup its investment in ADS-B Out. While PM can provide airlines an operational advantage value of up to 19% of the cost of their investment, other policies working in tandem would be necessary to help recoup the rest. Alternatively, extending PM to the rest of the national airspace could be sufficient, though this would require further investigation.

For future work, it would be more ideal to use a larger dataset and to include wind in the analysis. It would also be interesting to include surface area operations in the modeling, because the advantage of arriving earlier is most likely compounded when taking into account delays avoided on the surface. Also, if PMRS is to be implemented, further investigation into the cost and feasibility of same-track passing should be conducted, as well the distance upstream that this type of scheduling can be feasibly managed. This should also include input from air traffic controllers and the FAA.

Inevitably, it will be up to the FAA and the airlines to decide if the airtime savings and earlier position in the arrival queue provided by PM offers enough of an incentive to make the investment in ADS-B Out desirable. However, from this research it is clear that Preferential Merging can provide at least a part of the operational incentive necessary to convince Airlines to invest in ADS-B Out technology.

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