32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

IMPACT OF ENROUTE TIME-BASED METERING ON EQUITY IN DELAY DISTRIBUTION

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Abstract

Controlled enroute delays can alleviate some of the ground delay assigned to domestic flights. The current research presents a numerical simulation developed to evaluate the impact of enroute time-based metering (controlled enroute delays) on ground delay distribution of domestic departure flights. Real radar and wind prediction data is used to model arrival traffic at Tokyo International Airport. Simulations result show that the reduction in ground delay depends on the control parameters of the ground delay program, in particular the buffer describing the allowed airborne delay, but in all cases reductions in both the number and length of ground delays are observed. Furthermore, position shift analysis shows that controlled enroute delays contribute to more fair sequencing as well. By modeling two air traffic flow management initiatives simultaneously, decision and policy makers can make informed decisions on the control parameters of each initiative and potential benefits.

Keywords: air traffic flow management, ground delay, controlled enroute delay, delay distribution

1. Introduction

Many hub airports worldwide operate at full capacity due to recent increase in air traffic. Therefore, demand in peak hours and/or bad weather often exceeds the number of flights which can be handled by the airport and congested sectors around it. There are various air traffic management initiatives to handle the imbalance between demand and capacity. Generally speaking, aircraft can be either delayed on the ground before their departure, or when this is not possible, delayed in the air through path stretching or speed control. Airborne delays are more expensive and lead to higher air traffic controller workload. The computation of the right amount of ground delays, however, is complicated due to the numerous uncertainties affecting the traffic flow, such as departure time errors due to late passengers or delayed pre-flight maintenance, flight time errors due to differences in predicted and experienced flight conditions, uncertainties in airport acceptance rate, etc. If the computed ground delays are too short, aircraft will be held unnecessary in the air; on the other hand, if the computed ground delays are too long, capacity will be underutilized, and throughput will be lost. The same holds for assignments of arrival times at enroute fixes, or enroute time-based metering, as part of the 4D flight management. In Japan, the ground delay program (GDP) has been in operation for considerable time. The enroute air traffic flow management initiative is referred to as Calculated Fix Departure Time (CFDT) [1]. CFDT is going to be assigned to airborne flights, and along with the GDP, is expected to contribute to capacity management of congested sectors and airports. GDP targets domestic flights only, but CFDT can be assigned to both domestic and international flights. Therefore, CFDT is expected to introduce more equity in delay distribution. In Australia, an ATFM initiative similar to CFDT is referred to as long range air traffic flow management (LR-ATFM) [2]. An application has also been conducted in New Zealand and Singapore [3]. In Japan, CFDT trials were conducted in from 2011 to 2014, but differences in the predicted flight times between the ground and onboard systems stopped the CFDT trials temporarily. Since then, ground-based systems have been improved, and CFDT resumed trials in 2020 [4].

One of the main control parameters of the CFDT initiative is the maximum amount of airborne delay assigned to a flight. For example, assume the ground-based system expects a certain flight to cross the metering fix for which CFDT is assigned at 10:20. If the maximum airborne delay allowed is 2 min, then this flight can be assigned a CFDT as late as 10:22. The 2 min of maximum airborne delay allowed show how delayable the flight is through speed reduction and no path stretching. Compared with the case when CFDT is not applied, delay will be absorbed more evenly by all flights, which will increase the equity in delay distribution.

In practice, however, the problem is not as straightforward as one might expect, due to the numerous uncertainties which impact the GDP and CFDT. In this research, we consider departure time errors and flight time errors, and investigate the impact CFDT on ground delay. In order to do perform a quantitative evaluation, we develop a high-fidelity air traffic numerical simulation using real air traffic radar data to create realistic scenarios.

The rest of the paper is organized as follows: Simulation flow and major assumptions are presented in Section 2. Results and their analysis are discussed in Section 3. Concluding remarks can be found in Section 4.

2. Simulation Flow and Simulation Assumptions

2.1 Ground and controlled enroute delay calculation overview

2.1.1 Ground and controlled enroute delay calculation logic

Assume an airport which handles arrivals on a single runway separate from departures, i.e. departure aircraft do not influence arrival aircraft. In such a case, capacity id determined by the number of arrivals and required separation between a pair of aircraft. Assuming 2 min of required separation, the ideal traffic flow maximizing throughput and minimizing unnecessary airborne delay will happen when a flight arrives at the airport (or in its vicinity) every 2 min. The ideal flow for the flights shown in Figure **1** will be three flights arriving at 9:45, 9:47 and 9:49. These expected arrival times (ETA) form an ETA queue. When the ETA queue is 9:45, 9:47 and 9:49, no adjustments are necessary. Assume, however, that the ETA queue is 9:45, 9:47 and 9:45 and the only controllable flight is the third one. Then a delay of 4 min will need to be absorbed to satisfy the required separation. In a fully deterministic environment, assigning a ground delay of 4 min will solve the issue. In the real world, however, departure delays of 2 min in this example due to late passenger boarding, for instance, can cause the flight to arrive at the airport at 9:51, and this will cause throughput loss, as shown in the middle panel of the figure. Vice versa, in case of early departure, the aircraft will endure an unnecessary 2 min airborne delay, as shown in the bottom panel. Traffic flow control is applied in times of congestions, and therefore throughput loss should be avoided as much as possible. To compensate for uncertainties, a buffer is set (See Figure 2). Assume we set a buffer of 5 min, i.e. when the expected airborne delay is less than 5 min, no ground delay will be applied. In general, such a strategy increases the airborne delay, but decreases throughput loss. The tradeoff between throughput loss and unnecessary airborne delay determines the optimal buffer, as discussed in the authors' past work [5]. Discussions with stakeholders knowledgeable of flow control operations targeting Haneda Airport let us to investigate buffers between 6 and 12 min in this research.

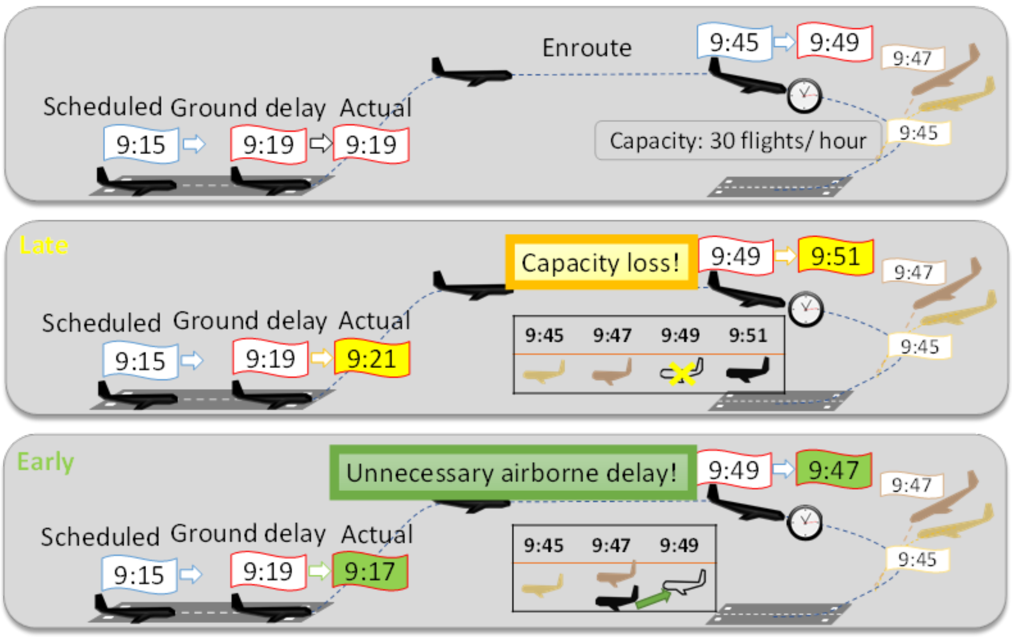

Figure 1 – Ground delay without any buffer

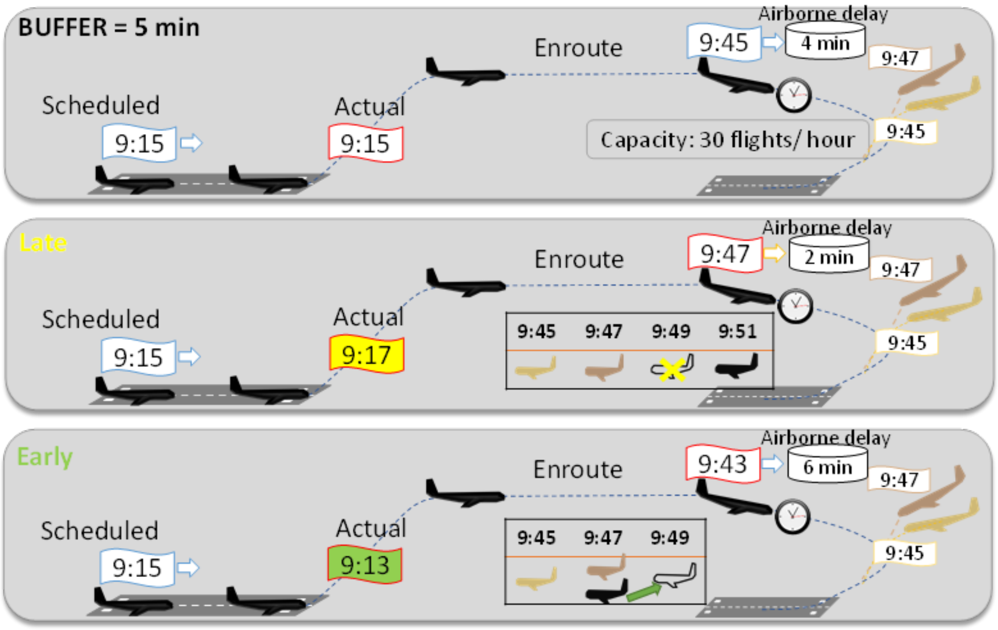

Figure 2 – Ground delay with a buffer

2.1.2 Maximum achievable controlled enroute delay

The example above illustrated the flow control case with ground delay, but the same logic applies to controlled enroute delays as well. From total flow control perspective, the main difference between ground delay and controlled enroute delay lies in the maximum delay which can be absorbed. As illustrated above, ground delay can theoretically be unlimited. Controlled enroute delay, on the other hand, is achieved by speed reduction. Aircraft operational constraints, traffic constraints and airline policies can all affect the maximum achievable controlled enroute delay. The maximum achievable delay depends largely on the length/duration of the enroute flight segment. Assuming flights can be assigned such enroute delays only once they enter the Japanese airspace Fukuoka FIR, the values of the maximum achievable enroute delay are in the 2-3 minutes range for most flight. Detailed analysis can be found in the authors' past work [6]. In our simulation, we set the maximum controlled enroute delay at 2 min for all international flights in Fukuoka FIR arriving at Haneda Airport.

2.1.3 Traffic (ETA queue) assumptions

The calculation of both ground and controlled enroute delays rely on traffic predictions, i.e. information available from flight plans. At present, however, the data available for researchers in Japan is limited to actual track data, CARATS Open Data [7], released by Japan Civil Aviation Bureau. Data is available for a week of flights every odd month (or every month, depending on the year). The radar data for each flight consists of pseudo flight number, aircraft type, as well as latitude, longitude and altitude data recorded every 10 seconds, on average. The data represents the traffic after all ATFM and pilot interventions, and therefore it cannot be used as representative of the planned traffic, or the ETA queue necessary for the calculations of ground and controlled enroute delays. To tackle this issue, we simulate unimpeded flight times, or the times if no ATC and pilot interventions have occurred. We assume that the unimpeded times are equivalent to the 20^{th} percentile of flight times for the same route. Note that the wind effect cannot be neglected, because even if two flights follow the same route and fly at the same true airspeed, their flight time might differ significantly due to strong directional winds. In order to obtain an adequate estimate of the unimpeded time, in this research we isolate the wind effect, calculate null-wind unimpeded time and, if necessary, estimate the unimpeded time for some assumed wind conditions, by adding the wind effect to the null-wind unimpeded flight time. The weather prediction data used in this study is based on the Meso Scale Model (MSM) provided by Japan Meteorological Agency. MSM covers Japan and its surroundings and includes 51-hour or 39-hour forecasts of wind and temperature on a three-dimensional grid every 3 hours [8]. The three-dimensional grid points are placed every 0.125 degrees in longitude and 0.1 degrees in latitude at every 50-100 hPa pressure altitudes. In our estimations, data for 0, 3, 6, 9, 12, 15, 18, 21 UTC time are used. Wind data in not explicitly interpolated to match the radar data temporally, i.e. the wind is assumed to be the same ±90 min of the original data time. For example, for a flight between 3:30 and 7:00 UTC, two wind data sets are used: the flight segment between 3:30 and 4:30 uses the 3 UTC wind data, and the remaining flight segment between 4:31 and 7:00 uses the 6 UTC wind data.

Under the above assumptions, null-wind flight times are calculated as follows:

1. Assume wind speed (both northward and eastward wind speed components) are constant between any two points A and B from CARATS Open Data. Use the location of the midpoint of the AB line segment to obtain the wind data from MSM.
2. Calculate the wind speed in the direction of the AB segment.
3. Estimate the null-wind flight time based on the wind speed determined above.

A sample calculation result is shown below. The altitude profile of this particular flight obtained from the radar data is shown in blue in Figure 3. Aircraft positions are consistent, on average, and available every 10 seconds, but at times data can be sporadic, as seen for the interval between 16:37:51 (altitude 12,250 ft) and 16:37:59 (altitude 13,218 ft). Since we are concerned with the total flight time, such data impurities are not corrected explicitly and no filtering is added. The red line shows the reference wind plot altitude. Note that the null-wind calculations do not consider constant wind altitude for the entire profile, but only single wind altitude reference between each two data points. The wind plot reference altitude is only shown for illustrative purposes to aid the readers understanding of the wind data shown in Figure 4. The estimated null-wind altitude profile is shown in green. According to this estimation, correcting for wind effects and assuming the same lateral flight profile, the arrival time would shift from 17:54:31 to 18:04:17, or almost 20 minutes later. Note that here we assume the aircraft follows the same route and does not make any additional speed adjustments. In reality, airlines might have chosen another route and/or changed the flight's cost index had there been no wind. For visual confirmation, the wind data for 250 hPa on 2016/05/11 18:00 is shown in Figure 4. The light blue arrows show the wind magnitude, and the color-coding of the cells corresponds to the eastbound and northbound wind components magnitude. For most of the flight, the aircraft experienced tail wind which explains why the null-wind estimated flight time is longer than the actual one.

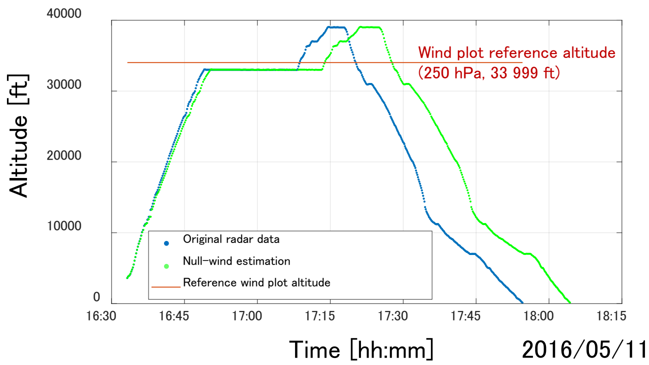

Figure 3 – Original and null-wind trajectory estimation sample

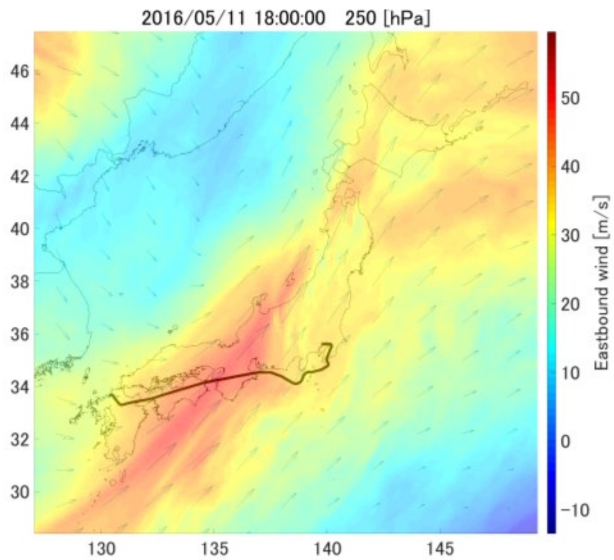

Figure 4 - Wind data for a sample null-wind flight time calculation

Once the null-wind flight times for each route are calculated, a reverse process can be used to determine the unimpeded time for each wind condition. These unimpeded flight times, together with some simulated ground delay times, are used to generate the ETA queue for each day. This ensures high-fidelity simulation assumptions and overcomes the lack of flight plan data. Note that the simulated ETA queues do not need to match the real data for the day, as comparison is made between two simulated data sets (CFDT and non-CFDT scenarios), and not between real data and simulations.

Simulations are performed for a single day of traffic (2015/11/13) arriving at Tokyo International Airport runway 34L. The simulated ETA queue includes 435 flights, with 77 (about 18%) being international flights, potentially subject to controlled enroute delays. The international and domestic arrivals distribution over the day, shown in 30 min blocks are shown in Figure 5. Assuming required separation of 2 min, the 30 min capacity is 15 landings. There are no interferences with departures.

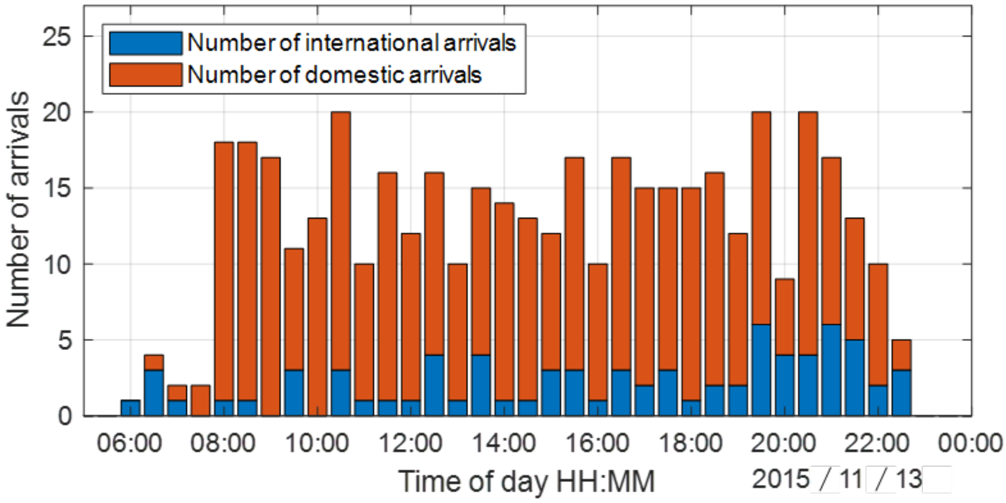

Figure 5 - Daily arrival traffic demand (number of arrivals per 30 minutes)

2.1.4 Resequencing

In order to achieve a fair delay distribution, both ground and controlled enroute delays should induce as small changes as possible to the original flight sequencing defined by the initial ETA queue. However, since international flights can be assigned only limited delay (i.e. 2 min according to our simulation assumptions) and domestic flights can, in theory, wait on the ground indefinitely, occasionally international flights need to be moved up the sequence. Controlled enroute delays are meant to bridge this gap to a certain extent.

2.1.5 Uncertainties modeling

Here, two types of uncertainties are modelled- departure time uncertainties and flight time prediction uncertainties. Not all flight can depart at their scheduled time, regardless of it being subject to GDP or not. There are numerous reasons behind this prediction errors, with aircraft operation preparation and late passengers being just a few. In this paper, departure time prediction errors are modeled separately for flights subject to GDP and non-GDP flights, as shown in our past work [5].

Further uncertainties which influence traffic flow management are associated with flight time predictions. Flight time prediction errors can be divided into two categories- onboard flight time prediction errors and ground system prediction errors. The former uncertainties are due to errors in the wind forecasts used by the onboard flight management system (FMS). Mori [9] analyzed ADS-C data to evaluate the error between actual and estimated time of arrival over waypoints along the route of international flights to conclude that the onboard flight time prediction error depends on routes and operating airline, but it can be modelled by a normal distribution with a standard deviation of 2% of the predicted flight time. This model is implemented in our simulations as well. Ground system prediction errors occur when the trajectory predicted onboard the aircraft is not downlinked and is expressed as the difference between the ETAs calculated by the ground system and the onboard FMS. In the simulation presented in this paper, the ground system prediction error is not considered and is subject to future work.

2.1.6 Ground and controlled enroute delays calculation updates

When the projected delay is expected to exceed the buffer discussed in Section 2.1.1, ground delay is assigned to domestic flights and controlled enroute delay is assigned to international flights. The exact amount of delay is dynamically calculated and updated prior to the freezing horizon (for example, 40 min before departure for domestic aircraft) and reflects the uncertainties in departure and arrival, as discussed in Section 2.1.5.

2.2 Ground and controlled enroute delay evaluation metrics

This paper investigates the distribution of delay among domestic and international flights and the influence of controlled enroute delays on air traffic flow. Generally speaking, there is a tradeoff between airborne delay and lost throughput- if the sole goal of the ATFM system is to minimize airborne delay, the buffer (see Section 2.1.1) can be simply set to zero, which would result in a lot of ground delay and lost throughput. Here, we consider the following metrics over all target flights for a day of arrival traffic at Tokyo International Airport, runway 34L:

1) Ground delay caused by the GDP (note that departure time errors are not part of the ground delay metric).

2) Controlled enroute delay

3) Airborne delay: delay due to vectoring, for example, usually absorbed within the buffer, excluding the controlled enroute delay. Ideally, controlled enroute delay implementation to international flights should decrease EDCT delay of domestic flights without increasing airborne delay.

4) Position shift: the difference between the position of a flight in the original ETA queue and its position in the final arrival queue.

2.3 Monte Carlo Simulations

Monte Carlo simulations are conducted to reflect the uncertainties effect on delay distribution. At each simulation run, a new set of departure time uncertainties and flight time prediction uncertainties are generated. The same random seeds have been used when comparing simulations with/without controlled enroute delays. To determine the necessary number of Monte Carlo runs, analysis of a separate day of traffic (2015/9/16) is performed. The total airborne delay over all flights (mean and median values) are shown in Figure 6. Therefore, considering calculation time constraints as well, we set the number of Monte Carlo runs to 500.

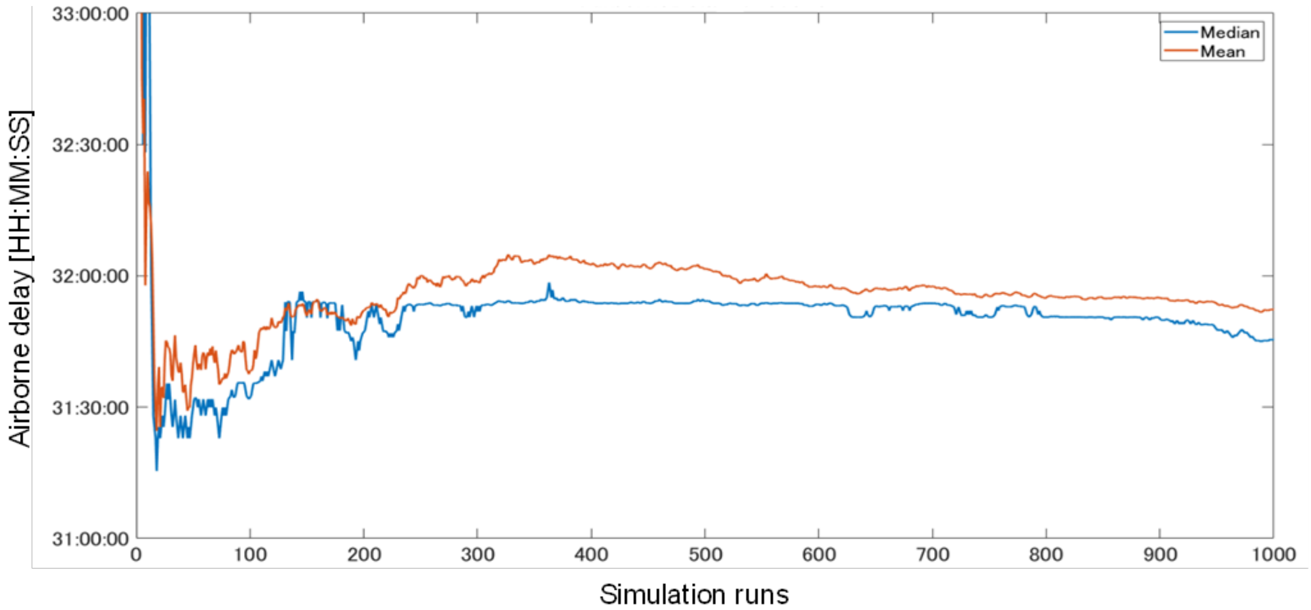

Figure 6 – Monte Carlo simulation convergence test results

3. Simulation results

To investigate the effect of various ATFM control parameters, several simulation series are performed. First, the buffer is set to take discrete values from 6 to 12 min and for each buffer value, ground delay ATFM is assumed and 500 Monte Carlo simulations are run. Next, for the same random seeds of departure and flight time prediction errors, another set of 500 Monte Carlo simulations are run, this time assuming both ground delay and controlled enroute delay. Furthermore, to analyze capacity (throughput) loss, non ATFM control (nominal case) simulations are also performed. The above simulation results are evaluated from two aspects. First, the effects of the buffer values on ground and airborne delays, as well as capacity loss are considered. Second, the impact of controlled enroute delays on ground delays is investigated. Third, to further analyze delay distribution equity, position shift for the cases with/without controlled enroute delay is investigated.

3.1 Buffer effects

Ground delays and controlled enroute delays are calculated based on the allowed airborne delay buffer, i.e. how much additional flight time can be absorbed through vectoring in the terminal area, for example. As discussed in Section 2.1.1, a small buffer leads to small airborne delay, but increases both ground delay and capacity (throughput) loss. This has been verified through our simulations as well. The buffer has been varied between 6 and 12 min, with each value used in 500 Monte Carlo simulation runs. The ground and delays for all flights and all simulation runs for the ground delay and controlled enroute delay case are shown in Figure **7**. Ground and airborne delays are visualized in boxplots. The red line in the middle of each box is the median, and the bottom and top of each box (shown in blue) are the 25th and 75th percentiles, respectively. Outliers are shown in red. The median of the ground delay for the smallest buffer considered (6 min) is 5:40 min, with the 75th percentile reaching 11:52 min and the 25th percentile being 0 min. As the buffer increases, less ground delay is seen, to reach a median of 0 min (75th percentile: 3:20 min) for a buffer of 12 min. Therefore, as the buffer increases, both the median ground delay and the ground delay interquartile range degrease. On the other hand, the airborne delay increases as the buffer increases, as seen in the middle panel in Figure **7**. For visualization purposes, the buffer value for each series of Monte Carlo simulations is shown in green. For most buffer values, the whiskers extend below the buffer value, which shows that apart from the outliers, the airborne delay is managed within the buffer. The capacity (throughput) loss is also investigated. The capacity loss generated by the delay of each flight is defined as the difference in the arrival times between the ATFM controlled case and a nominal case in which no ground and controlled enroute delays are applied. The overall capacity loss is then calculated as the sum over all flights for the day. The median values for each buffer are shown in the bottom panel of Figure **7**. For a buffer of 7 min, for example, an average delay of 1 min per flight is observed. The trends are similar when enroute ground delay is added. These simulation results show that there exists a tradeoff between ground delay, capacity loss and airborne delay, so the optimal buffer value depends on the relative weight of each metric.

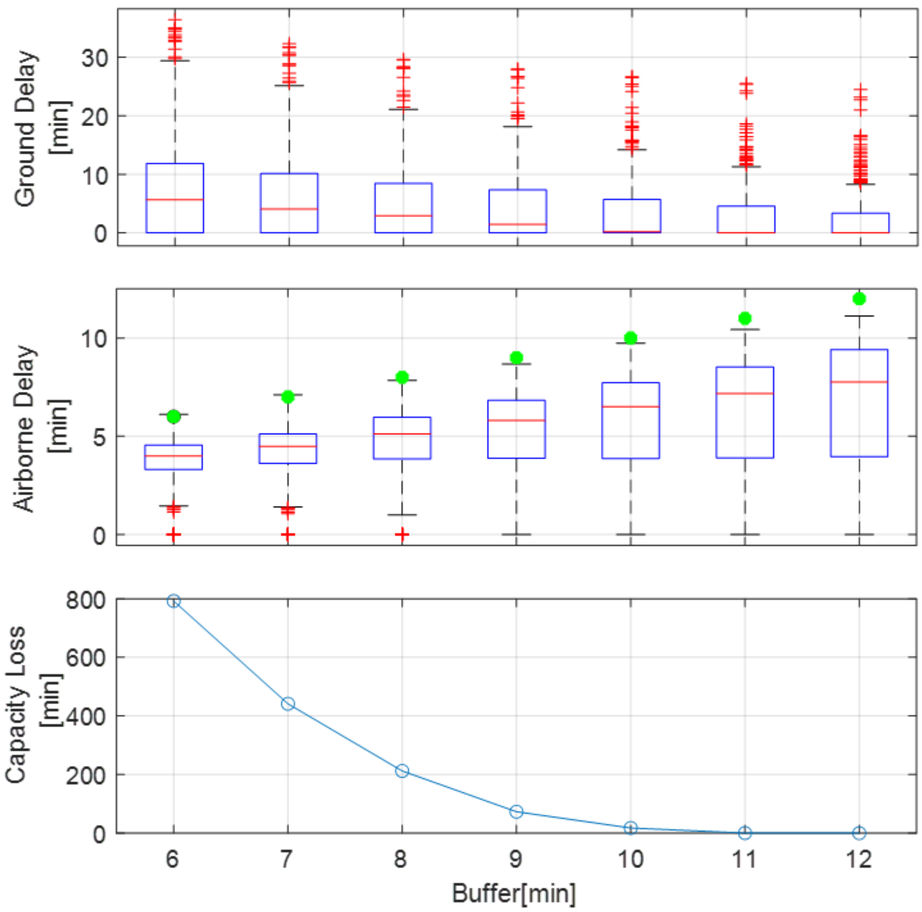

Figure 7 – Buffer effect on ground delay, airborne delay and capacity (throughput) loss

3.2 Effects of Controlled Enroute Delays on Ground Delays

Introduction of controlled enroute delays on international flights should relieve some of the ground delay assigned to domestic flights. Due to the constraints on maximum controlled enroute delay and relatively small number of international flights, however, the above effect is expected to be limited. Boxplots of the ground, controlled enroute and airborne delays for ATFM with/without controlled enroute delays are shown in Figure 8. Regardless of the buffer value, both the average ground delay and number of flights subject to ground delay decreases when controlled enroute delays are assigned to international flights. This proves that such ATFM initiatives contribute to equity in delay distribution. Small increase in airborne delays is seen, however, and this trend is going to be a subject of detailed future analysis.

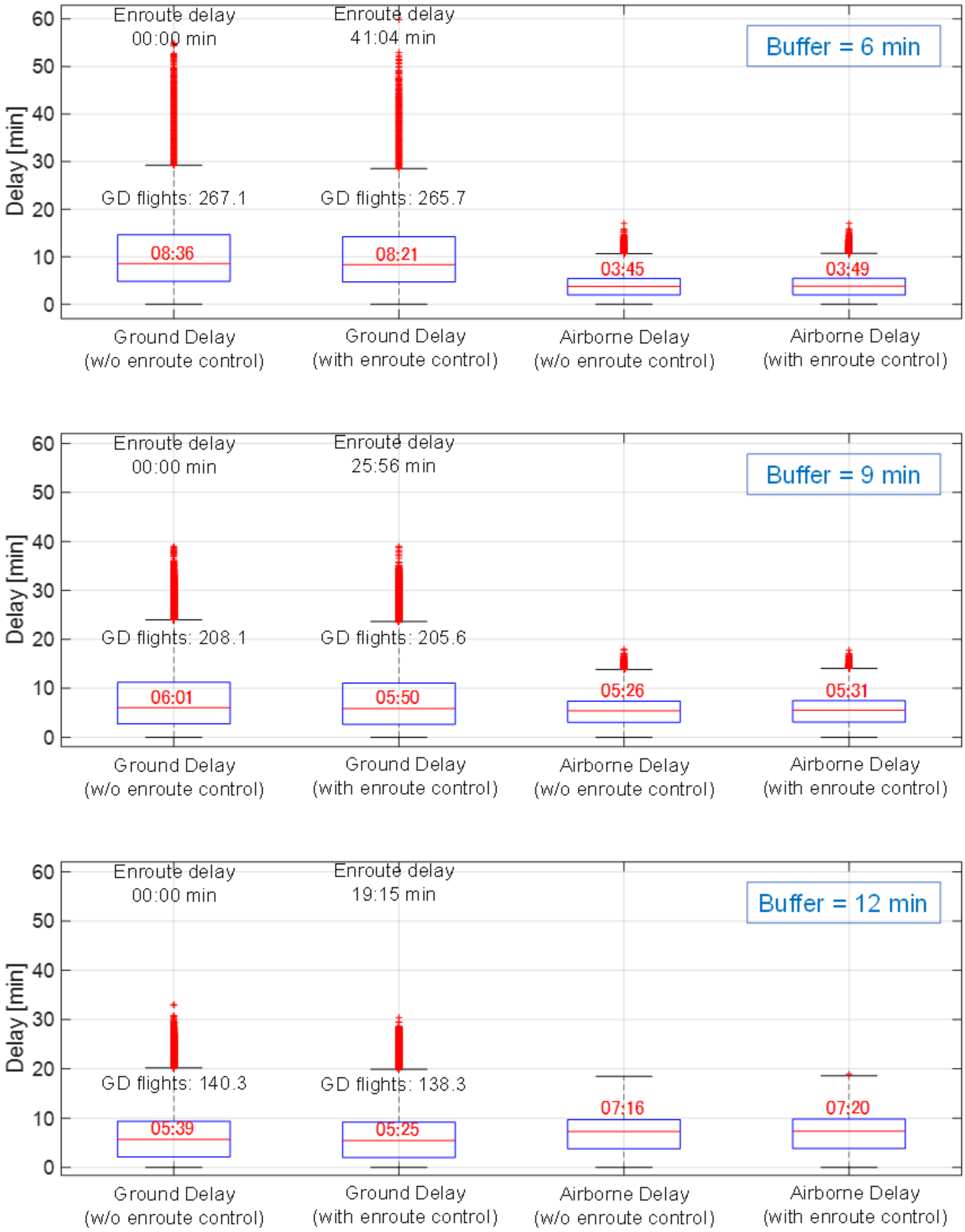

Figure 8 – Ground delay reduction due to controlled enroute delays for several buffers

3.3 Position shift

The equity in delay distribution has been considered from position shift perspective as well. Position shift is defined as the difference in the position of flight *i* in the original ETA queue, and the position of the same flight *i* in the final arrival queue. For example, assume the 5th flight in the final arrival sequence was scheduled to arrive 8th in the original ETA sequence. In such a case, the position shift will be 3. Here, the total number of position shifts for all international aircraft is analyzed. The position shifts for all 77 international flights in the ETA sequence are shown in Figure 9. For all values of the buffer, introducing controlled enroute delays decreases the number of position shifts for international flights. In other words, fewer international flights overtake domestic flights, which contributes to more equity in delay distribution.

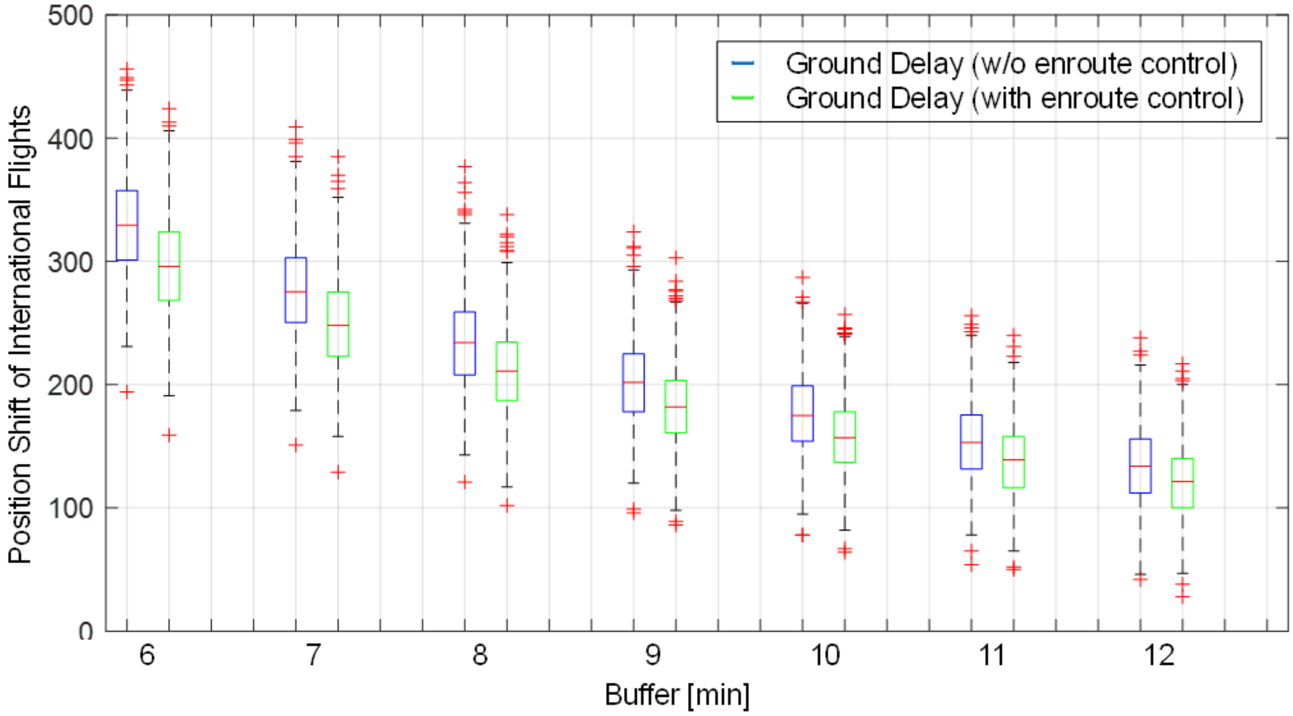

Figure 9 – Position shift of international flights

4. Concluding Remarks

This research considered the introduction of controlled enroute delays, sometimes refereed as long range air traffic management, and the effect on ground delays to domestic aircraft in Japan. Our high-fidelity numerical simulation mimicking arrival traffic at Tokyo International Airport, runway 34L, showed that both the average ground delay and the number of flights subject to it can be reduced by the implementation of controlled enroute delays to international flights. Position shifts of international flights also reduced, which supports more fair delay distribution. Further research is necessary to evaluate the impact of the maximum allowed enroute delay, as well as acceptance/rejection ratio on the equity of delay distribution.

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References

[1] Japan Civil Aviation Bureau. ATFM/CDM in JAPAN. *The Third Meeting of the International Civil Aviation Organization Asia/Pacific Air Traffic Flow Management Steering Group*, Singapore, 2014.

[2] Airservices Australia. Long Range Air Traffic Flow Management (LR-ATFM) [Online]. Available: https://www.airservicesaustralia.com/about-us/projects/collaborative-decision-making-cdm/long-range-air-traffic-flow-management/. [Accessed 21 5 2021].

[3] Airways Corporation of New Zealand and Civil Aviation Authority of Singapore. Long Range ATFM Concept Trials. *The Eighth Meeting of the International Civil Aviation Organization Asia/Pacific Air Traffic Flow Management Steering Group*, New Delhi, India, 2018.

[4] Japan Civil Aviation Bureau. CARATS Main Activities and Results in 2020 (in Japanese).22/3/2021. [Online]. Available: https://www.mlit.go.jp/common/001399994.pdf. [Accessed 21 5 2021].

[5] Andreeva-Mori A, Matsuno Y, and Matayoshi N. Considering Time Uncertainties in Ground Holding for Optimal Traffic Flow Management. *2018 Aviation Technology, Integration, and Operations Conference*, 2018.

[6] Matsuno Y, and Andreeva-Mori A. Analysis of Achievable Airborne Delay and Compliance Rate by Speed Control: A Case Study of International Arrivals at Tokyo International Airport. *IEEE Access,* vol. 8, p. pp.90686–90697, 2020.

[7] Oka M. CARATS Open Data- Explanations (in Japanese)," 2019. [Online]. Available: http://www.mlit.go.jp/common/001231892.pdf.

[8] Japan Meteorological Agency, [Online]. Available: https://www.jma.go.jp/jma/en/Activities/nwp.html..

[9] Mori R. Safety Assessment for Reduced Time-Based Separation Minima on Oceanic Routes. *Journal of Mechanical Systems for Transportation and Logistics,* Vol. 4, No. 1, pp. 39-49, 2011.