Analysis of Achievable Airborne Delay and Compliance Rate by Speed Control: A Case Study of International Arrivals at Tokyo International Airport

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ABSTRACT Metering air traffic requires aircraft to delay their fly-over time at designated enroute fixes. This paper presents an analysis of achievable airborne delays by speed control. To ease real-world implementation, current practices set the same achievable airborne delay to all flights flying the same airway, instead of customizing the achievable delay for each flight. Using past actual radar track and flight data, the achievable delay and its potential compliance rate are analyzed statistically through illustrative numerical simulations for the international arrivals at the Tokyo International Airport. In addition, the potential benefits of fuel savings by speed control are also investigated. Simulation results indicate that 2–4 min delays per 30 min flight time are achievable on average with high compliance rate and 2–3% fuel savings are potentially expected by speed control despite the flight time increase. The analysis conducted allows decision makers to set appropriate achievable airborne delay values to each airway for real operations.

INDEX TERMS Air traffic control, air traffic flow management, air transportation, calculated time over, speed control, trajectory-based operations.

I. INTRODUCTION
The air traffic demand has been growing rapidly over the past decades, and current air traffic management (ATM) systems are under considerable stress. To accommodate the increasing demand, the International Civil Aviation Organization (ICAO) published a new operational concept of global ATM [1]. In order to support the new era of air transportation, the Next Generation Air Transportation System (NextGen) [2], the Single European Sky ATM Research (SESAR) [3] and the Collaborative Actions for Renovation of Air Traffic Systems (CARATS) [4] are ATM modernizations programs that are currently being implemented in the United States, Europe, and Japan, respectively. These programs are aimed at increasing throughput and capacity, improving safety and efficiency, and reducing environmental impact.

As noted by Kistan et al. [5], in their review of the current air traffic flow management (ATFM) research and development programs undertaken in recent years, there are many ATFM techniques to enhance safety and efficiency in view of growing air traffic. A common technique is a ground delay program (GDP) [6]. A GDP is implemented when the destination airport is expected to have insufficient capacity to accommodate forecast demand due to traffic congestions or weather. Ground delays are considered to be less expensive than airborne delays because fuel can be saved by waiting at the apron without turning the engines on instead of delaying the aircraft in the air by putting them in a holding pattern or radar vectoring them. Also, by the GDP, air traffic controller (ATCo) workload can be decreased in sectors where aircraft are required to be airborne delayed. However, the GDP is typically planned conservatively to last longer than actually needed, and this can lead to unnecessary ground delays that cannot be recovered [7]. The unnecessary ground delays can be partially recovered by increasing speed, but the resulting fuel consumption is more than what is initially planned for the flight profile [8].

One of the key concepts of the future ATM systems, as proposed in the NextGen, SESAR and CARATS programs, is the...
paradigm shift of the airspace-based ATM operations to the four-dimensional (4D) trajectory-based operations (TBO), defined as a precise description of an aircraft trajectory in three-dimensional space and time. In the concept of 4D TBO, aircraft 4D trajectories are tactically managed, and times over different designated fixes along the planned routes are controlled through speed adjustments. When a calculated time over (CTO) [9], also known as target time over (TTO) [10] or calculated fix departure time (CFDT) [11], is assigned to aircraft by air traffic control (ATC), the pilot uses speed control to meet the specified time over the fix. Speed control, the core method for CTO operations, has been the subject of several ATM researches. To partially absorb ground delays assigned by implementing the GDP and transfer them to airborne delays, a cruise speed reduction strategy was proposed by Prats and Hansen [12]. Aircraft assigned ground delays are enabled to perform airborne delay and fuel saving with respect to the initially planned nominal flight by flying at the fuel-minimum speed that is typically slower than the initially planned nominal speed. The cruise speed reduction strategy was further explored by Delgado and Prats [13], where the assigned ground delay can be absorbed in the air by flying at the lowest possible speed without extra fuel consumption as initially planned. Thereafter, more related works to the strategy have been conducted by discussing the impact to the GDP [14], [15] and the effects of wind [16]. More recently, the speed control strategy has been extended to include the climb and descent phases [17]–[19], and the approach has been proposed to handle delay assignments flexibly at different places and times along the planned trajectory [20], [21]. In addition, similar research was undertaken by Jones et al. [22], [23], where a speed control approach was proposed to transfer delay away from the terminal to the enroute phase, and significant fuel savings were yielded. Other research has recently presented a stochastic optimization approach for transferring delay by speed control under demand uncertainty [24]. Instead of typical airborne delay by means of airborne holding or radar vectoring, the speed control strategy only adjusts speed to absorb the assigned delay and lets the aircraft fly its planned route. Moreover, as the real application for speed control, a similar strategy was implemented in Australia [25], where aircraft are required to reduce their speed to avoid arriving at an airport before its operational hours, and thereby reduce unnecessary airborne holding. More recently, in New Zealand and Singapore, Long Range ATFM concept trials were conducted to tactically manage the schedules across meter points through speed control [26]. Australia has also announced implementation plans for Long Range ATFM [27].

In Japan, the Japan Civil Aviation Bureau has been considering the implementation of CTO operations to alleviate heavy airspace congestion for the Tokyo International Airport arrivals [11]. The CTO trial operation in Japan begun in August 2011, but was temporarily suspended in September 2014. Several issues with CTO compliance rates and ATCo workload were identified. Work has progressed to address them and CTO operations are due to resume in September 2020. A major reason for the suspension was the difference between airborne and ground-based trajectory predictions. Generally, trajectory predictability in ground systems does not rely on information such as airspeed, aircraft intent, and aircraft and engine performance information. Since the CTO is assigned to aircraft by ATC based on the ground-based trajectory prediction, accurate trajectory prediction is of vital importance. The trajectory prediction is significantly influenced by various uncertainties such as weather prediction errors, navigation errors, and pilots’ intents [28], and consideration of these uncertainties is needed as studied in previous works [29]–[31]. In addition, as studied by Bronsvoort et al. [32], the accuracy of trajectory prediction has improved by synchronizing the airborne and ground-based predictions by downlinking trajectory information such as estimated time of arrival computed by the on-board flight management system (FMS). By synchronizing the airborne and ground-based predictions, the discrepancy in trajectory predictions can be reduced. In order to guarantee the ground-based trajectory prediction accuracy, the airborne trajectory data were downlinked via controller pilot data link communications (CPDLC) and automatic dependent surveillance-contract (ADS-C) in the Long Range ATFM concept trials [26]. However, the accuracy improvement depends on the aircraft’s CPDLC/ADS-C datalink equipage, and a renovation is also required both for aircraft and ATC systems. In addition, even with improved trajectory prediction accuracy, it is still necessary to assign the CTO that can be achieved by speed control. Therefore, in this study, the achievable airborne delay and its compliance rate by speed control are analyzed. Although existing research [12], [13], [16], [18], [19] investigated speed control ability for a single aircraft under a given condition, the achievable delay by speed control is different for every flight because it depends on the aircraft type, nominal airspeed, flight distance, weight, flight level, temperature and wind, to name a few. In the initial implementations of CTO operations in Japan, the same CTO delay for all flights flying the same airway is assigned instead of customizing the CTO delay for each flight. Thus, in this study, the achievable delay acceptable for all flights flying the same airway and its compliance rate are analyzed statistically based on past actual flight data, which have not been investigated in existing research [12], [13], [16], [18], [19]. Also, the potential benefits of fuel savings by speed control are investigated. Although GDP targets domestic flights only, CTO can be assigned to both domestic and international flights. In the initial implementations of CTO operations in Japan, in order to introduce equity in delay distributions, CTO is to be assigned to international flights mainly and combined with GDP assigned to domestic flights [33]. In other words, part of the delays traditionally absorbed by domestic flights only can be assigned to international flights through the CTO initiative. Ground delay times can be updated before the expected departure time. Thus, when a pilot rejects an assigned CTO,
domestic flights’ ground delays are likely to increase to compensate for the delay not absorbed by the international flight. Therefore, it is important to assign the acceptable CTO that can be achieved by speed control. Moreover, since voice communication between pilots and ATCo is applied to the CTO assignment without the datalink systems, the acceptable CTO assignment is important without increasing unnecessary exchange of communication between pilots and ATCo.

The paper is organized as follows. Section II presents the achievable airborne delay by speed control. In Section III, an approach to airspeed estimation is introduced based on radar track data. Through illustrative numerical simulations in Section IV, the achievable delay and its compliance rate are analyzed statistically. The paper ends with conclusions in Section V.

II. ACHIEVABLE AIRBORNE DELAY BY SPEED CONTROL

A. AIRCRAFT DYNAMICS

Fig. 1 illustrates the definition of relation between the ground speed, airspeed and wind speed in the horizontal plane; $v_g$ is the ground speed; $v$ is the true airspeed; $\psi$ is the true track angle; $w$ is the wind vector in the horizontal plane; $w_c$ and $w_a$ are the cross- and along-track wind speed, respectively; and $w_n$ and $w_e$ are the wind speed in northward and eastward directions, respectively. Then, the following relations are obtained:

$$v_g = \sqrt{v^2 - w_c^2 + w_a}$$  (1)

$$w_c = w_n \sin \psi - w_e \cos \psi$$  (2)

$$w_a = w_n \cos \psi + w_e \sin \psi$$  (3)

The wind prediction data provided by operational weather prediction agencies are generally in the form of grid point values of $w_n$ and $w_e$. In typical commercial flight operations, since the lateral path is prescribed based on the planned route and composed by a set of predefined fixes, the aircraft dynamics in two-dimensional horizontal plane are given by the following point mass model:

$$\frac{ds}{dt} = v_g$$

$$\frac{ds}{dt} = \sqrt{v^2 - w_c^2 + w_a}$$  (4)

$$\frac{dm}{dt} = -f$$  (5)

where $t$ is the time; $s$ is the along-track distance; $m$ is the aircraft weight; and $f$ is the fuel flow. In this study, $f$ is described as the function of temperature, pressure altitude, weight, and airspeed, which is obtained from the Base of Aircraft Data (BADA) Family 4 model [34] developed by EUROCONTROL. As mentioned above, the lateral path is composed by a set of predefined fixes based on the planned route, and $\psi$, $w_n$ and $w_e$ in (2) and (3) can be given by prescribed functions of $s$. Accordingly, $w_c$ and $w_a$ are also given by prescribed functions of $s$. In addition, employing $s$ instead of $t$ as the independent variable, (4) and (5) are rewritten as follows:

$$\frac{dt}{ds} = \frac{1}{\sqrt{v^2 - w_c^2 + w_a}}$$  (6)

$$\frac{dm}{ds} = -\frac{f}{\sqrt{v^2 - w_c^2 + w_a}}$$  (7)

The flight time and fuel consumption from the initial position to the CTO fix are calculated by numerical integration of (6) and (7):

$$t_f = \int_{s_0}^{s_f} \frac{1}{\sqrt{v^2 - w_c^2 + w_a}} ds$$  (8)

$$m_f = \int_{s_0}^{s_f} \frac{f}{\sqrt{v^2 - w_c^2 + w_a}} ds$$  (9)

where $t_f$ and $m_f$ are the flight time and fuel consumption from the initial position to the CTO fix, respectively; $s_0$ is the initial position; and $s_f$ is the total along-track distance from the initial position to the CTO fix.

B. SPEED CONTROL

When planning a scheduled flight, operators consider the trade-off between the amount of fuel consumption and the flight time needed to fly a certain route. The relative weight of fuel- and time-based costs is typically expressed as the cost index (CI), which is defined as the time-based cost divided by the fuel-based cost and multiplied by a scalar [35], [36]. The higher the CI is, the higher the priority of time-based cost is and the faster the scheduled cruise airspeed is. Airlines can manage the operating costs by the CI settings on the scheduled flights, and the cruise airspeed for a given flight is changed depending on the importance of time-based cost. The CI values higher than zero are usually preferred due to the importance of time-based cost, and the scheduled flight determined with the airline-preferred CI is regarded as the nominal flight in this study. The nominal cruise airspeed is usually referred to as the economic (ECON) speed, which is denoted by $v_{ECON}$.

![Figure 1. Triangle of velocities.](image-url)
BADA Family 4, we can use the precise performance models for major aircraft types, and information on all aircraft types considered in this study is available.

C. ACHIEVABLE DELAY AND FUEL SAVING

Since the time over the CTO fix is controlled through speed control by reducing airspeed from \( v_{ECON} \), the achievable delay by speed control is given by the difference of flight times with the two different cruise speeds:

\[ \text{Achievable Delay} = t_{f|v=v'_{eq}} - t_{f|v=v_{ECON}} \]  

(13)

where \( v' \) is the airspeed after speed control. The positive achievable delay in (13) means delay, and the negative one indicates early passing over the CTO fix. In this study, in order to investigate the achievable delay, we evaluate the achievable delay based on the three types of speed reduction control, \( v_{MRC}, v_{MEC} \) and \( v_{eq} \), as described in Section II-B.

In addition, we evaluate the amount of fuel saving by speed control, which can be estimated by the following equation:

\[ \text{Amount of Fuel Saving} = m_{f|v=v_{ECON}} - m_{f|v=v'} \]  

(14)

The positive amount of fuel saving in (14) means reduction of fuel consumption, and the negative one indicates increase in fuel consumption. Using the BADA model, we can precisely estimate the flight time and fuel consumption in (8) and (9), and accordingly the achievable delay and amount of fuel saving in (13) and (14).

III. AIRSPEED ESTIMATION

The Japan Civil Aviation Bureau has released a set of aircraft track data for all scheduled commercial instrument flight rules flights in enroute airspace in Japan [37]. The track data are derived from air route surveillance radars, which include time histories of longitude, latitude and altitude with assigned pseudo call signs and aircraft types. The track data are recorded over a week of odd months. In this study we use the 112 days track data from September 2014 to March 2017.

In this study, \( v_{ECON} \) of each flight is estimated based on the track data of each corresponding flight. Using the track data with time histories of longitude and latitude, only the ground speed \( v_g \) in Fig. 1 can be estimated. Then, the northward and eastward wind speed components, \( w_n \) and \( w_e \), are obtained from the numerical weather prediction data. For the numerical weather prediction data, we employ the Meso Scale Model (MSM) provided by the Japan Meteorological Agency. The MSM data\(^1\) include atmospheric properties such as wind and temperature on a three-dimensional grid, and are published every three hours. 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 the analysis, the wind and temperature data are interpolated to match the aircraft track data spatially and temporally by

\(^1\)The data were collected and distributed by Research Institute for Sustainable Humanosphere, Kyoto University (http://database.rish.kyoto-u.ac.jp/index-e.html).
using linear interpolation. Thus, by using the radar track data and MSM data, the time history of true airspeed $v$ in Fig. 1 can be calculated.

Aircraft in cruise are typically controlled to maintain a constant Mach number (or indicated airspeed (IAS)) and pressure altitude, hence $v_{ECON}$ and flight level are assumed to be constant during cruising. Using the radar track data and MSM data, the time history of true airspeed $v$ in Fig. 1 are calculated for each flight, and a single value of $v_{ECON}$ is determined by the linear least-squares method. In order to demonstrate the accuracy of airspeed estimation, actual and estimated airspeeds are compared. The actual airspeed is obtained from a quick access recorder (QAR), which is an on-board flight data recorder. Fig. 3 shows a comparison between actual and estimated airspeeds with 558 flight data. It should be noted that the airspeed in Fig. 3 is in IAS. In Fig. 3, each dot relates the actual and estimated airspeeds for each flight, and a good agreement suggests accurate estimation. The root mean square error between actual and estimated airspeeds is 2.40 kt among 558 flight data, which is small enough to suggest that the airspeed can be accurately estimated by using the radar track data and MSM data. Since wind prediction error is considered as a main source of speed prediction error as explored by Mori [38], more accurate wind information is required for further improvement of airspeed estimation. On the other hand, the airspeed estimation error induces flight time uncertainty, which is out of scope in this paper. Further investigation on uncertainties will be considered in future research.

### IV. NUMERICAL SIMULATIONS
#### A. PROBLEM DESCRIPTION

In this study, the achievable delay and fuel saving by speed control are analyzed through illustrative numerical simulations. Inbound flights to the Tokyo International Airport are simulated, with a focus on international arriving flights from the westward (East Asia and Southeast Asia). We evaluate four representative airways as shown in Fig. 4 and Table 1. Fig. 4 shows the all extracted track data flying the four airways, and Table 1 shows the extracted number of flights from the radar track data and the total flight distances from the Fukuoka flight information region (FIR) entry fixes to the CTO fixes. Flights are subject to CTO only once they enter Fukuoka FIR. In addition, Figs. 5 and 6 illustrate the histograms of aircraft types and flight levels flying the four airways. Note that frequency in Figs. 5 and 6 is among the subtotal number of flights of each airway. As shown in Figs. 5 and 6, the flights have a large variety of aircraft types and flight levels. Each flight has a different achievable delay by speed control because the achievable delay depends on the aircraft type, flight distance, nominal airspeed, weight, flight level, temperature, and wind. However, in the initial implementations of CTO operations in Japan, the same CTO delay for all flights flying the same airway is assigned instead of customizing the CTO delay for each flight. Thus, in this study, the achievable delay acceptable for all flights flying the same airway and its compliance rate are analyzed statistically by using the past actual flight data. Customizing the achievable delay for each flight will be applicable for the future ATM operations.
To assess the achievable delay and fuel saving for each representative airway, we analyze statistically the achievable delay and fuel saving by using all extracted flights on the same airway. Especially, to evaluate the potential compliance rate of achievable delay, we define the following metric for a given assigned achievable delay
FIGURE 7. Achievable delays by speed control.

\[ \text{Compliance Rate} |_{T_{\text{min}}} = \frac{\text{Number of flights that achievable delay is over } T_{\text{min}}}{\text{Subtotal number of flights targeted for analysis}} \]

Note that this metric is calculated for each airway. For example, when \( T = 2 \) min and the compliance rate is 0.8 (80%), 2 min delay can be achieved by 80% of flights targeted for analysis. Using this metric, the achievable delay acceptable for a greater number of flights can be evaluated. The simulations are performed in MATLAB on a computer with a 3.60 GHz Intel Xeon E5-1650 v4 processor and 8 GB RAM.

B. SIMULATION RESULTS AND DISCUSSION

Fig. 7 shows the achievable delays by three speed control strategies. We consider three different initial weights when the aircraft enter the Fukuoka FIR: 80, 90 and 100% nominal weights in the BADA model. The red lines in Fig. 7 represent the median values, and the box shows the 25th and 75th percentiles. The upper and lower whiskers show the maximum and minimum values. As shown in Fig. 7, the achievable delays differ greatly even on the same airway because the aircraft types and flight levels shown in Figs. 5 and 6 vary significantly. Comparing the achievable delays among the four airways, the achievable delays on airway 1 are shorter since the total distance of airway 1 is shortest among the four airways as shown in Table 1. As to the speed control strategies, the achievable delays by the MEC speed are longer than those by the MRC speed, and it is obvious that the MEC speed is lower than the MRC speed and the ranges of speed reduction are different. With respect to delay, the MEC speed has longer delay than the MRC speed and fuel-equivalent speeds. However, the fuel consumption by the MEC speed is greater as clearly shown in Fig. 2. On the other hand, though the fuel consumption by the MRC speed is less than the MEC speed, the amount of delay by the MRC speed becomes shorter. Thus, considering the trade-off between delay and fuel saving, it is reasonable to assign the achievable delay based on the evaluation results by applying the fuel-equivalent speed. In addition, comparing the achievable delays for three different weights, lighter aircraft can achieve longer delays. This is because the MRC and MEC speeds become lower for lighter weight. In previous research [39], the weight difference between the actual weight from QAR data and the nominal weight in the BADA model was investigated, and the actual weight is equivalent to the 75–85% nominal weight in BADA. Therefore, the 80% nominal weight in BADA is used in the following evaluation.

Fig. 8 illustrates the achievable delays when the CTO compliance rate is achieved to 70, 80 or 90%. Note that
FIGURE 8. Achievable delays with different compliance rates.

the horizontal axis shows the CTO assignment time prior to the CTO fix, which is equivalent to the flight time from the CTO assignment to the CTO fix. As shown in Fig. 8, CTO assignments further from the CTO fix increase the achievable delays. However, since CTO is assigned to the flight only in Fukuoka FIR under the current CTO operational concept in Japan, for airway 1 where the CTO fix is close to Fukuoka FIR entry fix, the CTO assignments need to be close to the CTO fix. Accordingly, the flight time to the CTO fix is relatively shorter for airway 1 and the maximum achievable delay becomes smaller for airway 1. Airways 2, 3 and 4 result in the longer achievable delay since the CTO assignment times can be sufficiently far from the CTO fixes. Comparing airways 2 and 3, the maximum achievable delays are almost same, though CTO assignments of airway 3 can be further than those of airway 2. The achievable delay for airway 2 becomes maximum at the CTO assignment time of 50 min, while the maximum achievable delay for airway 3 is at the CTO assignment time of 80 min. The reason is that the number of flights flying at lower flight levels for airway 2 is greater than that for airway 3, as shown in Fig 6. The relation between flight levels and achievable delays is described later in detail. Also, as shown in Fig. 8, the MEC speed has longer delay than the MRC and fuel-equivalent speeds. By applying the fuel-equivalent speed, Fig. 8 indicates that 2 min delay for airway 1, 6 min delay for airways 2 and 3, and 10 min delay for airway 4 can be achieved with the compliance rate of 70%; 2 min delay for airway 1, 3–4 min delays for airways 2 and 3, and 6 min delay for airway 4 can be achieved with the compliance rate of 80%. On the average, 2–4 min delays per 30 min flight are achievable by applying the fuel-equivalent speed with the higher compliance rate.

In addition, Fig. 9 illustrates the compliance rates when achievable delay is assigned to 2, 4 or 6 min. Figs. 8 and 9 have a similar trend, and CTO assignments further from the CTO fix would increase the CTO compliance rate. Fig. 9 indicates that 6 min delay can be achieved by applying the fuel-equivalent speed with the higher compliance rate over 70% except for airway 1. As to airway 1, 2 min delay can be achieved with high compliance rate. On the other hand, longer the CTO assignment time is, larger the influence of uncertainties such as wind prediction errors on flight time prediction is. Concern about uncertainties is out of scope in this paper, however, it will be considered in future research.
Moreover, as shown in Figs. 8 and 9, a drop is seen in all cases around longer CTO assignment time. It is because the CTO assignment time is preceded by the entry time to Fukuoka FIR as shown in Fig. 10. Also, Fig. 10 illustrates the Fukuoka FIR entry rates in different seasons. It should be noted that summer data are comprised of May, July and September, while winter data consist of November, January, and March. Polar jet stream wind blows over Japan from west to east throughout the year, and generally the jet stream tends to be stronger in winter than in summer. Accordingly, for airways 1 to 4, the flight times to the CTO fixes generally become shorter in winter than in summer because of the stronger tail wind in winter. Thus, as shown in Fig. 10, the FIR entry rates with CTO assignment times are different between in summer and winter. In order to compare the compliance rates in summer and winter, Fig. 11 shows the compliance rates in summer and winter by applying the MRC speed when delay is assigned to 4 min. Although the maximum compliance rates both in summer and winter are similar, the CTO assignment time when the compliance rate becomes
maximum is longer in summer than in winter. It indicates that the CTO operations efficiency depends on an appropriate seasonal/wind selections of CTO assignment times, because wind conditions affect both flight times and CTO assignment times.

Furthermore, Fig. 12 illustrates the compliance rates on different flight levels by applying the MRC speed when delay is assigned to 2, 4 or 6 min. Here, year-round simulation results are shown. Fig. 12 indicates that the compliance rate generally becomes higher at lower flight level. This is because the range of speed reduction becomes wider at the lower altitude in terms of aircraft performance. It clearly shows that 4 or 6 min delay can be achieved even by applying the MRC speed for the flights flying at lower flight level with higher compliance rate. In contrast, as for airways 3 and 4, the compliance rates at the flight level of 410 are higher than the flight level of 390. Since the ranges of speed reduction depend on aircraft types even at the same flight level, the compliance rate relies on the ratio of aircraft types that are different from every flight levels. For example, some aircraft types prefer to fly at higher flight levels and others prefer lower flight levels. As shown in Figs. 5 and 6, the ratios of aircraft types and flight levels are different among the airways, and the compliance rates also vary according to aircraft types and flight levels. Thus, it indicates that the CTO operations efficiency depends on an appropriate flight level selections of achievable delays. Setting the achievable delay based on each flight’s flight level and aircraft type is expected to further increase the efficiency in future ATM operations.

Lastly, Fig. 13 shows the fuel savings for the CTO compliant flights when delay is assigned to 1 to 6 min. As described above, since it is possible to achieve delay of up to approximately 6 min with higher compliance rate, fuel savings are evaluated when delay is assigned to up to 6 min. Despite the flight time increase, potential fuel savings are expected as shown in Fig. 13. As shown in Figs. 8 and 9, more than half of flights can achieve up to 6 min delay by reducing airspeed to the MRC speed. Accordingly, the flights can save enough fuel by speed control despite the flight time increase, and 2–3% fuel savings can be expected on the average as shown in Fig. 13. In current ATM operations, airborne holding or radar vectoring are commonly used instead of speed control for flight time management. In the case of imposing the same amount of delay, speed control can save fuel consumption, though holding requires an additional fuel by flying at
nominal airspeed. It is clear that the speed control strategy is significantly effective with respect to fuel savings. When implementing the CTO operations, the fuel savings can be an incentive for airlines as well.

Based on the analysis in this study, decision and policy makers as well as ground-system developers can make informed decisions on the achievable CTO delay and appropriate CTO assignment time with high compliance rate. Once the CTO is assigned to aircraft by ATC, the pilot only adjusts the cruise speed to meet the assigned CTO, which can be controlled by using the on-board FMS without installing new or additional equipment. In addition, in order to manage congestions more efficiently, CTO operations in the enroute phase are supposed to collaborate with an arrival manager (AMAN) in the terminal area. An AMAN assists ATCo to ensure an optimal sequencing and spacing of arrival traffic [5]. Also, throughput can be increased by optimizing runway allocation and arrival sequences [40]. Thus, it is expected to contribute to capacity management of congested terminal areas and airports more efficiently by integrating CTO operations with an AMAN.

V. CONCLUSION

In this paper, we have proposed an approach to analyze the achievable delay by speed control. In the initial implementations of CTO operations in Japan, the same achievable delay for all flights flying the same airway is assigned instead of customizing the achievable delay for each flight. Using the past actual radar track and flight data, the achievable delay acceptable for all flights flying the same airway and its compliance rate have been analyzed statistically. Through the numerical simulations for the international arrivals at the Tokyo International Airport, the achievable delays, CTO assignment times, compliance rates and their relationships have been investigated. Considering the trade-off between delay and fuel saving, it is reasonable to assign the achievable delay based on the evaluation results by applying the fuel-equivalent speed, which is the minimum airspeed yielding the same fuel consumption as flying at the nominal cruise airspeed. The achievable delays acceptable for the representative airways have been evaluated, with the conclusion that 2–4 min delays per 30 min flight time are achievable on average by applying the fuel-equivalent speed with high compliance rate. In addition, the potential benefits of fuel savings by speed control have also been investigated. Despite the flight time increase, the flights can save enough fuel by speed control, and 2–3% fuel savings are averagely expected. Although this paper has focused on the case study of the international arrivals at the Tokyo International Airport, our proposed approach is applicable to any other airways. Through the illustrative numerical simulations, the achievable delay and its compliance rate by speed control have been effectively analyzed.

In this study, the achievable airborne delay by cruise speed control was analyzed in a deterministic environment. In reality, there are various uncertainties that influence the CTO performance. Possible future directions are to extend the analysis to deal with uncertainties such as weather prediction errors, navigation errors, and pilots’ intents and to include the climb and descent phases.

ACKNOWLEDGMENT

The authors would like to thank the members of the CARATS Working Group on Time-Based Air Traffic Flow Management for the valuable and fruitful comments on this article. They would also like to thank the Japan Airlines Company, Ltd., for providing QAR data.

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