

POTENTIAL COST-BENEFIT ANALYSIS FOR THE ASSESSMENT OF AIR CORRIDOR INSTALLATION INTO JAPANESE AIRSPACE

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ABSTRACT

The air corridor is an airspace concept to optimize operational efficiency of flights inside it. However, it inevitably becomes a huge obstacle for aircraft flying outside it. In this study, the cost-benefit analysis is performed in order to clarify the feasibility and the conditions at which the air corridor installation becomes beneficial. The increases of the operational cost of the flights outside the air corridor is analyzed through the comparison between the actual trajectories and numerical simulations of the trajectories to avoid the air corridor. The reduction of the operational cost by flying along the optimum trajectories inside the air corridor is also analyzed through comparison with actual trajectories. It has been clarified that even a small number of flights operated inside the air corridor achieves total operational cost reduction. It is further concluded that the air corridor should be installed as early as onboard self-separation capability becomes available.

1 INTRODUCTION

1.1 Air Corridor Concept

Recently, the introduction of air corridors is being investigated as one of the long-term plans to cope with increasing air traffic demand (Japan Civil Aviation Bureau 2010; NextGen Joint Planning and Development Office 2011). Sometimes referred to as flow corridors, they are projected to become long and narrow airspaces connecting high demand cities and areas. Aircraft will be required to be capable of self-separation using airborne separation assurance systems (Wing and Cotton 2011) to fly within the air corridors following their optimum trajectories punctually. They do not need to obey air traffic control (ATC) instructions to reach the destination. The airspace outside the air corridor will be operated in the same way as current ATC. In this way, the air corridor concept is expected to enhance both traffic throughput and efficiency in the whole airspace without degrading safety. The basic concept of the airspace operation after the air corridor installation is depicted in Figure 1.

In addition, the air corridor is one of the concepts that enable the appropriate treatment of the air traffic where the self-separation capable and non-capable aircraft are mixed. The ratio of air traffic volume between some specific airports and cities in Japan has currently increased significantly (Takeichi et al. 2012). As more than 20% of all domestic flights are between Tokyo and only four other airports, it is expected that the installation of air corridors into such flight routes is suitable.

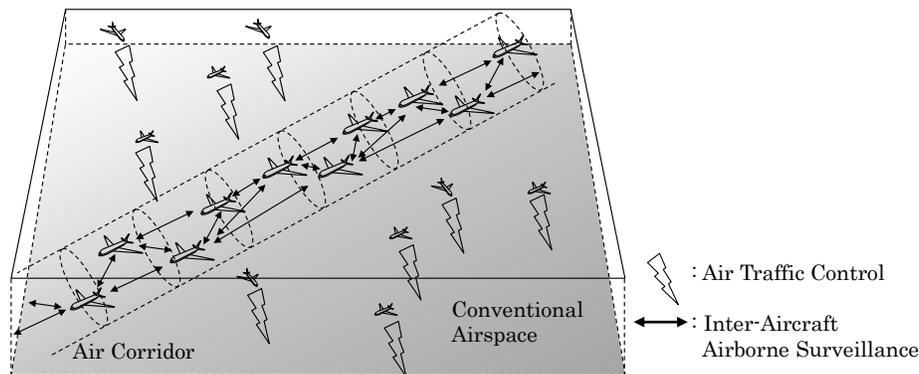


Figure 1: Concept of airspace operation after air corridor installation.

1.2 Previous Studies on Air Corridor

Following the introduction of the concept of the air corridor (Alipio et al. 2003; Yousefi et al. 2004), several studies have been conducted on its operational concepts (Yousefi 2010; Horst 2005), allocation optimization (Yousefi 2004; Sridhar et al. 2006; Hoffman and Prete 2008; Wing et al. 2008; Xue and Kopardekar 2009), and potential benefit assessment (Yousefi and Zadeh 2013; Xue and Zelinski 2010; Takeichi and Abumi 2016). Concerning the allocation of the air corridor, its usefulness was optimized by grouping heavy traffic routes or high-demand airports to simplify the complex air traffic network in the United States through the application of numerical methodologies such as vector field analysis (Yousefi et al. 2004), cluster analysis (Sridhar et al. 2006; Hoffman and Prete 2008; Wing et al. 2008), and Hough transformation (Xue and Kopardekar 2009). The potential benefit of the air corridor was evaluated through some indices such as the potential delay reductions (Yousefi and Zadeh 2013) and the complexity as a measure of the air traffic controller workload (Xue and Zelinski 2010).

In contrast to the complex air traffic network in the United States, the air traffic network in Japan has a simpler topology. Flight trajectories between major city pairs in Japanese airspace on one day in 2014 are depicted in Figure 2. As Figure 2b implies, the flight trajectories between large cities are originally separated from each other except for some congested sectors for ATC near major airports. Therefore, the allocation of the air corridor can also be simplified. In the authors' previous study, the potential reduction of fuel consumption was evaluated assuming that the installation of the corridor airspace would include the optimum trajectories of various types of aircraft in the most congested air traffic route in Japan (Takeichi and Abumi 2016). However, the corridor airspace becomes a huge obstacle for aircraft outside it. Hence, aircraft outside the corridor need to make detours or altitude changes to avoid the corridor airspace, therefore consuming extra fuel and time. It is possible that such operational cost increases can exceed the potential reductions achieved by aircraft inside the air corridor. However, the operational cost increase of aircraft outside the air corridor has never been investigated in previous studies.

1.3 Purpose of This Study

In this study, the total potential benefit, defined as the difference between the potential reductions and increases of operational costs, is analyzed to assess the installation of air corridors. The air traffic from Fukuoka to Tokyo, the heaviest traffic flow in Japan shown in Figure 2b, is especially focused on as a practical example. An example of one-day traffic trajectories from Fukuoka to Tokyo is depicted with blue lines in Figure 3. Aircraft in this traffic route begin descent and obey the ATC after the waypoint FLUTE. The air corridor should be allocated so as not to disturb the ATC in this sector. In this study, therefore, the air corridor is allocated on the inner side of the ATC sector, identified with a red line in Figure 3, so that it rarely affects the ATC of the aircraft outside it.

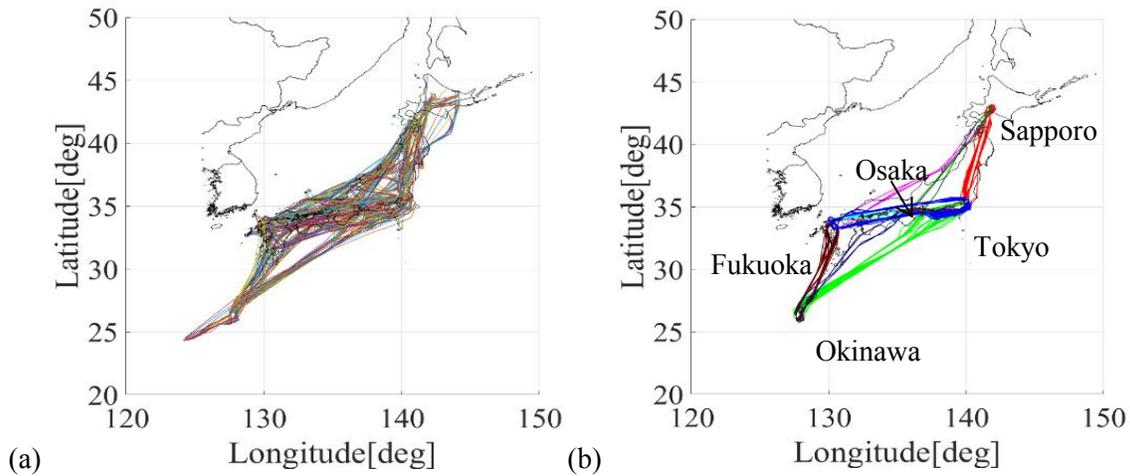


Figure 2: One-day traffic in Japanese airspace in 2014: (a) all domestic trajectories, and (b) trajectories between 5 major cities.

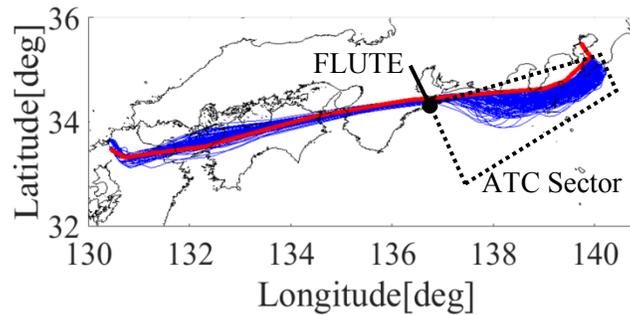


Figure 3: Trajectory of one-day traffic and a proposed air corridor from Fukuoka to Tokyo. Blue lines: actual trajectories, red line: proposed air corridor.

2 ASSESSMENT AND ANALYSIS METHODOLOGIES

2.1 Operational Cost Evaluation and Interpretation for Assessment

As aircraft inside an air corridor can fly along their optimum trajectories, it is possible to estimate their operational cost through trajectory optimization analysis. In addition, the operational cost of actual flights can be estimated using empirical data. Therefore, the potential reduction of operational costs is evaluated as the difference between the current average operational cost of a specific aircraft type and the optimum operational cost of the same aircraft type.

Aircraft outside the air corridor need to modify their trajectories to avoid the corridor airspace. The potential increase in operational costs to modify the trajectory is evaluated as the difference between the operational cost of the modified trajectories and the original ones. Because the trajectory modification strongly depends on each situation, the potential increase of operational costs is evaluated as the daily mean of the summation of potential cost increases of all flights.

In this way, the potential reductions and increases of operational costs are evaluated per aircraft and per day, respectively. From the evaluation results, the required number of flights inside the air corridor to achieve a reduction of the total operational cost is calculated. Through a comparison between the required number of flights and the number of actually operated ones, it is possible to identify the point at which the air corridor installation becomes beneficial.

2.2 Operational Cost Calculation Methodology

The operational cost is defined as the linear summation of fuel and time consumption as follows (Robertson 2007):

$$\begin{aligned} \text{Cost} &= \text{Fuel}[\text{kg}] + \text{CI} \left[\frac{\$/\text{hour}}{\text{cents}/\text{lb}} \right] \times \text{Time}[\text{s}] \\ &\cong \text{Fuel}[\text{kg}] + \frac{\text{CI}}{79.4} [\text{kg}/\text{s}] \times \text{Time}[\text{s}] \end{aligned}$$

where CI is the cost index. The fuel consumption is calculated using the BADA aircraft performance model (Nuic 2015). In this model, the fuel flow is estimated using the thrust force calculated from the following mathematical model:

$$(T - D)V_{TAS} = mg \frac{dh}{dt} + mV_{TAS} \frac{dV_{TAS}}{dt}$$

$$D = \frac{1}{2} \rho V_{TAS}^2 S C_D$$

$$C_D = C_{D0} + C_{D2} C_L^2$$

$$C_L = \frac{2mg \cos \gamma}{\rho V_{TAS}^2 S}$$

$$\gamma = \text{atan} \left(\frac{dh}{dx} \right)$$

$$\frac{dx}{dt} = V_{TAS} \cos \gamma + W$$

$$\frac{dh}{dt} = V_{TAS} \sin \gamma$$

where T is the thrust force, D is the drag force, V_{TAS} is true air speed (TAS), W is wind speed in the direction of flight, γ is the flight path angle, x is the distance from the initial position, h is altitude, m is the aircraft mass, S is the wing area, ρ is air density, g is the gravitational constant, and C_D and C_L are the aircraft drag and lift coefficients, respectively. C_D is calculated using the parasite drag coefficient C_{D0} and induced drag coefficient factor C_{D2} . The fuel flow is calculated through the following equations:

$$f_{nom} = C_{f1} \left(1 + \frac{V_{TAS}}{C_{f2}} \right) T$$

In the case of steady state cruise, the fuel flow slightly reduces as given in the following equation:

$$f_{cr} = C_{fcr} f_{nom}$$

In addition, when idle thrust is applied, the fuel flow is given as a function of the altitude as follows:

$$f_{min} = C_{f3} \left(1 - \frac{h}{C_{f4}}\right)$$

The rate of mass reduction is given as

$$\frac{dm}{dt} = f_{con}$$

where f_{con} is f_{nom} , f_{cr} , or f_{min} . The drag and fuel flow coefficients $C_{f1} \sim C_{f4}$ and C_{fcr} of each aircraft type are provided in the BADA data set.

2.3 Optimum Trajectory Analysis Methodology

The optimum trajectories are analyzed in order to evaluate the minimum operational cost and to determine the corridor airspace in this study. The objective function is defined as the summation of the fuel and time consumptions of the whole trajectory given as follows:

$$\begin{aligned} Cost &\square \int_0^{t_{fin}} f_{con} dt + \frac{CI}{79.4} t_{fin} \\ &= \int_{x_{ini}}^{x_{fin}} \frac{f_{con}}{V_{TAS} \cos \gamma + W} dx + \frac{CI}{79.4} \int_{x_{ini}}^{x_{fin}} \frac{1}{V_{TAS} \cos \gamma + W} dx \end{aligned}$$

where x_{ini} and x_{fin} are the initial and terminal flight distances along the air corridor. In addition, the upper and lower limits of the indicated air speed (IAS) V_{IAS} and thrust force, and the upper limits of the altitude are considered for the optimization constraints. In the optimization analysis, the IAS and the altitude are treated as the state variables to be optimized. The optimization problem is described as follows:

$$\min Cost \square \int_{x_{ini}}^{x_{fin}} \frac{f_{con}}{V_{TAS} \cos \gamma + W} dx + \frac{CI}{79.4} \int_{x_{ini}}^{x_{fin}} \frac{1}{V_{TAS} \cos \gamma + W} dx$$

where

$$V_{TAS} = \left[\frac{2}{\mu} \frac{p}{\rho} \left\{ \left(1 + \frac{p_0}{p} \left[\left(1 + \frac{\mu}{2} \frac{\rho_0}{p_0} V_{IAS}^2 \right)^{\frac{1}{\mu}} - 1 \right] \right)^{\mu} - 1 \right\} \right]^{\frac{1}{2}}$$

subject to the following constraints:

$$V_{IAS,min} \leq V_{IAS} \leq V_{IAS,max}$$

$$T_{min} \leq T \leq T_{max}$$

$$h \leq h_{max}$$

The maximum and minimum values are provided in the BADA data set. Because the fuel consumption is described as a nonlinear function, this optimization problem becomes a nonlinear programming subject to inequality constraints. In this study, the sequential quadratic programming provided in the MATLAB Optimization Toolbox (Mathworks 2018) is applied for numerical optimization using the multi-start method to avoid local-minimum solutions.

3 POTENTIAL COST REDUCTION EVALUATION

3.1 Actual Data Analysis

In this chapter, the potential reduction of the operational cost is analyzed by comparing the operational performances of actual and optimized trajectories. The actual operational performance is analyzed in this section. For the analysis, the operational track data from 42 days in 2014 provided by the Japan Civil Aviation Bureau (Japan Civil Aviation Bureau 2015) and numerical weather forecast data provided by the Japan Meteorological Agency (Honda et al. 2005) are applied.

According to the operational data, about 50 flights are operated from Fukuoka to Tokyo per day on average. About 50%, 20%, and 30% of them are operated, respectively, by large-sized aircraft such as the B772 and B773, middle-sized aircraft such as the B763 and A330, and small-sized aircraft such as the B738 and A320. In this study, the B772, B763, and B738 are especially focused on as representative types of aircraft for each class. Because mass information is not included in the track data, the initial aircraft mass is given as 90%, 80%, and 90%, respectively, of the standard mass values provided in BADA for the B772, B763, and B738 in all analyses in this study, according to the average of the actual operational mass in Japanese domestic flight (Nakamura and Kageyama 2013). As the cost index information is neither provided, 80, 60, and 40 are applied for the large, middle, and small aircraft classes, respectively, according to Japanese airline captains. The average operational costs of each aircraft type per flight on the actual trajectories above 5000 ft are summarized in Table 1.

3.2 Analysis on Optimum Trajectories

To clarify the potential cost reduction, trajectories with minimum operational cost of the representative aircraft types, B772, B763, and B738, are analyzed. As the lateral trajectory of the air corridor shown in Figure 3 is fixed, the profiles of the pressure altitude and IAS are optimized. The optimum trajectories are analyzed so as to connect the points at 5000 ft on the standard departure and arrival routes. The initial and terminal flight speeds are determined according to the BADA reference profiles. For weather data, the 1-year average of the forecast wind and temperature are applied. The trajectory optimization is performed by discretizing the whole trajectory of 917.6 km into 100 segments. The computational time for one trajectory optimization with for 20 cases of initial conditions was about 10000s on average using a PC with Intel Core i7-7700. The operational costs of the optimum trajectories for B772, B763, and B738 are also summarized in Table 1.

Table 1: Potential Reduction of Operational Cost per Flight.

	Large Size (B772)	Middle Size (B763)	Small Size (B738)
Operational cost per aircraft on actual trajectories	10749.6	8111.9	4815.5
Operational cost per aircraft on optimum trajectories	9363.0	6951.4	4277.3
Potential cost reduction	1386.6	1160.5	538.2

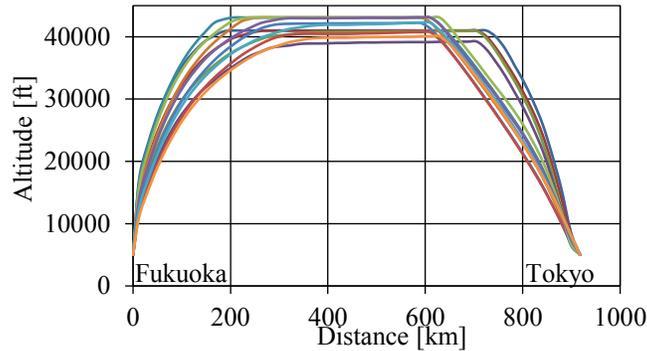


Figure 4: Pressure altitude profiles of optimum trajectories for various mass cases of B772, B763, and B738.

From the operational cost comparison between the actual and optimum ones, the potential reduction of the operational cost per flight is also obtained. In addition, the optimum trajectories of these types of aircraft are also analyzed while changing their initial masses from 70% to 100% of the BADA reference mass. The pressure altitude profiles of these optimum trajectories are summarized in Figure 4, where the horizontal axis shows the distance from the initial position of the air corridor. These trajectories are used for the determination of the corridor airspace.

4 EVALUATION OF OPERATIONAL COST INCREASE

4.1 Corridor Airspace

The vertical airspace of the air corridor is determined so as to include the optimum trajectories for various types of aircraft with various mass. Additionally, as it is expected that overtaking would frequently occur inside it [15], a thickness of 5 NM is given to the corridor airspace. The schematic of the corridor airspace is depicted in Figure 5. As this figure indicates, the corridor airspace becomes quite large.

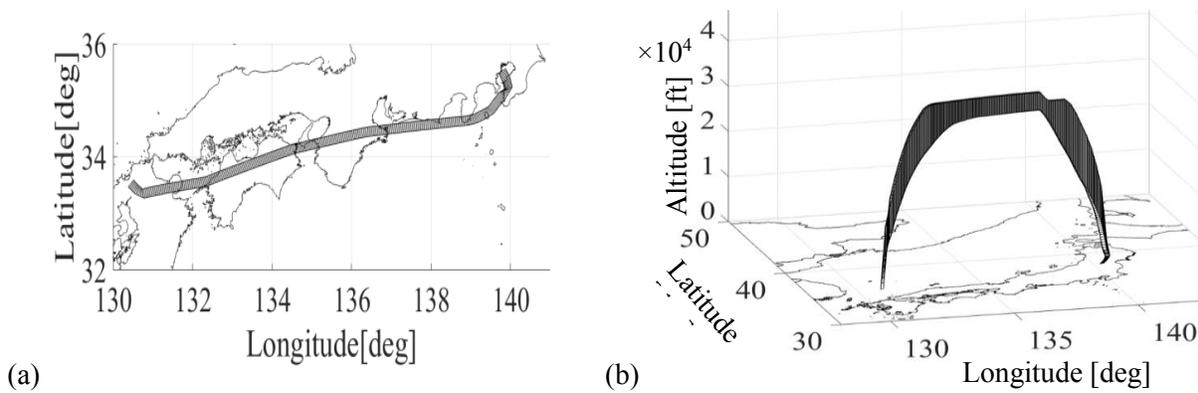


Figure 5: Corridor airspace derived from optimum trajectories: (a) top view and (b) bird's-eye view.

4.2 Extraction of Conflicting Flights

As shown above, the corridor airspace becomes a huge obstacle for aircraft outside it, avoiding which will need consumption of extra fuel and time. In this chapter, the increase of operational costs in the overall airspace is evaluated. To this end, the actual trajectories that conflict with the corridor airspace are extracted from the actual track data. The flights arriving at Tokyo are excluded in this analysis because the air corridor is allocated so that it does not disturb the ATC around Tokyo, as mentioned above. The trajectories

conflicting with the corridor airspace on an example day and the points of conflict are shown in Figure 6. The majority of the conflicting flights are international ones that fly over Japan and domestic flights between regional airports. The total number of conflicting flights was 1877 among the total of 149197 recorded flights over 42 days. Only 44.7 flights per day conflicted with the corridor airspace on average, which corresponds to only 1.3% of the total flights. As is implied by Figure 2, heavy traffic air routes in Japan are originally allocated so that they do not intersect each other with lateral or vertical separation. This is the reason for the small number of flights that conflict with the corridor airspace.

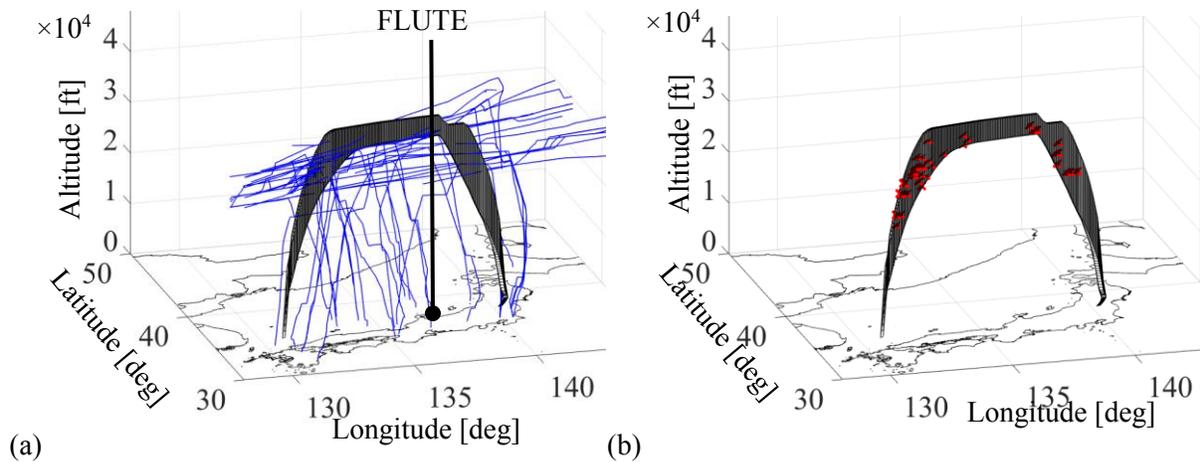


Figure 6: Extracted trajectories of flights conflicting with the corridor airspace: (a) trajectories and (b) point of conflict.

4.3 Trajectory to Avoid Corridor Airspace

In this study, it is assumed that trajectories that can be flown using flight management systems (FMSs) or mode control panels (MCPs) are operated to avoid the corridor airspace. It is possible to easily change the azimuth angle or pressure altitude through the simple operation of the MCP. It is also possible to prepare flight routes in advance by setting waypoints with altitude using the FMS. In this study, therefore, the increases of the fuel and time consumption of two types of trajectories, lateral and vertical avoidance, are analyzed to imitate the trajectories using the FMSs or MCPs. In the analysis, it is also assumed that the flight speed of an avoidance trajectory is the same as its original one.

To avoid the corridor airspace while maintaining a lateral clearance larger than 5 NM, aircraft are supposed to fly along the trajectory connecting the tangential lines with a constant distance of 5 NM from the airspace, as shown in Figure 7a. The initial and final points of the avoidance trajectory are determined such that the changes in azimuth angle are as small as possible. To avoid the corridor airspace by maintaining a vertical clearance larger than 1000 ft, aircraft are supposed to fly along the trajectory, shown in Figure 7b, while applying a constant rate of climb or descent (ROCD) of 900 ft/min. The ROCD is determined according to actual track data of altitude change. Example lateral and vertical avoidance trajectories are depicted in Figure 8.

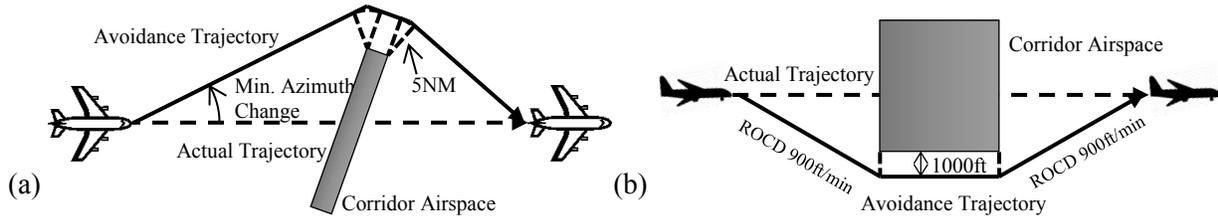


Figure 7: Avoidance trajectories: (a) lateral avoidance and (b) vertical avoidance.

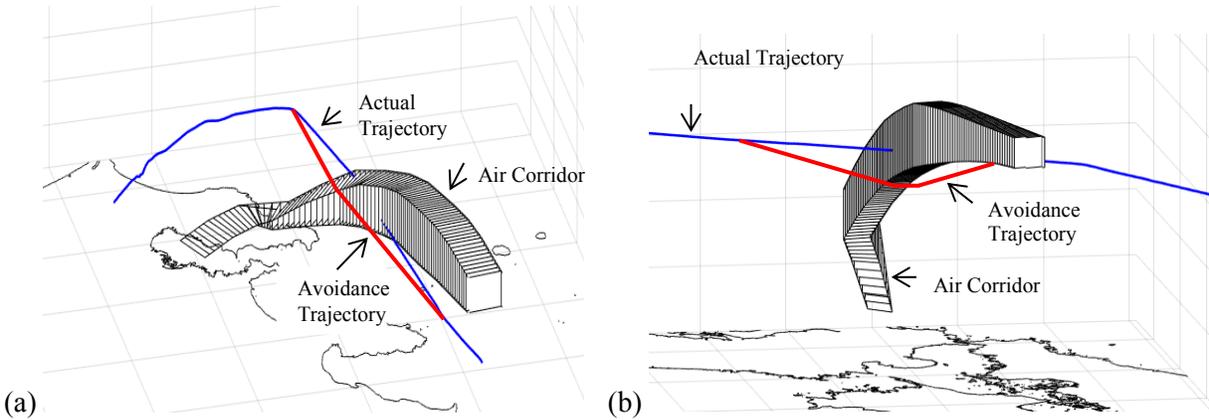


Figure 8: Example avoidance trajectories: (a) lateral avoidance and (b) vertical avoidance.

4.4 Operational Cost Increase Evaluation

The cost increases are analyzed through comparison between numerical simulations and empirical data analysis for both the lateral and vertical avoidance trajectories for all conflicting flights, and the trajectories with smaller cost increases are selected for each conflict avoidance trajectory. The evaluation result for all conflicting flights is summarized in Table 2. Table 2 establishes that the installation of the air corridor must be able to reduce the operational cost by more than 4500 per day so as to be beneficial for the whole airspace.

Table 2: Summary of Potential Operational Cost Increase.

Number of conflict flights in 42 days	1877
Number of flights with a lateral avoidance trajectory	868
Number of flights with a vertical avoidance trajectory	1009
Total operational cost increase	188889.3
Operational cost increase per day	4497.4

5 ASSESSMENT OF AIR CORRIDOR INSTALLATION

5.1 Assessment of the Whole Corridor Airspace

Potential cost reductions achieved by the optimum trajectory flights and potential cost increases induced by the air corridor installation have been evaluated in the previous chapters. In this chapter, the condition at which the establishment of the air corridor becomes beneficial is clarified through a comparison between the potential reduction and increase of operational costs.

Table 3 summarizes the following: (a) the average number of flights per day operated from Fukuoka to Tokyo, (b) the potential operational cost reduction per flight, (c) the required number of flights inside the

air corridor to achieve a potential operational cost reduction that is larger than the potential cost increase, and (d) the ratio of this number to the average number of flights. The result shows that the operation of more than 3.24, 3.88, and 8.36 flights per day for large, middle, and small size aircraft, respectively, in the air corridor are required to achieve a larger cost reduction than the cost increase in the whole airspace. This also means that the installation of the air corridor becomes beneficial if at least 12.4%, 33.4%, and 55.7% of large, middle, and small aircraft, respectively, are equipped with airborne separation systems. It has been clarified that only one-eighth of large size aircraft are required to be equipped with airborne separation systems to make the air corridor beneficial, while more than one-third and half of the middle and small aircraft, respectively, are required.

Table 3: Summary of Operational Benefit Analysis.

	Large Size (B772)	Middle Size (B763)	Small Size (B738)
Number of flights per day	26.2	11.6	15.0
Operational cost reduction per flight	1386.6	1160.5	538.2
Number of flights per day for total cost reduction	3.24	3.88	8.36
Ratio of flight for total cost reduction [%]	12.4	33.4	55.7

6 CONCLUSION

In this study, the cost-benefit analysis is performed for the assessment of the air corridor installation. An air corridor from Fukuoka to Tokyo is investigated as an example case, and both the potential reduction and increase of the operational cost, accounting for all flights in Japanese airspace, are evaluated.

The results clarified that only a small portion of large size aircraft are required to be equipped with airborne separation systems to make the installation of an air corridor beneficial. In contrast, in the case of small size aircraft, it is necessary to equip more than half of them with airborne separation systems. This means that the installation of the air corridor can become beneficial by installing airborne separation systems into large size aircraft prior to other types of aircraft, even if the overall installation ratio of the airborne separation systems are still lower. It should also be noted that the installation of the air corridor works as a kind of promotion of the airborne separation systems. Therefore, it is concluded that the air corridor should be installed as soon as airborne separation systems becomes available.

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