

IMPACT OF DYNAMIC METERING OPERATIONS UNDER ADVERSE WEATHER AND MITIGATION THROUGH OPTIMAL SEQUENCING

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Abstract

Dynamic metering operations are being considered as a potential approach to maintain safe operations under adverse weather conditions. However, the reassignment of metering fixes driven by weather avoidance can disrupt traffic flows and lead to increased operational inefficiencies. This study quantitatively evaluates the impact of dynamic metering operations on arrival performance and investigates the effectiveness of optimization-based sequencing in mitigating such inefficiencies. A mixed-integer linear programming framework is developed to optimize arrival sequencing while considering multiple delay absorption mechanisms, including speed control, radar vectoring, and the point merge system (PMS). The proposed approach is evaluated using a realistic case study based on flight tracking data around Tokyo International Airport under lightning-affected conditions. The results show that dynamic metering operations increase total delay due to traffic concentration at available metering fixes. However, the proposed optimal sequencing approach reduces total delay by effectively redistributing delays among aircraft compared with the conventional first-come, first-served strategy. In addition, the analysis reveals that the optimal approach shifts delay absorption from downstream PMS operations to upstream control actions, enabling more efficient traffic management under weather disruptions. These findings highlight the importance of integrating optimization-based sequencing into dynamic metering operations to enhance the robustness and efficiency of arrival traffic management in weather-impacted environments.

Keywords: Adverse Weather; Air Traffic Flow Management; Dynamic Metering; Mixed Integer Linear Programming

1. Introduction

Aviation demand has been rapidly growing over the last few decades due to globalization, economic development, and the expansion of air transportation networks. This continuous growth has led to increasing congestion in terminal airspace and airports, making efficient air traffic flow management (ATFM) an essential component for maintaining safety, punctuality, and sustainability of air transportation systems. To cope with these challenges, various ATFM initiatives have been introduced, including ground delay programs and time-based flow management concepts [1].

Time-based metering is one of the promising ATFM initiatives that aims to regulate traffic flows by assigning target times of arrival at designated metering fixes. By controlling aircraft arrival times upstream, time-based metering can smooth traffic demand, reduce controller workload, and improve runway throughput predictability [2]. These benefits are particularly important in high-density terminal airspace such as that surrounding major international airports.

Despite its advantages, the effectiveness of time-based metering is highly sensitive to uncertainties, among which adverse weather conditions represent a dominant source of disruption. When adverse weather phenomena such as thunderstorms or lightning are expected, aircraft may need to dynamically avoid hazardous regions by rerouting or by changing originally assigned metering fixes.

A number of studies have proposed methods to mitigate the impact of adverse weather on arrival operations. For example, Erzberger et al. [3] developed an integrated framework for conflict resolution, arrival management, and weather avoidance, highlighting the importance of combining multiple operational functions in weather-impacted environments. In addition, optimization-based approaches have been proposed to explicitly incorporate uncertainty into air traffic flow management, such as chance-constrained formulations under uncertain conditions [4]. Furthermore, Hayashi et al. [5] evaluated a dynamic weather avoidance rerouting tool that provides decision support for maintaining arrival metering operations under weather disturbances.

While these studies primarily focus on route adjustments and conflict management under weather uncertainty, the implications of dynamically changing metering structures have received less attention.

In particular, changing the originally assigned metering fix can disrupt carefully planned traffic flows and lead to operational inefficiencies, including increased airborne delay, excessive vectoring, and higher fuel consumption. From an operational perspective, arrival sequencing plays a key role in absorbing such disruptions. Previous research has extensively studied aircraft sequencing and scheduling problems at airports, often formulating them as optimization problems [6]. More recent studies have proposed integrated frameworks that combine arrival sequencing, dynamic routing, and speed control to absorb delays [7].

However, in current air traffic management (ATM) practice, aircraft are typically sequenced based on a first-come, first-served (FCFS) policy, which is simple and robust but does not necessarily yield optimal system performance under dynamically changing conditions. When traffic demand becomes uneven due to rerouting or metering fix reassignments, FCFS may result in inefficient delay allocation and increased operational cost.

Despite the practical importance of these issues, the inefficiencies induced by dynamic metering operations under adverse weather conditions have not been sufficiently quantified in the existing literature. Furthermore, the potential benefits of integrating optimization-based sequencing into dynamic metering operations remain underexplored. This gap motivates the need to analyze the performance degradation caused by dynamic metering and to explore how such inefficiencies can be mitigated through more advanced ATFM strategies.

In this study, we investigate the inefficiency caused by dynamic metering operations under adverse weather conditions, with a particular focus on lightning-induced disruptions in terminal airspace. We further demonstrate that such inefficiencies can be mitigated through the application of optimal sequencing rather than conventional FCFS operations. To this end, we develop a mixed-integer linear programming (MILP) framework for the arrival sequencing problem, incorporating multiple delay absorption mechanisms such as speed control, radar vectoring, and the point merge system (PMS). The proposed approach is evaluated through numerical simulations based on realistic traffic scenarios around Tokyo International Airport.

2. Adverse Weather

This study focuses on lightning as a representative adverse weather phenomenon that has a significant impact on aircraft operations, especially in terminal airspace. Lightning is often associated with convective weather and poses safety risks to aircraft, leading to airspace capacity reductions and rerouting requirements.

We utilize a lightning prediction algorithm proposed by Yoshikawa and Ushio [8], which classifies lightning occurrence into high or moderate categories based on meteorological data. Figure 1 illustrates an example of lightning prediction around Tokyo International Airport. In Figure 1, red and yellow areas indicate regions with high and moderate likelihood of lightning, respectively. Figure 1 also shows radar echo-top heights. Although the lightning prediction data are provided in two dimensions, lightning cannot occur above the echo-top height. Therefore, this study defines lightning risk zones as regions that exhibit both a high likelihood of lightning and altitudes below the corresponding echo-top height. In other words, predicted lightning regions are confined below the radar echo-top heights, and no lightning is assumed to occur above these levels.

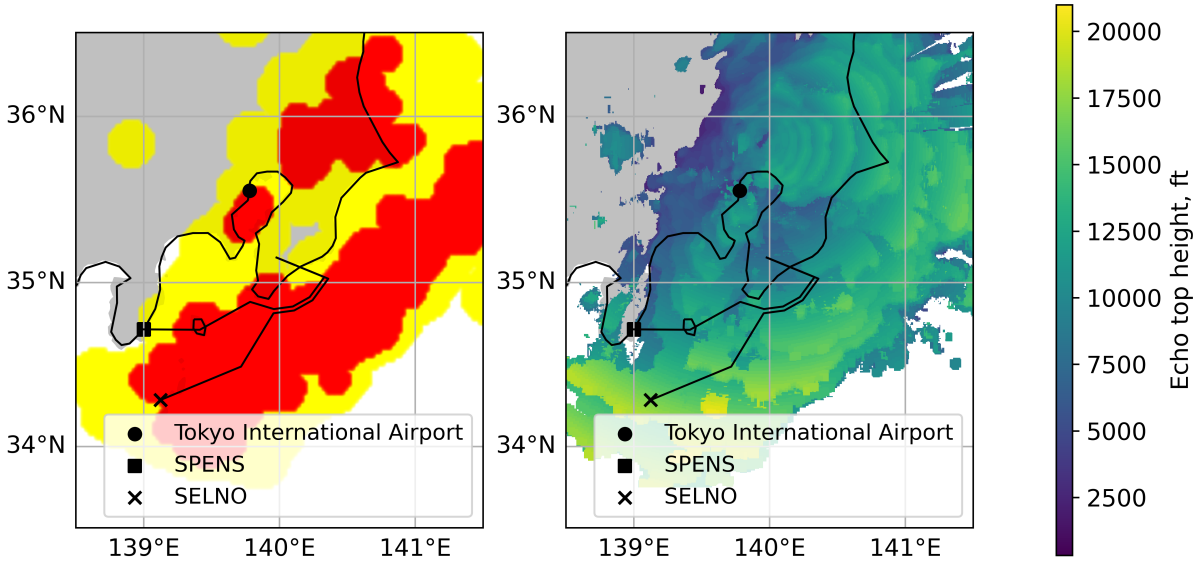


Figure 1 – Example of lightning prediction around Tokyo International Airport.

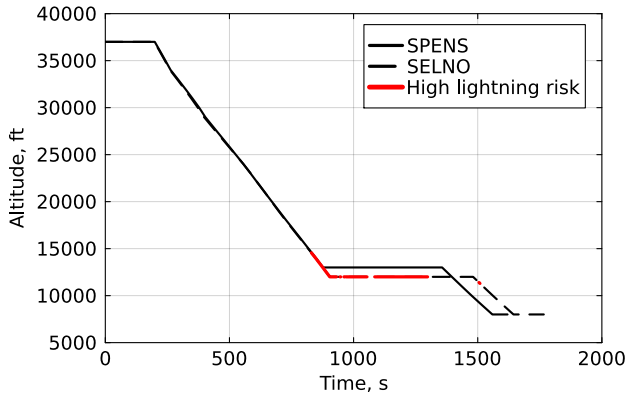


Figure 2 – Example of arrival routes and lightning prediction.

3. Dynamic Metering Operations

Under dynamic metering operations, we assume that aircraft avoid flying over metering fixes that are covered by lightning-predicted areas. When a metering fix is affected by lightning-predicted areas, aircraft originally assigned to that fix are dynamically reassigned to alternative fixes that are less affected by adverse weather.

This study focuses on arrival traffic to Tokyo International Airport, one of the busiest airports in Japan. In particular, we consider arrival flows approaching the airport from the west and the south, which represent major inbound traffic streams. Figure 1 also illustrates two primary arrival routes. Aircraft arriving from the west are assumed to fly over a metering fix called SPENS, while those arriving from the south are assumed to pass over another metering fix named SELNO.

Figure 2 illustrates the time histories of these two primary routes under the same lightning conditions shown in Figure 1. High lightning risk indicates positions of the aircraft trajectories that are covered by high risk lightning areas. As shown in Figure 2, the arrival route through SELNO is more affected by lightning-predicted areas than the route through SPENS. In such a case, traffic originally assigned to SELNO is reassigned to pass over SPENS under dynamic metering operations.

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3.1 First-Come, First-Served Sequencing

As a baseline, we consider an FCFS sequencing policy, which is widely employed in current ATM operations. Under FCFS, aircraft are sequenced according to their order of entry into the sequencing area, without optimization. Specifically, aircraft are ordered based on the time at which they enter the sequencing area, and required separations are ensured by introducing additional delays as needed. When separation constraints are violated, the trailing aircraft is delayed to satisfy the minimum separation requirement. These delays are absorbed through available control actions, namely radar vectoring and the PMS, which are commonly used in current ATFM practices.

Under dynamic metering operations, when aircraft are reassigned to alternative metering fixes due to adverse weather conditions, the FCFS rule is applied independently within each route based on the order of entry into the corresponding sequencing area. While FCFS is simple and operationally feasible, it does not account for system-wide efficiency or the optimal allocation of delays across aircraft. Therefore, FCFS serves as a benchmark to evaluate the performance improvement achieved by the proposed optimal sequencing approach.

3.2 Optimal Sequencing

We formulate the arrival sequencing problem as an MILP problem solved in a receding-horizon manner. Arrival aircraft merge at an initial approach fix prior to landing. We consider flights from approximately 200 NM from the airport to the merge point, and metering fixes are located upstream of the merge point. The entry locations and entry times of aircraft at the 200 NM boundary are obtained from actual flight tracking data, ensuring that the initial traffic conditions reflect realistic operations.

Let $\mathscr{F}$ denote the set of aircraft considered at each decision epoch. For each aircraft $i \in \mathscr{F}$, the arrival time at the merge point T_i is given by:

$$T_i = t_i^{\mathrm{ETA}} + d_i^{\mathrm{spd}} + d_i^{\mathrm{vec}} + d_i^{\mathrm{pms}}. \tag{1}$$

where t_i^{ETA} is the estimated time of arrival (ETA) at the merge point; d_i^{spd} is the delay due to speed control; d_i^{vec} is the delay due to radar vectoring; and d_i^{pms} is the delay due to the PMS. This study considers three ATFM initiatives: speed control, radar vectoring, and PMS.

Aircraft adjust their flyover times at a metering fix for time-based metering operations. Speed control is typically used to adjust the flyover time without altering the planned lateral path. In contrast, conventional ATM operations often increase airborne delay by extending the lateral path through radar vectoring, whereas time-based metering operations absorb the assigned delay primarily through speed control along the planned trajectory. However, our previous studies [9, 10] have analyzed the feasibility of time-based metering operations and reported that speed control alone may be insufficient to absorb the assigned delay. In such cases, a combination of speed control and radar vectoring is required to increase airborne delay.

Metering times $T_{i,r}^{\mathrm{meter}}$ are defined for each route associated with each metering fix $r \in \mathscr{R}$ as:

$$T_{i,r}^{\mathrm{meter}} = \begin{cases} t_{i,r}^{\mathrm{meter}} + d_i^{\mathrm{spd}} + d_i^{\mathrm{vec}}, & r = r_i \\ 0, & \text{otherwise} \end{cases} \qquad \forall r \in \mathscr{R}. \tag{2}$$

where $t_{i,r}^{\mathrm{meter}}$ is the estimated metering time for route r, and r_i denotes the assigned route of aircraft i. We assume that delays due to speed control and radar vectoring are imposed before the metering fixes, whereas delays due to PMS are imposed after the metering fixes.

The control variables are bounded as:

$$0 \le d_i^{\mathrm{spd}} \le \bar{d}^{\mathrm{spd}}, \quad 0 \le d_i^{\mathrm{vec}} \le \bar{d}^{\mathrm{vec}}, \quad 0 \le d_i^{\mathrm{pms}} \le \bar{d}^{\mathrm{pms}}. \tag{3}$$

To enforce a minimum separation time t_{sep}, binary variables $z_{i,j}$ are introduced for all $i < j$. Runway separation is imposed using a Big-M formulation:

$$T_j \ge T_i + t_{\mathrm{sep}} - M(1 - z_{i,j}), \tag{4}$$

$$T_i \ge T_j + t_{\mathrm{sep}} - M z_{i,j}. \tag{5}$$

When $z_{i,j} = 1$, aircraft i precedes aircraft j, implying $T_j \geq T_i + t_{\text{sep}}$. Conversely, when $z_{i,j} = 0$, aircraft j precedes aircraft i, implying $T_i \geq T_j + t_{\text{sep}}$.
Similarly, separation at metering fixes is enforced for aircraft assigned to the same route. For each route $r \in \mathscr{R}$ and for all $i < j$ such that $r = r_i = r_j$:

$$T_{j,r}^{\text{meter}} \geq T_{i,r}^{\text{meter}} + t_{\text{sep}} - M(1 - z_{i,j}), \tag{6}$$

$$T_{i,r}^{\text{meter}} \geq T_{j,r}^{\text{meter}} + t_{\text{sep}} - M z_{i,j}. \tag{7}$$

The minimum separation for metering is set equal to that for runway separation.
The objective function minimizes the total delay and control effort:

$$\min \sum_{i \in \mathscr{F}} \left(w_{\text{delay}}(T_i - t_i^{\text{ETA}}) + w_{\text{spd}} d_i^{\text{spd}} + w_{\text{vec}} d_i^{\text{vec}} + w_{\text{pms}} d_i^{\text{pms}} \right). \tag{8}$$

To ensure consistency with previously arrived aircraft, separation constraints are imposed as:

$$T_i \geq L^{\max} + t_{\text{sep}}, \tag{9}$$

$$T_{i,r}^{\text{meter}} \geq M_r^{\max} + t_{\text{sep}}, \quad \forall r \in \mathscr{R}. \tag{10}$$

This optimization problem is solved repeatedly in a receding-horizon framework. At each time step, aircraft within a finite horizon t_{horizon} are selected, and only decisions within a short freeze window t_{window} ($\leq t_{\text{horizon}}$) are implemented. The current time is then advanced, and the problem is re-solved, enabling adaptive arrival management under dynamic conditions.

4. Numerical Simulations

This section considers a representative dynamic metering scenario under adverse weather conditions, building on the operational framework described in Section 3.. We describe the problem setting and present numerical simulation results.

4.1 Problem Setting

The focus of this study is on arrival traffic to Tokyo International Airport, which is one of the busiest airports in Japan. In particular, we consider arrival flows approaching the airport from the west and from the south, which represent major inbound traffic streams.
Under nominal conditions, aircraft arriving from the west are assumed to fly over a metering fix called SPENS, while aircraft arriving from the south are assumed to pass over another metering fix named SELNO. These metering fixes serve as entry points to the terminal airspace prior to merging at the initial approach fix.
In the considered scenario, lightning-predicted areas cover the region around one metering fix, making it unavailable for metering operations. In contrast, another metering fix remains less affected by lightning and is therefore the only available metering fix. Following the dynamic metering concept described earlier, aircraft originally assigned to the affected metering fix are dynamically reassigned to the alternative metering fix to avoid hazardous weather regions.
Based on this rerouted traffic configuration, two approaches for arrival sequencing are compared: the FCFS approach and the optimal sequencing approach described in Section 3.. The FCFS approach represents conventional operations, in which aircraft are sequenced without global optimization. In contrast, the optimal sequencing approach employs the MILP model to minimize total delay while satisfying operational constraints such as separation requirements and feasible delay bounds.
Multiple delay absorption mechanisms are considered, including speed control, radar vectoring, and PMS. The FCFS approach considers only radar vectoring and PMS, reflecting current ATFM practices, whereas the optimal sequencing approach utilizes all three mechanisms to achieve more effective delay management. The upper bounds of control variables in Eq. (3) are set as follows: $\bar{d}^{\text{spd}} = 1$ min, $\bar{d}^{\text{vec}} = 60$ min, and $\bar{d}^{\text{pms}} = 20$ min. The upper bound for delay absorption through speed control is relatively small and is set based on the values analyzed in [9, 10].
In addition, for the optimal sequencing approach, the weights in the objective function in Eq. (8) are defined as follows: $w_{\text{delay}} = 1$, $w_{\text{spd}} = 1$, $w_{\text{vec}} = 10$, and $w_{\text{pms}} = 100$. Since the altitude at which PMS

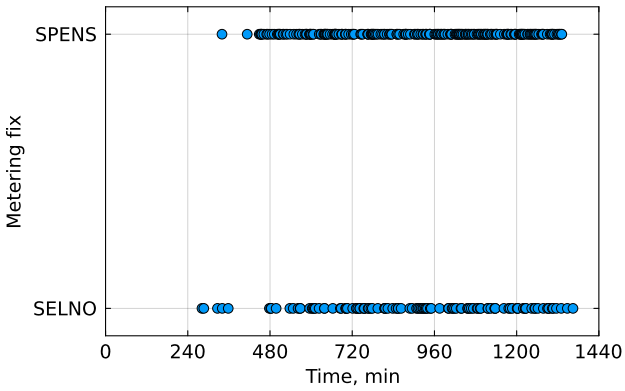


Figure 3 – Time histories of originally assigned metering fixes.

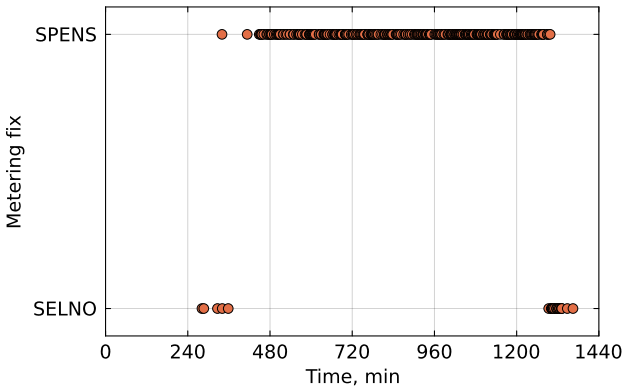


Figure 4 – Time histories of reassigned metering fixes under dynamic metering operations.

is applied is typically lower than that of radar vectoring, fuel consumption tends to be higher at lower altitudes. Accordingly, a larger weight is assigned to PMS in the objective function. The weights reflects the higher fuel cost associated with operations at lower altitudes.

4.2 Simulation Results

In this study, we analyze a representative day during which lightning was observed around Tokyo International Airport. A set of actual flight tracking data provided by the Japan Civil Aviation Bureau is used [11]. The total number of flights considered is 345.

Regarding the originally assigned metering fixes, 231 flights (67%) are routed through SPENS, while 114 flights (33%) are routed through SELNO. The time histories of the originally assigned metering fixes are shown in Figure 3. The time axis in Figure 3 represents the entry time into the sequencing area.

Under the dynamic metering strategy, metering fixes are reassigned based on lightning predictions, with preference given to fixes that are less affected by lightning. Figure 4 illustrates the time histories of the reassigned metering fixes. In this case, 322 flights (93%) are routed through SPENS, while only 23 flights (7%) are routed through SELNO. For the majority of flights, the assigned metering fix is changed to SPENS. This demonstrates a significant redistribution of traffic toward SPENS due to lightning-avoidance operations.

As a baseline for comparison, the actual time of arrival (ATA) is considered, which is obtained from the actual flight tracking data. Figure 5 shows the total delays relative to the ATA for two sequencing approaches: FCFS and optimal sequencing. The results indicate that delays under dynamic metering operations increase compared to the original operations, as changing the metering fix introduces additional delay relative to the original ATA.

However, this increase in delay can be mitigated through optimal sequencing. As shown in Figure 5,

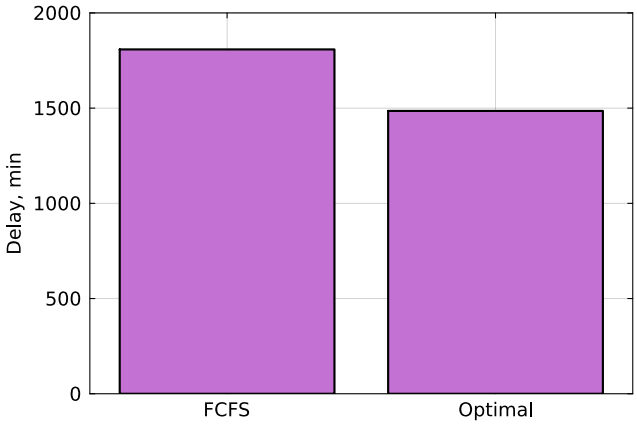


Figure 5 – Comparison of total delays relative to ATA under FCFS and optimal sequencing approaches.

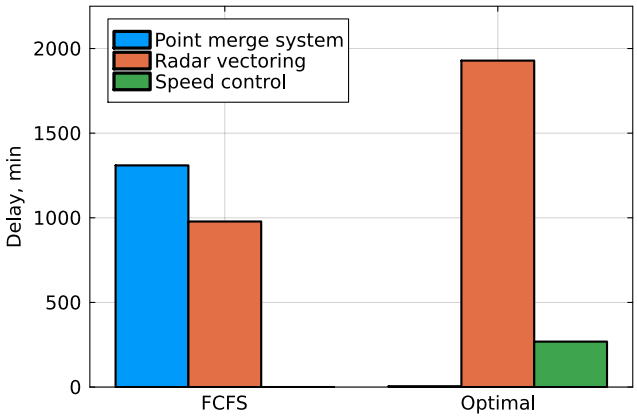


Figure 6 – Distribution of delays among speed control, radar vectoring, and PMS under FCFS and optimal sequencing approaches.

the total delay is reduced by approximately 18% compared with FCFS. In addition, the average delays per flight are 5.24 min and 4.31 min under FCFS and optimal sequencing, respectively. The corresponding median values are 4.60 min and 1.05 min, respectively. Compared with FCFS, the optimal sequencing approach more effectively redistributes delays among aircraft, resulting in a lower total delay. This demonstrates the effectiveness of optimization in mitigating weather-induced inefficiencies.

Furthermore, Figure 6 illustrates the breakdown of delays among the three types of delay absorption mechanisms. Under the FCFS approach, PMS accounts for a large portion of the total delay, reflecting its role in absorbing excess demand downstream. In contrast, PMS is rarely utilized under the optimal sequencing approach because the objective function in Eq. (8) penalizes delay absorption by PMS. Instead, delays are absorbed upstream before aircraft pass over the metering fix. Consequently, speed control and radar vectoring become the primary means of delay absorption.

The average delays per flight due to radar vectoring are 2.84 min and 5.59 min under FCFS and optimal sequencing, respectively, while the corresponding median values are 1.77 min and 1.15 min. The average and median delays due to speed control are 0.78 min and 1.00 min, respectively, indicating that most flights utilize speed control up to its maximum allowable bound of 1 min. In contrast, the average delays due to PMS are 3.80 min and 0.01 min under FCFS and optimal sequencing, respectively, while the median values are 2.62 min and 0.00 min.

It should be noted that the total delays shown in Figure 6 differ from those in Figure 5. This difference arises because the delays in Figure 5 are measured relative to the ATA, whereas the delays in Figure 6 are measured relative to the scheduled time of arrival (STA) to quantify the contributions of individual delay absorption mechanisms.

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In addition to delay performance, the impact on operational risk is evaluated in terms of exposure to lightning. The total time that aircraft trajectories pass through lightning-predicted areas is reduced by approximately 32% under dynamic metering operations. The baseline is defined as the total exposure time of actual flight trajectories within these hazardous regions. This result indicates that dynamic metering contributes to risk mitigation by enabling more effective avoidance of adverse weather, albeit at the expense of increased delay.

These results highlight the importance of selecting appropriate delay absorption mechanisms under dynamic metering operations. In particular, the proposed optimal sequencing approach effectively redistributes delays across aircraft and mitigates the operational inefficiencies induced by adverse weather conditions. Moreover, the combined analysis of delay and lightning risk demonstrates a fundamental trade-off between efficiency and safety in dynamic metering environments, and shows that optimization-based sequencing can help achieve a better balance between these competing objectives.

5. Conclusions

This paper presented numerical results on the inefficiency caused by dynamic metering operations under adverse weather conditions. The results demonstrated that while dynamic metering inevitably increases delay due to the reduction in available metering fixes, such inefficiency can be mitigated through optimal arrival sequencing based on an MILP framework.

Through a realistic case study around Tokyo International Airport, it was shown that dynamically reassigning metering fixes leads to significant traffic concentration and increased delay. However, the proposed optimal sequencing approach effectively redistributes delays among aircraft by utilizing multiple delay absorption mechanisms, resulting in a substantial reduction in total delay compared with the conventional FCFS approach.

In addition, the analysis of delay absorption mechanisms revealed that the proposed method shifts delay absorption from downstream PMS operations to upstream control actions such as speed control and radar vectoring. This result is obtained under the assumption of deterministic flight times. When uncertainty in flight time is taken into account, the use of PMS may increase to provide additional buffering and mitigate potential capacity loss. Similar observations have been reported in previous studies that incorporate uncertainty and highlight the importance of buffering strategies under uncertain conditions [12, 13].

These findings highlight the importance of integrating optimization-based sequencing strategies into dynamic metering operations to improve system performance in weather-impacted environments. Overall, this study provides a quantitative assessment of the performance degradation induced by dynamic metering and demonstrates the effectiveness of optimization-based mitigation strategies.

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