On Required Distances to Absorb Metering Delays

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Abstract

We analyze the distance that is required to absorb metering delays during the cruise phase. This is a simple but fuel efficient strategy for future traffic synchronization. This distance depends on the level of airspace congestion, but also on aircraft performance. We see how the distance changes over time and how it is distributed in some special scenarios. Our main result is that we discover the probabilistic structure of the problem. Based on this many refinements can be done to increase the understanding of airspace congestion.

1 Introduction

Air Traffic management coordinators (TMC) are responsible to create the conditions for smooth, safe and efficient flows. When they detect an imbalance between airspace demand and its capacity, the typical measures like ground delays and miles-in-trail, or more recent ones like arrival slot swappings can be taken. At all moments, a TMC needs predictions of demand and capacity. If these predictions were error-free, no more delays would occur during the remaining flight. But this is not the case. For example at hub airports, delays in the arrival phase are a common phenomenon [1]. The reason is that uncertainty factors, including competition for punctual arrivals and weather conditions, make demand and capacity predictions imprecise.

In the future, trajectory-based operations (TBO) promise more accurate executions of planned flights [2, 3]. The common picture then is to identify the times, at which aircraft should cross certain points in the airspace, such that the flows become more regular. ICAO calls this concept traffic synchronization', and characterizes it as a tactical flow measure because it takes place in the shortest of the flow management time horizons [4].

A tool that supports traffic management coordinators already today is the 'Traffic Management Advisor' (TMA) [5]. It predicts the delays that airborne aircraft should absorb in order to avoid a capacity excess at the entry gates to a terminal airspace. The tool is used in many en-route control centers and is also improved by current research projects [3, 6]. In Japan, the radar data processing system (RDP) has similar functionality, but few documentation is available.

The drawback of such tools is that they do not give any guarantees that their calculations are applicable. For example, how much airspace is necessary to absorb the predicted delays ? Or what is the maximum delay that such a tool predicts ?

The purpose of our research is to answer such questions in order to derive strategies for traffic management coordinators to create more efficient arrival flows. In this paper we analyze the most congested Japanese arrival flow and the simplest of all strategies: speed control in the cruise-phase. The paper contains three parts: a radar data analysis, a theoretical analysis, and a summary including the future work.

2 Data Analysis

At Tokyo Int'l Airport, which is one of the busiest ones in Asia, traffic enters the approach area through three gates; one from the South, one from the West and one from the North (Figure 1). On a normal day about 450 flights arrive at the airport, 70% from South and West, and 30 % from the North. Usually, one runway is available exclusively for landings.

There are two main reasons for arrival delays:

Table 1: Average western arrival flow to Tokyo Int'l airport (T09).

Origin	**Aircraft**	**airborne (min)**	h_{in} **(ft)**	v_{in} **(kt)**	v_{out} **(kt)**
Central	137 (49 %)	23.3 (6.0)	291 (54)	484 (39)	379 (28)
South	129 (46 %)	44.2 (3.2)	357 (44)	507 (39)	382 (29)
Int'l	13 (5 %)	59.1 (20.3)	372 (37)	522 (35)	378 (25)

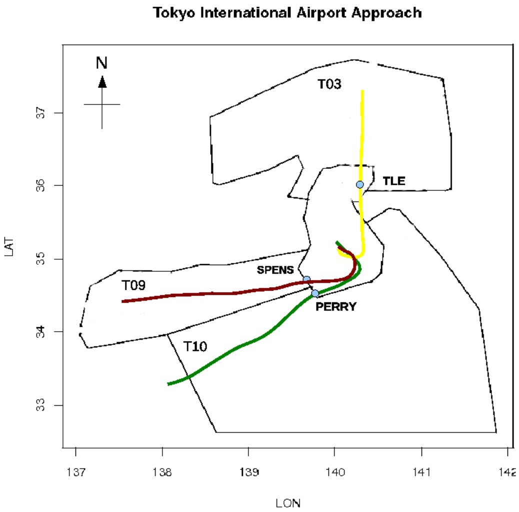

Figure 1: Arrival flows to Tokyo Int'l Airport.

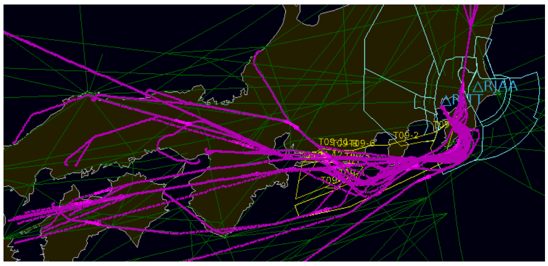

Figure 2: Lateral inefficiencies.

- Metering constraints at the entry gates
- Merging of flows inside the approach area

In order to protect the approach area from congestion, aircraft are separated by $s_m = 10$ NM on the West and North gates, and 20 NM on the South gate. This is larger than the minimum $s_e = 5$ NM radar separation, so delays have to be expected. In the remainder we call such delays *metering delays*. Once the aircraft entered the terminal area, the three flows are merged into one. Delays may occur here, as well.

In this paper we analyze the traffic at the West gate because it creates the highest metering delays. The West gate lies inside the en-route sector T09, belonging to the Tokyo Area Control Center. The size of T09 is approximately 150 NM x 60 NM. We selected 10 days of 'normal' traffic from the months August, October and December 2008, i.e., where no exceptional events or delays were reported. We removed outliers by hand (about 10 % of missing or erroneous fields in the source data). On a typical day, about 450 aircraft per day enter it, and about 290 of them are arrivals to Tokyo Int'l Airport. The main tasks for the controllers in T09 are to meter the aircraft at the gate, and to supervise the crossing of the other ones.

Aircraft enter the sector on all altitudes between FL 200 and FL 410, but all leave the sector at the metering point on flight level 160. This means that the top of descent (tod) lies inside T09. We grouped the origins of the arriving aircraft into three regions: 1: Central Japan (Osaka area and Nagoya), 2: South Japan (Kyushu Island), 3: International flights (China, Korea). Properties of these flows can be seen in Table 1. Aircraft arrive roughly in equal number from Central and South Japan, and only 5% of the flights are international (column 2). The average en-route times of domestic flights are 23.3 and 44.2 minutes (column 3). The numbers in parentheses are the standard deviations in the corresponding units. Flights from Central Japan arrive in average on a lower flight level (FL 291) than those from South Japan (FL 357) or international (FL 372). The average ground speed at the sector entry grows with the flown distance, increasing from 484 kt, over 507 kt to 522 kt (column

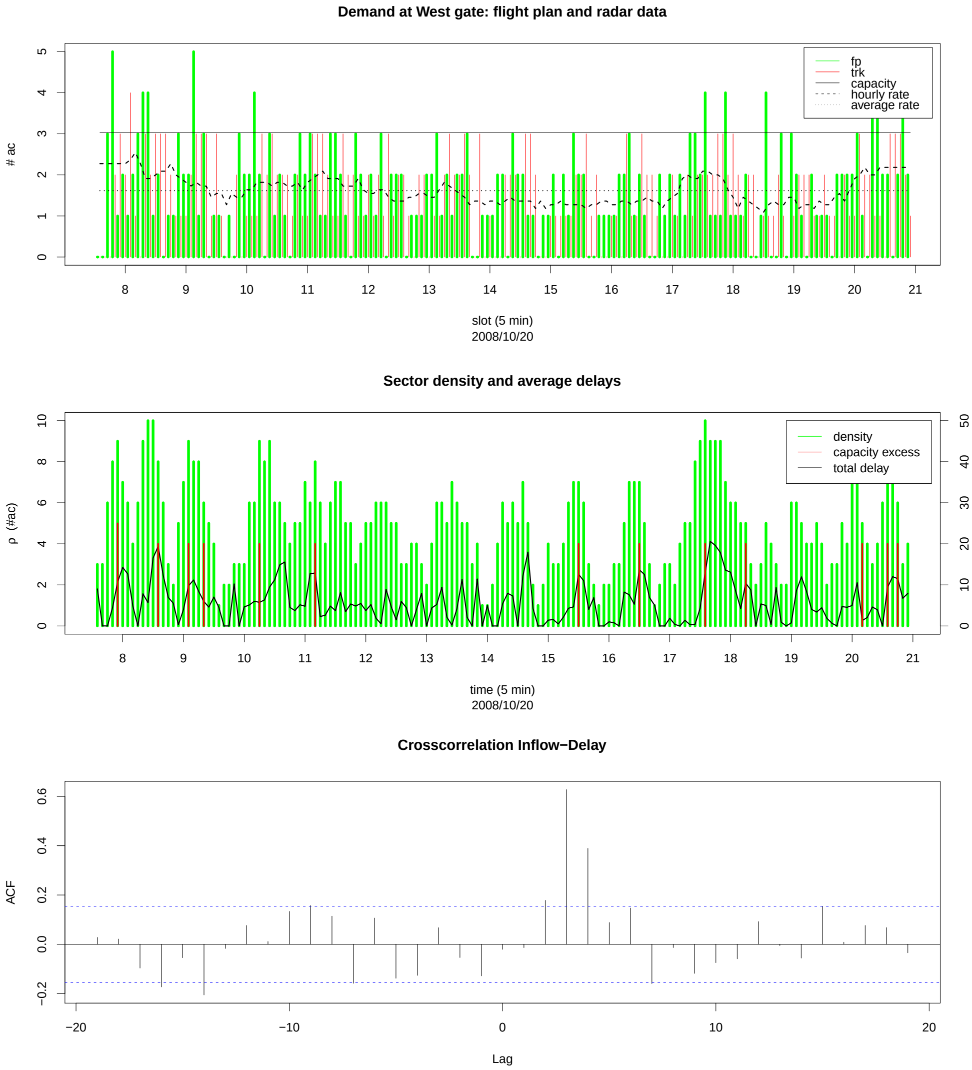

Figure 3: Top: Planned and observed flights. Middle: Sector density and total delay. Bottom: Sample cross-correlation.

6). At the sector exit, the average speed is equally about 380 kt with 27 kt standard deviation. The inefficiencies due to vectoring can be seen in Figure 2. Aircraft enter T09 from the West, and are visibly deviated from their shortest paths. After leaving the sector, they turn left to towards the final approach. Again, delays may occur because of merging.

In order to better understand why delays occur, please take a look at Figure 3. The top panel shows the flow (number of flights/5 minutes) at the metering point between 7:30 and 21:00. The green bars are from the flight plans, the red ones from the radar data. One can see a fluctuating demand, with slightly higher periods in the morning and evening hours. The dotted horizontal line is the daily average arrival flow $\sim 0.3[min]^{-1}$ (it is almost the same for the planned and the realized flights). The bold horizontal line is the capacity at the metering point $\mu = \bar{v}_{out}/s_m = 0.63[min]^{-1}$, where $\bar{v}_{out}$ is the average speed of all aircraft at the sector exit. While the flight plans sometimes exceed the capacity, the radar data generally lies below it. The middle panel shows the sector density $\rho(t+1) = \rho(t) + q_{in}(t) - q_{out}(t)$ (number of aircraft in sector in time slot t) (green) and total delay (black). Here, $q_{in}(t)$ and $q_{out}(t)$ are the corresponding flows with unit $[min]^{-1}$. One can see oscillating sector load with a period of $\sim 30\ min$ throughout the day. At the end of each oscillation, the total delays take peak values. The red bars are the demands where the capacity at the metering point is exceeded. Accordingly, the sample cross-correlation function between inflow and total delay has two peaks of about 0.6 and 0.4 at lags 3 and 4, corresponding to the average sector traversal time (bottom panel).

We conclude that the main causes for delays are that the flight plans exceed the capacity and that there are spontaneous traffic peaks. This confirms the intuition that, despite changing wind conditions and fleet mixes, the traffic density is a major delay driver.

3 Analysis of Speed Control

In this section we analyze the consequences of absorbing a metering delay by a speed reduction during the cruise phase. This is the simplest and most fuel efficient strategy we can think of.

For clarification we start with the following definitions:

Definition (Metering delay)
The difference of the estimated and the scheduled time of arrival at a metering point due to a metering constraint.

Definition (Speed control delay)
The difference of the estimated and the scheduled time of arrival at a sector entry due to speed control.

Definition (Change-point)
The distance from the sector entry at which speed reduction occurs.

Today, arriving aircraft suffer from metering delays, which are caused by a 10 NM separation rule at the gate to the terminal area. These delays are typically absorbed by vectors during descent. If such delays were absorbed during the cruise phase, a following aircraft would have to reduce its cruise speed in order to avoid loss of minimum separation (5 NM). It will suffer from speed control delay. Speed reductions depend on the cruise speed, atmospheric conditions, aircraft type, and more. A comparison of metering delays and speed control delays seems useful.

3.1 Imposed delays

Consider two successive aircraft A_i, A_j flying with cruise speed v_i and $v_j = lv_i$,$l > 0$. Let their estimated time of arrival at the sector entry be eta_i and eta_j, $eta_i < eta_j$. The first aircraft has to absorb a metering delay w_i. When t_i is the time to fly a distance s_i at speed v_i, and t_{ki} is the time at reduced speed $k_i v_i$ ($0 < k_i < 1$) then $w_i = t_{ki} - t_i = \frac{s_i(1-k_i)}{k_i v_i}$. Thus, the required distance to absorb w_i minutes of delay at reduced speed $k_i v_i$ is $s_i = \frac{k_i v_i w_i}{1-k_i}$. Accordingly, A_i will reduce its cruise speed at time $tc_i = (x_{i0} - s_i)/v_i$, where x_{i0} is its distance from the sector entry at time $t = 0$. . In order to keep separation, the following aircraft will eventually reduce its own speed at time tc_2. An illustration can be seen in Figure 4. Time is on the x-axis, distance from the sector entry on the y axis. A_1 (black) flies at 450 kt. It has to absorb

90 sec metering delay by a 10% speed reduction $k_1 = 0.9$, leading to a required distance of $s_1 \sim 101NM$. A_2 (red) flies at a cruise speed 10% larger than A_1. Its separation to A_1 at the estimated time of arrival is 15 NM (filled circles). As a result, it needs to absorb 46 s. Its change-point is at 56 NM (empty circles). The latest moment to do so, when the maximal speed reduction is 10 %, is 8.8 min after A_1 reduced its speed. The question in this subsection is if the speed control delay of aircraft A_j is larger than its metering delay. In the next one we analyze how the change-points jump in the sequence of n aircraft.

At the time of its speed change tc_j, A_j is s_j NM away from the sector entry. Until arrival at the sector entry it flies at speed $k_j l v_i$, so its distance to A_i changes by

$$d_{ij} = \frac{s_j}{k_j l v_i}(k_j l v_i - k_i v_i) \quad (1)$$
$$= s_j(1 - k_i/k_j l), \quad (2)$$

assuming that $tc_j > tc_i$. Our goal is to find the smallest s_j such that

$$|f_j(tc_j) - f_i(tc_j)| \geq s_e + d_{ij}, \quad (3)$$

where $f_j(t) = v_j t - x_{j0}$, $f_i(t) = k_i v_i(t - tc_i) - s_i$ and s_e is the minimum separation between aircraft in the en-route airspace. Substituting $tc_i = (x_{i0} - s_i)/v_i$ in (3) and solving for s_j gives

$$s_j \geq \frac{s_i k_j l(1-k_i)}{k_i(1-k_j)} - \frac{k_j(x_{j0} - l x_{i0})}{1-k_j} + \frac{k_j l s_e}{k_i(1-k_j)}. \quad (4)$$

This is difficult to interpret but substituting $s_j = \frac{k_j v_j \Delta_j}{1-k_j}$ and $s_i = \frac{k_i v_i w_i}{1-k_i}$ in (4) and solving for Δ_j gives

$$\Delta_j \geq w_i - \frac{x_{j0} - l x_{i0}}{l v_i} + \frac{s_e}{k_i v_i} \quad (5)$$

The first term on the right side of (5) is A_i's metering delay, the second one equals $eta_j - eta_i$, the difference between the estimated times of arrivals, and the third one is the minimum separation, expressed in time relative to reduced speed $k_i v_i$. This is interesting, because it is exactly the delay that occurs in classical queueing problems (please see (6) in next paragraph), except that the en route separation is 5 NM and the metering separation in 10 NM. One could also solve the problem by showing that there exists always a conflict-free trajectory with arrival at ts_j. But then, details like the fact that the en-route separation is relative to the reduced speed would have to have guessed by the modeller. We conclude that metering delays and speed control delays are equivalent.

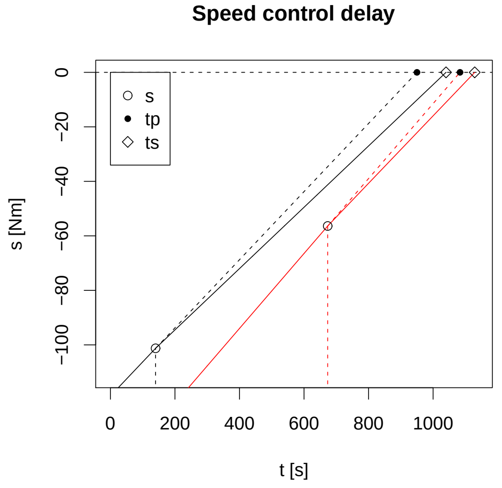

Figure 4: Example of speed control delay.

3.2 Required airspace

It was difficult to interpret the change-point equation (4) in the previous section. But the metering delays can be explained in a simpler way: Let $(eta_1, ..., eta_n)$ be the the estimated arrival times of the aircraft, and $m = s_m/v$ the separation due to the metering constraint (expressed as a time). Aircraft i will leave the metering point at time $tl_i = w_i + eta_i + m$, where w_i is its metering delay. If the following aircraft j arrives before tl_i, its metering delay is $w_j = tl_i - eta_j = w_i - (eta_j - eta_i) + m > 0$. If it arrives after tl_i, its metering delay is 0. Thus:

$$w_j = max(w_i - (eta_j - eta_i) + m, 0), \quad (6)$$

with $i \geq 1$, and $w_1 = 0$.

Equation (6) has the same form as (5) and it is the natural delay relation in queueing theory [7]. Since the change-point is a function of the metering delay, understanding one means understanding the other. It is known that, under minimal assumptions on the arrival times, the delay process will not explode to infinity, because the average arrival rate

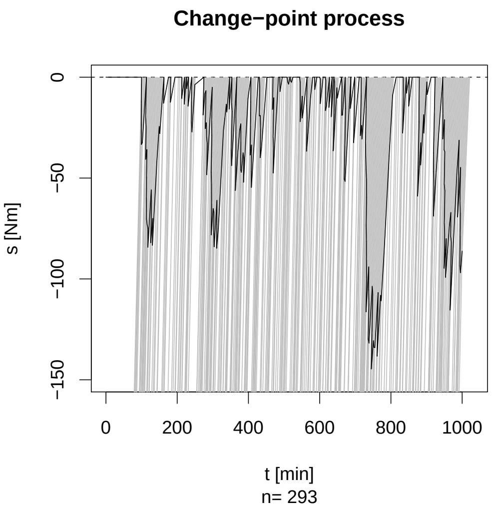

Figure 5: Sample path of the change-point process.

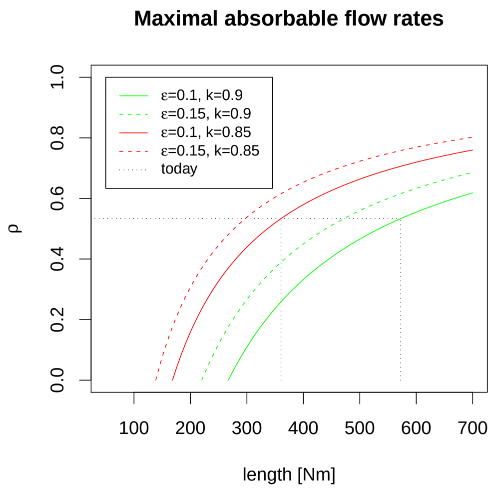

Figure 6: Maximal absorbable flow rates in a given airspace.

is lower than the capacity [8]. Also, the probability that a delay is larger than α is the same as the probability that a certain random walk crosses the threshold α [8]. Intuitively, the reason why metering delays occur at all are the spontaneous peaks in the arrival rate. When the arrival rate is fixed, delays will increase with its variability.

In order to better understand the process, we simulated arrival flows, varying the distributions of initial spacings between aircraft and the cruise speeds. The rule was that aircraft i, j fly at cruise speed until the change-point predicted by (4), and reduce their speeds then by a factor k_i, k_j. When the speed of the follower was faster than the leader, we set $k_j = k_i$, the maximal allowable speed reduction. In the other case, we set $k_j = k_i/l$. This means that aircraft j adapts to the speed of A_i. Figure 5 shows a typical result for 293 trajectories. Time is on the x-axis, distance to the sector entry on the y-axis. The black line connects the change-points. They jump up and down in an irregular fashion: a sample path of a random walk. Our current results indicate that the highest change-points lie between 100 and 150 NM. Their distribution drops sharply with increasing distance. But there are also a few exceptions, going up to 180 NM. These exceptions need more attention before inferring any conclusions on the real airspace. Our point here is that the effect of speed control is a 'traffic synchronization' at the change-point.

Additionally to simulating equation (4), we also analyze it analytically. The question we pose is 'how much traffic can absorb its delays by speed control inside an airspace of length L ?'. This allows to see how the controller workload will be distributed among upstream sectors and even control centers.

As a baseline scenario, we assume that the spacings between estimated times of arrival $a_i = eta_i - eta_{i-1}$ and the metering spacings s_{mi} are independent and exponentially distributed random variables with parameters λ and μ. In this case, it is known that the equilibrium distribution of the delay w is exponential with parameter $\mu - \lambda$ [7]. In reality, the metering delays are almost constant at 10 NM. This means that our calculation will overestimate the delays, or rather the change-points.

For an aircraft i and $0 < \epsilon < 1$ we have

$$
\begin{aligned}
1 - \epsilon &< P(s_i \leq L) && (7)\\
&= P\left(\frac{kv_i\Delta_i}{1-k} \leq L\right) && (8)\\
&= P\left(\Delta_i \leq \frac{L(1-k)}{kv_i}\right). && (9)
\end{aligned}
$$

Since $\Delta_i \sim exp(\mu - \lambda)$ we have

$$e^{-(\mu-\lambda)\frac{L(1-k)}{kv_i}} < \epsilon. \tag{10}$$

Solving for λ gives

$$\lambda < \mu + ln(\epsilon)\frac{kv_i}{L(1-k)}. \tag{11}$$

The results can be seen in Figure 6. The curves show the largest flow (y-axis) whose delays can be absorbed by speed control with high probability $(1-\epsilon)$ in an area of length l (x-axis). Green: speed control k=10%. Red: speed control by k=15%. The black dotted lines show the area needed with today's sector usage of $\rho = \lambda/\mu \sim 0.5$. As stated above, this calculation over-estimates the delays. We currently analyze the delay distribution in more detail to quantify this effect.

4 Conclusions

In this paper we analyzed the most congested Japanese arrival flow to Tokyo Int'l airport. The purpose was to test whether absorbing metering delays during the cruise phase instead of the descent phase is feasible. The paper takes the perspective of a Traffic Management Coordinator, who needs to know roughly how much, and when to delay aircraft in order to create smooth and efficient flows.

We have seen that a reason for high metering delays are fluctuations in the traffic density. We then showed that absorbing metering delays during the cruise phase does not impose additional delays on the following aircraft. Based on this we analyzed the distance from the sector entry at which speed reduction has at the latest to take place. This is an irregular sequence, depending on the initial spacing between aircraft, their speeds and performance characteristics, whose natural description is a random walk.

In this paper, we did not solve the problem of arrival traffic synchronization. Our contribution is that we identified the probabilistic structure of the problem. Many refinements can be done now, from both, theoretical and practical point of view. For example practical ones, like more realistic simulations (trajectory model, wind conditions) and prediction uncertainties. Or theoretical ones like the identification of the change-point distribution. We think our approach is useful, because it gives more insight into the mechanisms of airspace congestion and trajectory control. Moreover, it can be generalized to other scenarios. This is necessary in Japan, because a new runway and new sectorization will be operational in the near future.

Acknowledgments

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