[EN-102] Study on Traffic Synchronization

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Abstract We give a short overview of recent activities in the field of traffic synchronization. Traffic synchronization is concerned with the tactical management of queues, both on the ground and in the air, in order to establish and maintain a safe, orderly and efficient flow of air traffic. We describe the major applications for traffic synchronization in Japanese airspace: arrival synchronization to Haneda airport and coordination between several departure airports. Finally, we briefly summarize our own results, namely the quantification and interpretation of metering delays by stochastic queueing models and the trade-off between low altitude (fuel inefficient) high altitude (fuel efficient) delay absorption.

Keywords Traffic Synchronization, Queue Management, Delay Propagation, Stochastic Model

1 INTRODUCTION

[1] There is worldwide activity in research and development of modern Air Traffic Management (ATM) systems [1, 2]. The reasons include that airspace demand keeps growing, technology is improving, and society raises new expectations, such as the environmentally sustainable air transportation.

The International Civil Aviation Organization (ICAO) proposes several components of a modern ATM system that are based on expectations of human capabilities and the ATM infrastructure [3]. One of these components is called 'Traffic Synchronization'. It is described as the 'tactical establishment and maintenance of a safe, orderly and efficient flow of air traffic'. Thus, traffic synchronization takes place at the day of operations. According to the ATM Master-Plan [4] (electronic version, frequently updated), it contains the following major functions:

- Departure Synchronization: the departure time of aircraft is adjusted. Optimizing departure sequences under uncertainties of push-back, start-up and taxi times and in coordination with surrounding airports and airspace structure will use the available capacity more efficiently.
- Arrival Synchronization: the en-route trajectories are re-optimized. Precise sequencing is performed by setting time constraints on arrival and en-route merging points.
- Interactions between arrivals and departures: Enabling complementary and optimized spacing of arrivals and departures, minimizing airborne delays and also minimizing departure queuing.

[1]This is a reprint of the paper published at ENRI's Annual Research Meeting (Happyo Kai 2010)

As can be seen, traffic synchronization includes the management and provision of queues both on the ground and in the air. It is interrelated with two other components, namely conflict management and demand and capacity balancing, and may in the future be indistinguishable from them [3].

The main enablers for traffic synchronization are improvements in 4D-trajectory prediction and control, and a collaborative way of distributing congested airspace resources. Future flight management systems will provide a required time of arrival (RTA) function, allowing the aircraft to navigate with higher time precision through the airspace than today. Based on this, flow managers can compute time-windows, in which aircraft shall pass designated way-points. Moreover, in the framework of Collaborative Decision Making (CDM), future operations such as slot swapping or trajectory negotiations, are also expected to smooth the airspace demand.

The main expected benefit of traffic synchronization is a better usage of the available capacity. This leads to more fuel and workload efficiency, because it will create smoother flows.

The remainder of the article is organized as follows: in the next section we describe on-going activity in the creation of concepts of operations for traffic synchronization. Then, we explain the possibilities, where traffic synchronization might be useful in Japanese airspace. This is followed by a summary of our own research results. Finally, we summarize the article and point out some ideas for future work.

2 CONCEPT OF OPERATIONS

A Concept of Operations (ConOps) is a document describing the characteristics of a proposed system from the viewpoint of an individual who will use that

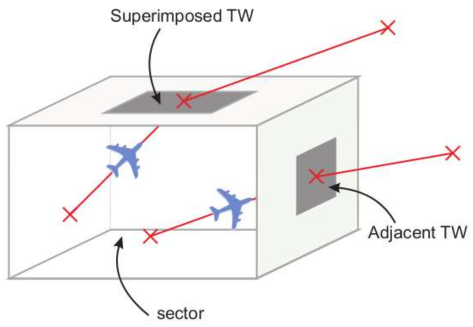

Figure 2 Target Windows (Source: [9]).

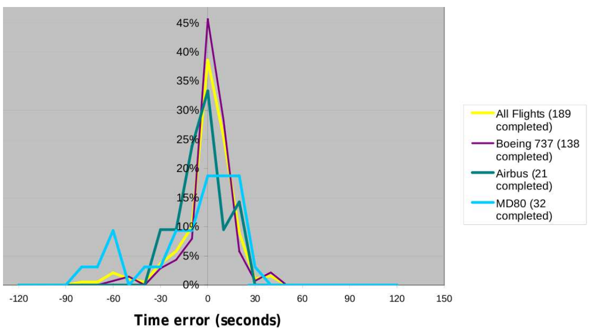

Figure 1 CTA error distribution (Source: [7]).

system. There are many projects related to traffic synchronization that build on new technology or innovative concepts and produce concepts of operations (see for example the Queue-Management category in SESAR's Joint-Undertaking web-page [5] or the Time Based Flow Management and extensions in the U.S.[6]). The following two examples give a short background on the research behind the ConOps in traffic synchronization.

- Accuracy of the RTA function (CASSIS project)
- Target-window concept (CATS project)

CASSIS In the CTA/ATC system integration studies (CASSIS), a large number of flight trials were carried out in Stockholm, Sweden [7]. These trials investigated how well aircraft could meet a controlled time of arrival (CTA) to a feeder fix, and how the aircraft's ability to meet this time could be used to improve arrival management. The trials were carried out using technologically advanced aircraft including Boeing 737, Airbus A321 and A330. The RTA function was used to allow aircraft to self manage their speed to meet a CTA. As a comparison, MD80 aircraft, which do not have the RTA functionality, were also involved in the trials to investigate how non-equipped aircraft could be handled in CTA operations. Of all trials, 90% met their assigned time with 30 seconds accuracy and 97% met their CTA with 60 seconds accuracy (see Figure 1). Moreover, some flights took place from a nearby airport, where delays were assigned prior to takeoff. When there was a peak situation, these flights were able to bypass the holding stack. Pilots were satisfied with the larger flexibility of planning the arrival phase, and with fewer times spent inside holding stacks. On the other hand, the amount of communication between ATC and the aircraft, and the workload inside the cockpit increased. The CASSIS project recommended that further work (trials, simulations and concept discussions) have to be carried out to quantify the benefits to be obtained from CTA use.

CATS Target Windows (TW), proposed by the Contract-based Air Transportation System project (CATS), are spatial and temporal constraints placed between sectors at different parts of the flight plan of each aircraft (Fig. 2), whose position and interval size reflects constraints imposed by downstream components such as punctuality at destination, congested en-route areas, or safety requirements. They represent the commitment of each actor (air traffic controllers, airports, airlines, air navigation service providers) to deliver a particular aircraft within a specific constraint set. The major aim of the project is to increase punctuality. The major technical steps for the feasibility of the concept include the quantification of the maneuverability-freedom of each aircraft constrained by a specific target window. To this end, simulation and modeling studies are currently on-going [8].

As mentioned above, these and other projects are in progress [5]. Their target is to identify the conditions, under which the new technologies and paradigms will prove most beneficial. Based on such results, new Concepts of Operations will be produced.

3 Traffic Synchronization in Japan

In Japan, the traffic flows are already pre-scheduled in order to respect the airspace capacities. But operational uncertainties (e.g. weather, tactical maneuvering) and competition for punctual arrivals may lead to temporary capacity excesses, especially in the vicinity of the airports. This leads to high controller workload and fuel-inefficiencies.

The specialists in the Air Traffic Management Center (ATMC) in Fukuoka already introduce tools for predicting, sequencing and optimizing traffic flows, such as traffic monitors, slot swapping terminals, and so on. Two typical problems in future traffic synchronization are the following:

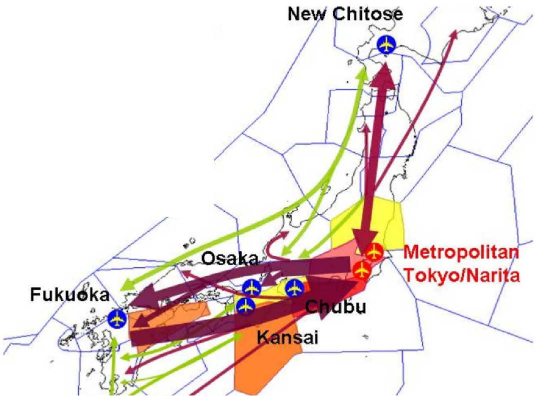

Figure 3 Major Japanese traffic flows.

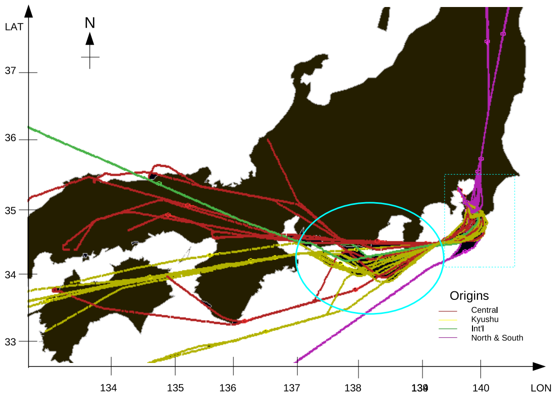

Figure 4 Lateral inefficiencies of the East-bound flow.

3.1 Arrival synchronization

The major source of Japanese air-traffic congestion is the arrival flow to Haneda airport [10]. The future concept of synchronization of the main arrival flow to Haneda airport concerns the east-bound arrival flow, as can be seen in Figures 3 and 4. The traffic synchronization will be divided into four phases [11]:

- Take-off phase: updated departure clearance-times for all aircraft are calculated, taking into account the airspace capacities and current traffic predictions.
- Early cruise phase: flight plan predictions are updated, based on shortcuts, and more accurate traffic predictions.
- Feeder phase (Osaka/Nagoya airspace): the scheduled time of arrival at the runway threshold is determined. Sequencing and spacing information is deduced. Contributing information is the change of runway capacity or configuration (due to weather conditions) and the aircraft types in the sequence.
- Arrival phase: the calculated information is combined with the ATC tools, such as arrival management software.

One expects from the new control techniques a more regular flow, which can be adapted to changing environmental conditions more efficiently and more safely.

3.2 Departure synchronization

As mentioned in the introduction, a source of flow inefficiency is the missing coordination between several airports. For example, sectors sometimes require larger spacing than the minimum separations (minutes-in-trail separation). The reasons are temporary capacity/demand imbalances, for example due to weather conditions. For the flow managers, this requires the coordination of departure times at the airports connected with these sectors. Today, such a task is often carried out by hand. In the future, more efficient strategies are sought. They also have to be flexible with respect to airline priorities (e.g passenger flights vs. cargo flights) and delayed departures (e.g. ground congestion).

In both projects, one expects workload and fuel reductions through the use of better strategies to coordinate and synchronize traffic flows.

4 CURRENT RESULTS

At ENRI, we are working on both traffic synchronization projects mentioned above. The work involves the analysis of radar data and the construction of mathematical models that are helpful for decision-making in flow control. In particular, we are interested in efficient sequencing/merging strategies under the impact of trajectory-uncertainties and in de-centralized concepts for the flow control. In this section, results from our research are briefly summarized. More information can be found in [12, 13, 14], the references therein or by contacting the authors.

4.1 Radar data analysis

We analyzed patterns in metering delay from arrivals to Haneda airport [12, 13]. Metering delays occur due to spacing aircraft more than the the minimum separation at the gate to the terminal area. A major factor for the metering delays was the traffic density. Traffic ‘peaks’ exceeding the capacity are handled by vectoring or speed control. These peaks occur spontaneously and are difficult to predict.

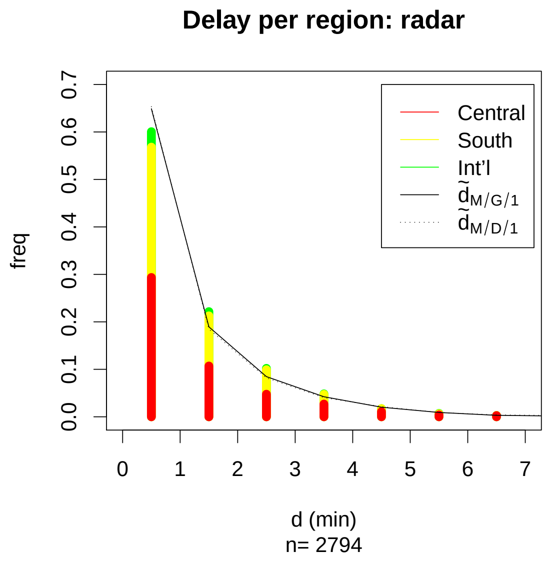

Figure 5 Observed and theoretical frequencies of metering delays.

4.2 Queueing-analysis

We modeled the metering delays by classical stochastic queueing theory [12, 13]. Two models were considered, a very simple one (with constant metering separations), and a more realistic one (with the empirically observed separations). The correspondence between data and models can be seen in Figure 5. The horizontal axis depicts the metering delay (unit: minutes). The vertical axis shows the frequency of the occurrence of these delays. The colored bars are extracted from the radar data. They were classified into three groups of origin airport (red: central Japan, yellow: south Japan, green: International). The straight lines are the predictions from our queueing models. Both models produce almost indistinguishable delay predictions. And both models correspond well to the empirical data. This means that the controllers currently solve the metering problem efficiently, because the theoretical models represent the minimum delays, given the first-come-first-served rule. An explanation for the good results is given in [15]. Based on a more realistic arrival flow model (with pre-scheduled arrivals), it is found that the congestion properties in medium traffic densities are similar to the ones of classical queueing theory.

4.3 Delay distribution analysis

We currently analyze efficient strategies for en-route metering delay absorption [13, 14]. In delay absorption, the following trade-off between individual and total fuel-efficiency in the presence of trajectory uncertainty is known from the literature [16]: when metering delays are absorbed in high altitudes, fuel burn is minimized for individual flights. But due to random delay, there is a risk of under-usage of the runway capacity. Lost landing slots may propagate back to the remaining aircraft, which increases the total delay, and as a consequence the total fuel burnt. This means that metering delays have to be distributed between the low altitudes (fuel inefficient) and high altitudes (fuel efficient), even when the objective is to minimize fuel consumption.

We analyzed the scheduling process in the presence of trajectory prediction errors (see Figure 6). It is a complicated process, consisting of initial schedules, absorption buffers, prediction errors and schedule updates (please see [14] for more details).

Our main result is in agreement with Erzberger's simulation study [16] and can be seen in Figure 7. The horizontal axis is the fraction of metering delay that is absorbed on low altitudes, designed by $\alpha \in [0, 1]$. The vertical axis has two units: additional delays and fuel consumption (both are normalized in our illustration). The green line is the additional delay that occurs due to trajectory prediction errors. It decreases sharply with increasing fraction of absorbed delay in low altitude. The intuition is that the low altitude serves as a buffer for late arrivals. The blue line is the fuel consumption in the case that no trajectory prediction errors occur. In this case, the most fuel-efficient strategy is to absorb all metering delays in high altitude ($\alpha = 0$). The red line is the fuel consumption under the effect of delay propagation. The trade-off between the low altitude (fuel inefficient) and high altitude (fuel efficient) delay absorption can be seen as the minimum value of the curve. Currently, our research identifies the conditions under which such minimum values exist, such as the traffic densities and the magnitude of trajectory prediction uncertainty.

The expected output of our research is improvement in human-centered decision making in flow control. Understanding better the mechanisms of congestion is a good basis for traffic management coordinators. Moreover, future automation tools (e.g. sequencing/merging) can incorporate such knowledge in their design and in their parameter settings.

5 Conclusions and Future Work

In this article, we gave a short overview of recent activities in the field of traffic synchronization. We stressed that traffic synchronization is concerned with the tactical management of queues, both on the ground and in the air, in order to establish and maintain a safe, orderly and efficient flow of air traffic. We then looked at activities in the creation of concepts of operations based on the two major enablers for traffic synchronization: better technology to predict and control aircraft trajectories, and better tools to share

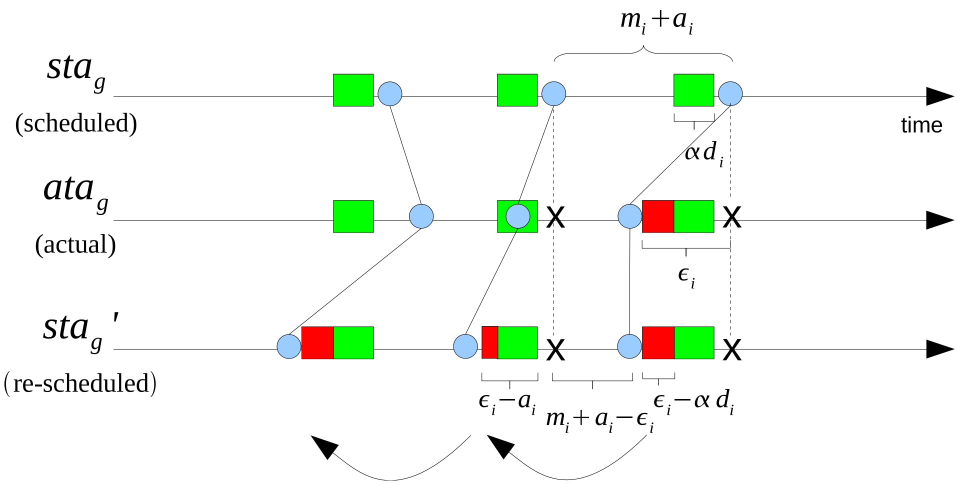

Figure 6 Real-time arrival scheduling, time-control errors and delay propagation.

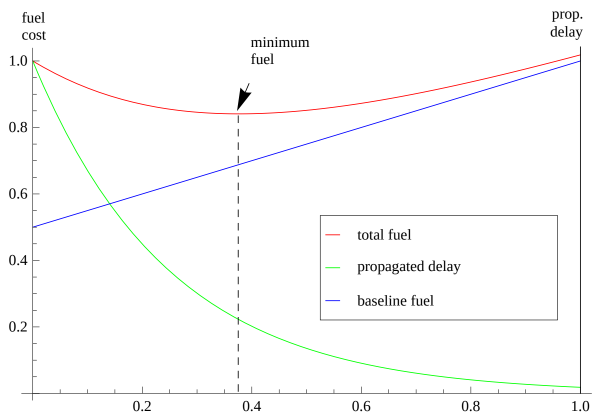

Figure 7 Trade-off in delay distribution.

flight plan information. We concluded that more experiments and research are necessary before creating a concept of operations. Then, we described the major applications for traffic synchronization in Japanese airspace: arrival synchronization to Haneda airport and coordination between several departure airports. Finally, we briefly summarized our own results, namely the quantification and interpretation of metering delays by stochastic queueing models and the trade-off between low altitude (fuel inefficient) high altitude (fuel efficient) delay absorption.

The expected output of our research is improvement in human-centered decision making in flow control. For this, we focus on the analysis of radar data and the construction of mathematical models. In particular, we are interested in efficient sequencing/merging strategies under the impact of trajectory-uncertainties and in de-centralized concepts for the flow control.

This is just the beginning of the journey, and for future work we propose to continue the fundamental approach to sequencing under uncertainty as well as a study on the impact of traffic growth on the Japanese congestion patterns.

6 ACKNOWLEDGMENTS

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