Potential Benefits of Arrival Time Assignment
Dynamic Programming Trajectory Optimization
applied to the Tokyo International Airport

ATM Seminar, Lisbon, June 25, 2015

Yoshikazu Miyazawa, Haruki Matsuda, Sadanari Shigetomi,
Akinori Harada, Tomoyuki Kozuka, Kyushu University, Fukuoka, Japan
Navinda Kithmal Wickramasinghe, Mark Brown, Yutaka Fukuda
Electronic Navigation Research Institute, Tokyo, Japan
Outline

1. Introduction
   - Background and research objectives

2. Approach for the potential benefit analysis
   - Flight parameters estimation from surveillance radar data
   - Trajectory optimization for each flight by Dynamic Programming
   - Arrival times optimization by Dynamic Programming

3. Application to flights inbound to the Tokyo International Airport
   - Efficiency evaluation by the potential benefit analysis
   - Arrival time assignment minimizing the effect on the performance

4. Conclusions
   - Concluding remarks and future works
Introduction: Background

Two major research projects, NextGen in the US and SESAR in Europe are under way for future safe and efficient air traffic system. ICAO has set GANP as a future plan. Japanese government set a plan for the country’s air traffic R&D named CARATS (Collaborative Actions for Renovation of Air Traffic Systems). Inclusion of universities’ resources is considered essential not only for education but for progress in the research.

Among many research topics, arrival management is one of the most intensive subjects in Japanese air traffic system. Quantitative efficiency evaluation, or potential benefit analysis has not been performed in detail for the Japanese airspace. Kyushu University and ENRI have been conducting a collaborative research on the two subjects, arrival management and efficiency evaluation since 2012.
Introduction: Research objectives, Arrival management

The Tokyo International Airport is the busiest airport in Japan. It is used more than half of total air travelers in Japan annually. Similar to other busy airports in the world, terminal airspace is a bottleneck of air traffic flow, and improvement in efficiency of inbound flights is a critical issue.

Arrival management system like CTAS(Center TRACON Automation System) and AMAN(Arrival Manager) has not been implemented at the Tokyo International Airport. Feasibility of the arrival management system is an issue of great concern. The potential benefits provide reference data towards possibilities in future development.
Introduction: Research objectives, Efficiency evaluation

A thorough evaluation on the efficiency of operations in the Japanese airspace should be performed to clarify potential benefits of the future ATM planned in CARATS. The analysis should be conducted using surveillance information in order to cover all aircraft in the airspace. Since surveillance information only provides position data unlike QAR data recorded by onboard equipment, the analysis needs intensive calculation with other information, such as meteorological data and aircraft performance model.
Potential benefit analysis for airspace efficiency evaluation

Flight parameters reconstruction

- Surveillance data
- JMA GSM Meteorological data
- BADA model

- Time Position
- GS
- Wind Temperature Pressure
- TAS CAS Mach

- CL, CD Thrust Fuel flow

(Aircraft mass assumed)

Trajectory optimization with the same condition

- Initial and terminal conditions
- Performance index

Dynamic Programming Trajectory Optimization

- JMA GSM Meteorological data
- BADA model

Optimal fuel consumption and flight time

JMA: Japan Meteorological Agency, GSM: Global Spectral Model, BADA: Base of Aircraft Data, GS: Ground speed, TAS: True air speed, CAS: Calibrated air speed

ATM Seminar: Potential Benefits of Arrival Time Assignment
Potential benefit analysis: previous works in Kyushu Univ.

- **GPS Logger data** recorded in an airliner cabin
- **QAR (Quick Access Recorder)** data provided by an airliner
- **SSR Mode S data** experimentally operated by ENRI

**Key technology**
- Flight parameter estimation
- Dynamic Programming trajectory optimization

**Resources**
- **AIP Japan**
  - [https://aisjapan.mlit.go.jp/Login.do](https://aisjapan.mlit.go.jp/Login.do)
- **Numerical weather prediction GPV**
  - by Japan Meteorological Agency
  - [http://www.jmbsc.or.jp/hp/online/f-online0.html](http://www.jmbsc.or.jp/hp/online/f-online0.html)
- **BADA (Base of Aircraft Data)**
  - developed and maintained by EUROCONTROL
  - [http://www.eurocontrol.int/services/bada](http://www.eurocontrol.int/services/bada) (ver. 3.9)
Environmental model: JMA GSM weather prediction data

Numerical weather prediction data have enough accuracy for benefit analysis of optimized flight trajectory.

Example of Evaluation

Accuracy has been evaluated with QAR flight data for wind and temperature.
- Temperature RMSE 1 degree
- Wind RMSE 3m/s

Interpolation not only three dimensional space but also time is necessary for GPV (Grid Point Value) data.

(RMSE: Root Mean Squared Error)

(Tokyo to Sapporo, August 2011)
Aircraft model: BADA model by EUROCONTROL

Example of evaluation by airliner’s QAR flight data

Dynamic Programming: Numerical method of optimization

Iso-grid system is defined for four dimensional space of range, cross-range, altitude, and velocity. DP calculates the optimal transition among all combinations of transition.
Trajectory optimization: Performance index and Cost index

Fuel and time are concerned.

\[ J = \int_{t_0}^{t_f} \mu(t) dt + \frac{m}{m_0} a(t_f - t_0) \]

Feasible solutions

Actual flight difference

Optimal flight

Cost Index based on monetary value

\[ CI = \frac{c_{\text{time}}}{c_{\text{fuel}}} \left[ \frac{\text{dollars/hour}}{\text{cents/pound}} \right] = 79.37 \frac{m}{m_0} a \]
Trajectory optimization and arrival time assignment

The optimal trajectory is ideal. It ignores various kinds of condition in real system, such as conflict, equipage, simple procedure, model error, uncertainty and so on.

Among various kinds of condition in real system, conflicts at the terminal area are the most critical for inbound flights to a congested airport. Effect of the condition can be studied by adding a constraint on time separation.
Trajectory optimization: Total PI for arrival time assignment

CI is a free parameter, but it should be a constant for the optimal trajectory to be compared as a reference with an actual flight. Furthermore, it should be a common constant in order to fairly assign arrival times of aircraft conflicting with each other.

Two types of total performance index are proposed.

\[ J_1^* = \sum_k J_k = \sum_k \left\{ \int_{t_{0_k}}^{t_{f_k}} \mu_k(t) dt + \frac{m_k}{m_0} a_k (t_{f_k} - t_{0_k}) \right\} \]

\[ J_2^* = \sum_k \frac{m_0}{m_k} J_k = \sum_k \left\{ \frac{m_0}{m_k} \int_{t_{0_k}}^{t_{f_k}} \mu_k(t) dt + a_k (t_{f_k} - t_{0_k}) \right\} \]

\( J_1^* \) does not consider the aircraft size, or fuel burn oriented PI.\( J_2^* \) equally evaluates the time of each aircraft by compensating the aircraft size.

\( J_2^* \) and \( a_k = 0.5 \text{ kg/s} \), \( m_0 = 208.7 \text{ ton} \) are adopted in this study.
Arrival time assignment: Additional inequality constraint

Arrival times are assigned to ensure safe separation at the terminal merging point.

Total PI

\[ J = \sum_k m_0 \frac{m}{m_k} J_k \]

Constraint

\[ |t_{f_k} - t_{f_l}| > t_{\text{min separation}} \]

for any \( k \) and \( l, k \neq l \)
Optimal arrival time assignment by Dynamic Programming

\[ \min [J_{opt}^*(i) + \Delta] = J_{opt}^*(i + 1) \]
Application to flights inbound to the Tokyo International Airport

CARATS Open Data are used for analysis

- Integrated surveillance information from multiple ARSR (Air Route Surveillance Radar) released by JCAB (Japan Civil Aviation Bureau) covers the entire airspace over Japan.
- Initial point for each analysis is at 10,000 ft altitude in the climb, and the terminal point is at merging point ARLON to Runway 34L.

The Tokyo International Airport (RJTT)
Arrival flights controlled for sequencing and safe separation

Flights arriving at ARLON from 20:00 to 23:00 (Japan time) are analyzed.

Wavy lines in the figure of distance to ARLON vs time indicate being controlled to generate safe separation before the landing queue.
Trajectory optimization: 73 arrival flights

- Actual flight distance difference, av. = -65 km
- Optimized, free arrival time
- Fuel burn difference, av. = -783 kg
- Flight time difference, av. = -184 s
Potential benefits: Stochastic performance, 73 flights

Total Performance index for 73 flights with a constraint of time separation is optimized. $t_{\text{min\,separation}} = 90\,s$ is used. Performance deterioration due to arrival time condition is limited.

**Fuel burn, kg**

-783 kg (-16.3%)
-755 kg (-15.7%)

**Flight time difference**

**Fuel burn difference**
Potential benefits: Stochastic performance, 73 flights

Average of flight time difference, 5% to 6% less than the actual flight, is smaller than those of fuel consumption and flight length.
Arrival times for three cases, from 20:00 to 23:00

Actual time of arrival
Estimated time arrival (without time constraint)
Scheduled time of arrival (with time constraint)

21:00 to 22:00

22:00 to 23:00

ATM Seminar: Potential Benefits of Arrival Time Assignment
Time separation at the merging point, histogram of 73 flights

Actual time of arrival (ATA)

Estimated time of arrival (ETA)
Optimal trajectory without arrival time constraint

Scheduled time of arrival (STA)
Optimal trajectory with arrival time constraint
Distance to merging point vs time

Actual time of arrival (ATA)
Distance to merging point vs time

Actual time of arrival (ATA)

Estimated time of arrival (ETA)
Optimal trajectory without arrival time constraint

Scheduled time of arrival (STA)
Optimal trajectory with arrival time constraint
Conclusions: Concluding remarks

Potential benefit analysis tool has been developed for ATM research to analyze efficiency of the Japanese airspace. It provides the maximum possible benefit achieved in ideal operating conditions.

It is applied to arrival flights to the Tokyo International Airport. Potential benefits in terms fuel and flight time are significant. Arrival times are optimized by the total performance index defined as the weighted summation of each performance index. The performance deterioration due to imposing the time separation condition is limited.
Conclusions: Future works

The followings are to be investigated as future works.

- Dynamic assignment of arrival time
- Conflict evaluation at all phases of flight
- Consideration of flight route constraint
- Consideration of practical procedure to control each arrival time

These extensive items of research are under way.

Some of the results will be presented at the 4th EIWAC (ENRI International Workshop on ATM/CNS), Tokyo, on November 17-19, 2015.
Thank you for your attention.