Civil Aviation University of China

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Estimation of Aircraft Fuel Consumption Based on Air Traffic 4D Trajectory Data

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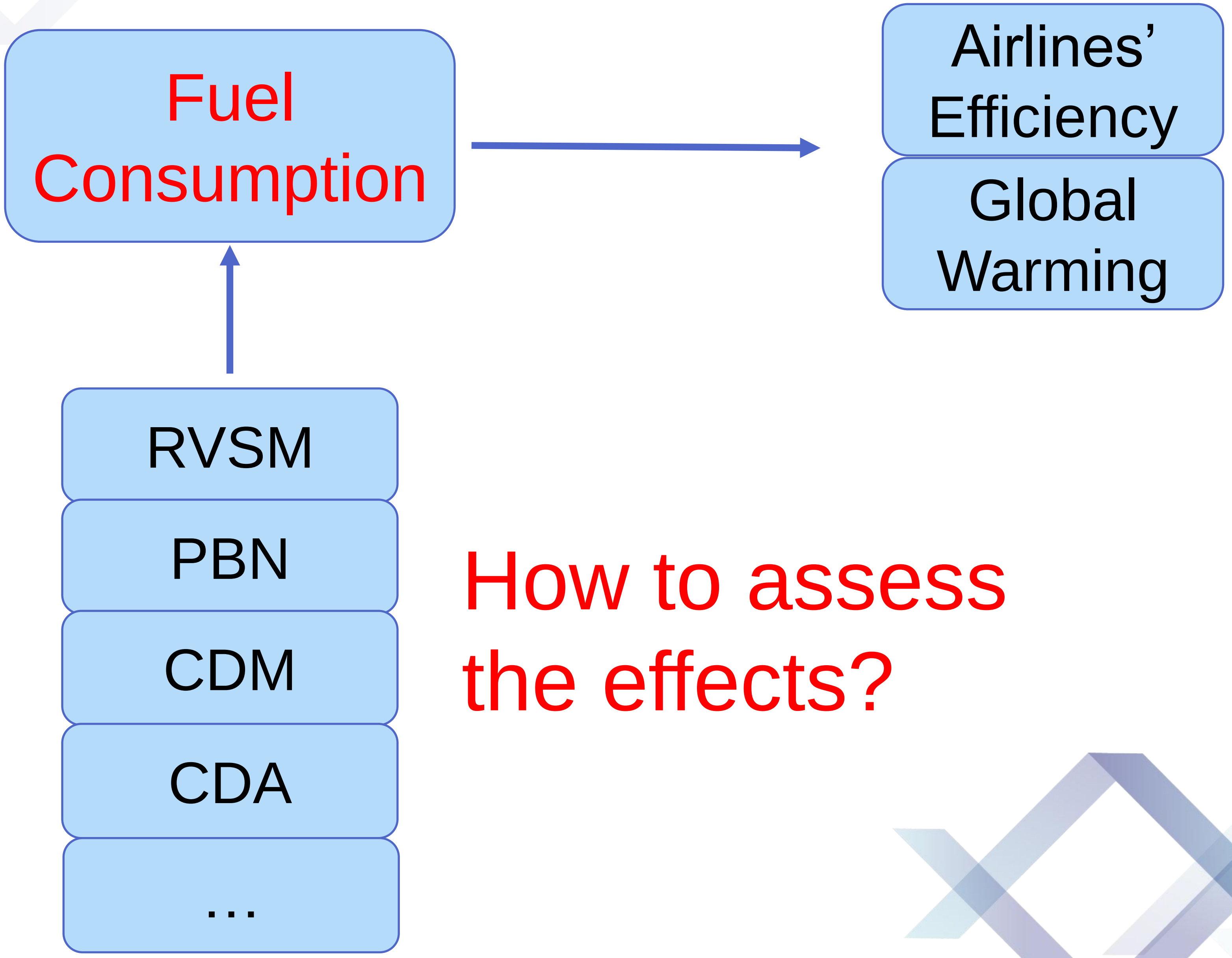
Background



How to assess the effects?

Background

Quick Access Recorder system (QAR)

Hard & Impossible

ATC surveillance data

Available & Easy

Lack of fuel consumption parameters

Introduction

ATC surveillance data

Estimation Method

Easy & Available

~~Lack of fuel consumption parameters~~

Estimation Method

- What is it?
- How accurate is it?
- What can we do with it?

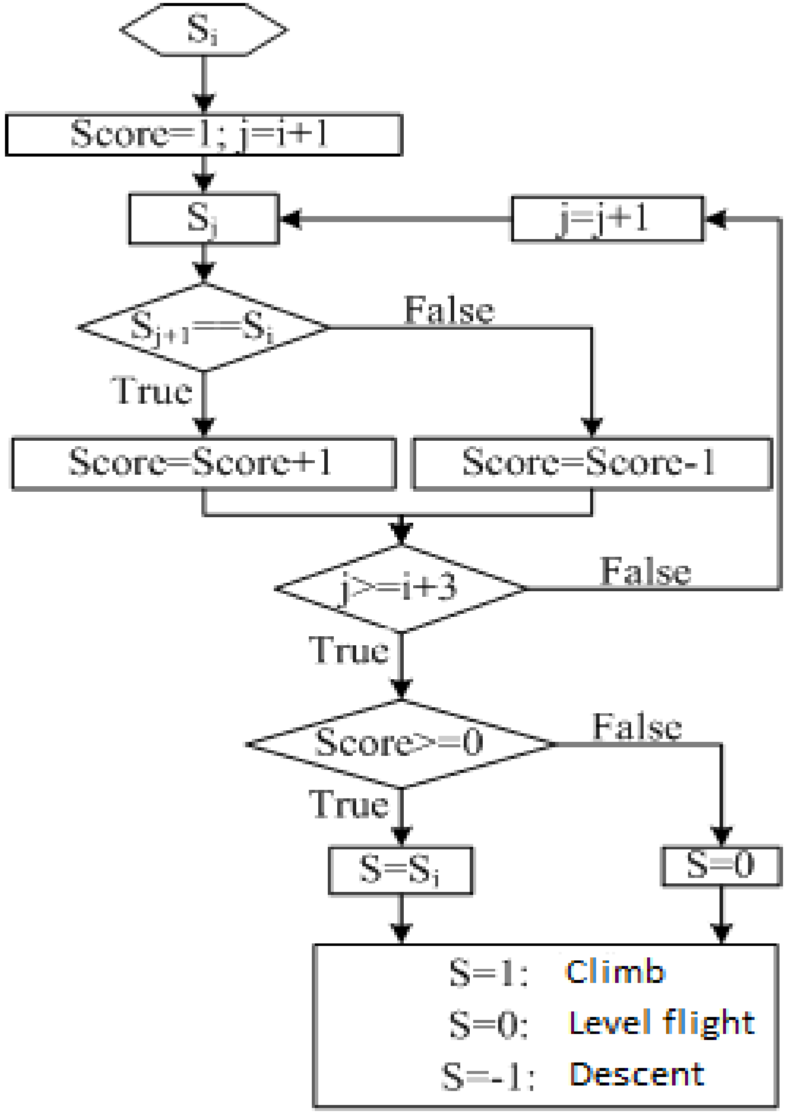
1.Classifying Flight Phases

Takeoff | Climb | Cruise | Descent | Landing

$$S_i = \begin{cases} 1, & (z_{i+1} - z_i) > Bar \quad \text{Climb} \\ 0, & |z_{i+1} - z_i| \le Bar \quad \text{Cruise} \\ -1, & (z_i - z_{i+1}) > Bar \quad \text{Descent} \end{cases}$$

Z is flight altitude (m), *Bar* is the tolerance,
i is flight time series, and S_i is flight phases

1.Classifying Flight Phases



The flow chart is used
to eliminate
the fluctuation interference
of acquired data.

2. Calculating Flight Speed and Attitude

$$\begin{cases} v_i = \dfrac{\sqrt{(y_i - y_{i-1})^2 + (x_i - x_{i-1})^2}}{t_i - t_{i-1}} \\ \varphi_i = \arcsin\left(\dfrac{x_i - x_{i-1}}{\sqrt{(y_i - y_{i-1})^2 + (x_i - x_{i-1})^2}}\right) \\ \theta_i = \arctan\left(\dfrac{z_i - z_{i-1}}{\sqrt{(y_i - y_{i-1})^2 + (x_i - x_{i-1})^2}}\right) \end{cases}$$

Speed

Heading

Pitch Angle

(x , y) is the aircraft position coordinates (in meters), t is time (in seconds).

2. Calculating Flight Speed and Attitude

$$\begin{cases} L_i \sin(\beta_i) = \mathrm{M}_i \, v_i \dfrac{\mathrm{d}\varphi_i}{\mathrm{d}t_i} \\ L_i \cos(\beta_i) - \mathrm{M}_i \, g \cos(\theta_i) = \mathrm{M}_i \, v_i \dfrac{\mathrm{d}\theta_i}{\mathrm{d}t_i} \end{cases}$$

L_i is lift (N), M_i is aircraft mass, β_i is bank angle (radian)

Bank Angle

$$\beta_i = \arctan\left[\frac{v_i\left(\varphi_i - \varphi_{i-1}\right)}{v_i\left(\theta_i - \theta_{i-1}\right) + g\left(t_i - t_{i-1}\right)\cos(\theta_i)}\right]$$

3. Calculating Fuel Flow during Climb

Climb

$$T_i = C_1\left(1 - \frac{z_i}{C_2} + C_3 z_i^2\right)$$

Thrust

$$FF_i = T_i C_4\left(1 + \frac{v_i}{C_5}\right)$$

Fuel Flow

Based on **DABA MODEL**, C_1, C_2 , C_3 , C_4 *and* C_5 are constants relative to engine type.

4. Calculating Fuel Flow during Cruise

Cruise

$$T_i = D_i + M_i g \sin(\theta_i) + M_i \frac{\mathrm{d}v_i}{\mathrm{d}t_i}$$

Thrust

$$FF_i = T_i C_4 \left(1 + \frac{v_i}{C_5}\right)$$

Fuel Flow

D_i is drag (N).

4. Calculating Fuel Flow during Cruise

Cruise

$$D_i = \frac{\rho_i v_i^2 s_w \left(C_{D0} + C_{D2} C_{L_i}^2 \right)}{2}$$

Drag

ρ_i is air density, S_w is wing area, C_{D0} and C_{D2} are aerodynamic constants determined by aircraft type, C_{Li} is lift coefficient.

$$D_i = \frac{\rho_i v_i^2 s_w C_{D0}}{2} + \frac{2 C_{D2} M_i^2}{\rho_i v_i^2 s_w \cos(\beta)^2} \left[\frac{(\theta_i - \theta_{i-1})}{(t_i - t_{i-1})} v_i + g \cos(\theta_i) \right]^2$$

4. Calculating Fuel Flow during Cruise

Cruise

Thrust

$$\begin{cases} T_i = aM_i^2 + bM_i + c \\ a = \dfrac{2C_{D2}\left[\dfrac{(\theta_i - \theta_{i-1})}{(t_i - t_{i-1})} v_i + g\cos(\theta_i)\right]^2}{\rho_i v_i^2 s_w \cos(\beta)^2} \\ b = \left[g\sin(\theta_i) + \dfrac{(v_i - v_{i-1})}{(t_i - t_{i-1})}\right] \\ c = \dfrac{\rho_i v_i^2 s_w C_{D0}}{2} \end{cases}$$

Fuel Flow & Mass

$$FF_i = T_i C_4 \left(1 + \frac{v_i}{C_5}\right)$$

$$M_i = M_{i-1} - FF_i (t_i - t_{i-1})$$

5. Calculating Fuel Flow during Descent

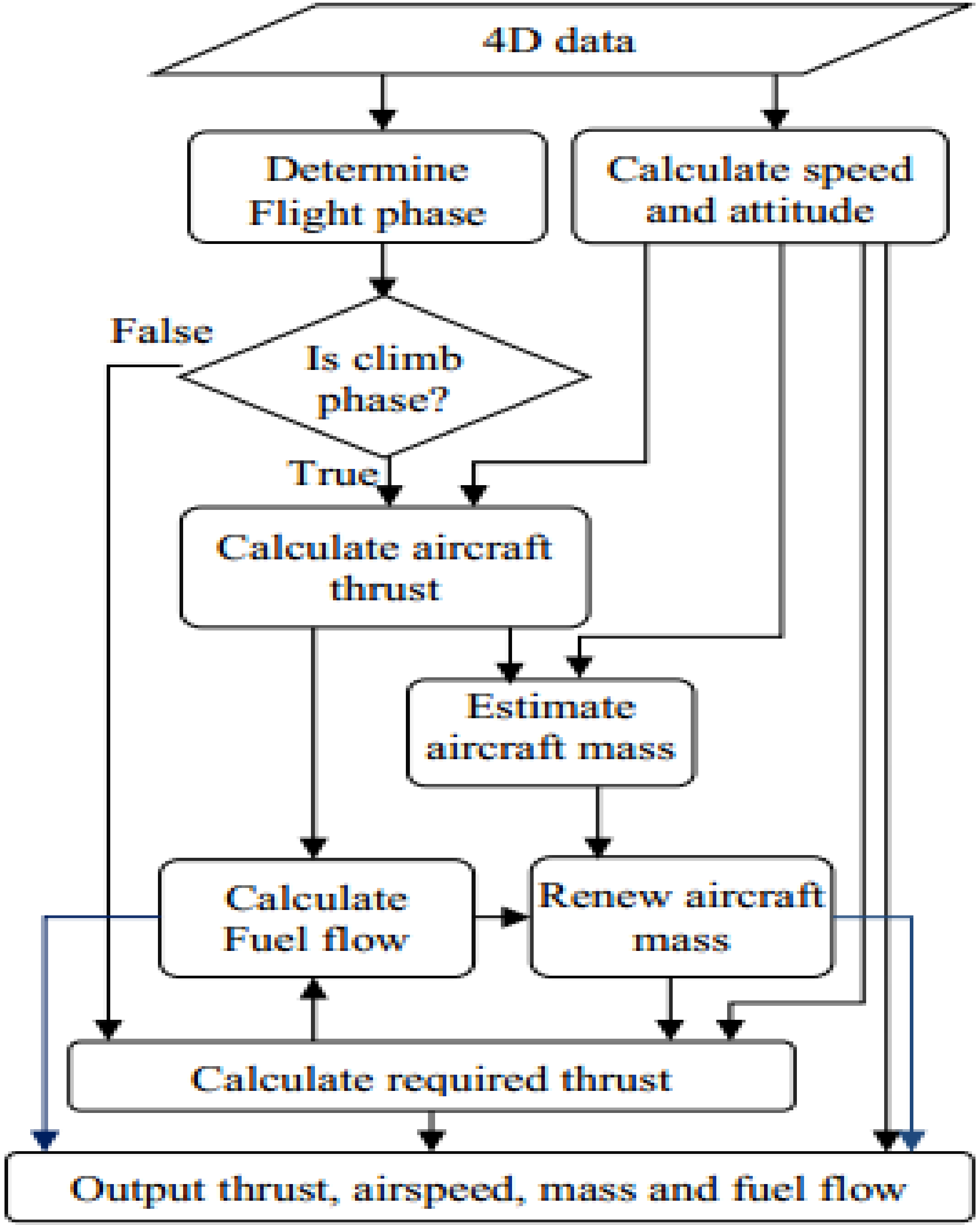
Descent

$$FF_{\min} = C_6\left(1 - \frac{h}{C_7}\right)$$

Fuel Flow

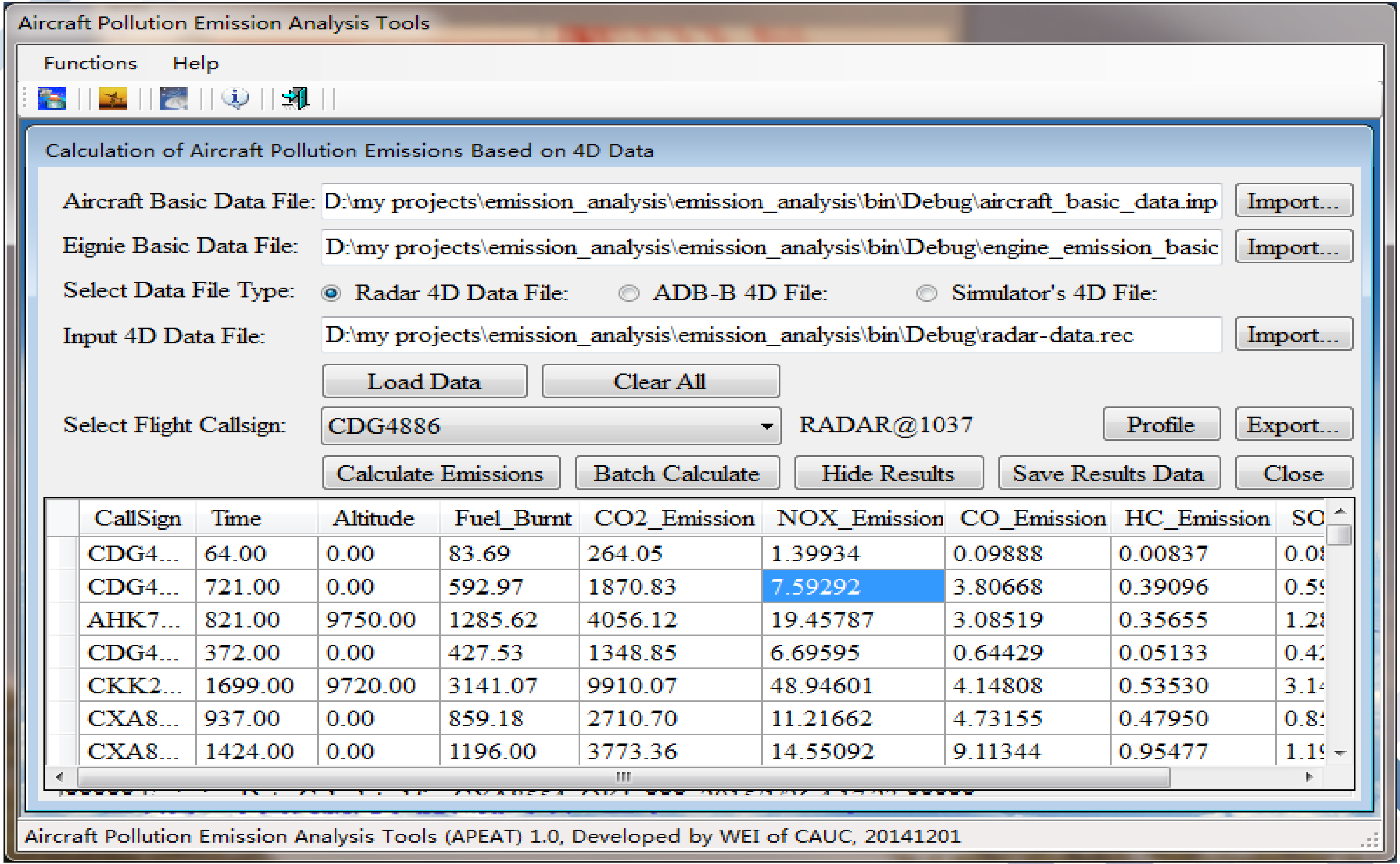
Based on **DABA MODEL**, C_6 *and* C_7 are descent fuel flow coefficients and *h* (ft) is the altitude above sea level.

Estimation Method



Flow chart to estimate aircraft performance parameters

Software Development



CallSign	Time	Altitude	Fuel_Burnt	CO2_Emission	NOX_Emission	CO_Emission	HC_Emission	SO
CDG4...	64.00	0.00	83.69	264.05	1.39934	0.09888	0.00837	0.0
CDG4...	721.00	0.00	592.97	1870.83	7.59292	3.80668	0.39096	0.5
AHK7...	821.00	9750.00	1285.62	4056.12	19.45787	3.08519	0.35655	1.2
CDG4...	372.00	0.00	427.53	1348.85	6.69595	0.64429	0.05133	0.4
CKK2...	1699.00	9720.00	3141.07	9910.07	48.94601	4.14808	0.53530	3.1
CXA8...	937.00	0.00	859.18	2710.70	11.21662	4.73155	0.47950	0.8
CXA8...	1424.00	0.00	1196.00	3773.36	14.55092	9.11344	0.95477	1.1

Accuracy of the Estimation Model

ATC surveillance data

Estimation Method

Quick Access Recorder system (QAR)

Two ways :

a. finding the mass differential between takeoff mass and landing mass;

b. calculating fuel consumption by time integration based on recorded fuel flow data.

Accuracy of the Estimation Model

QAR No.	Takeoff Mass (KG)	Fuel Consumption（KG）				Relative Deviation
		Direct Calculation	Integration Calculation	Reference Fuel Consumption	Estimated Fuel Consumption	
1	64772	4898	4833	4865	4750	-2.37%
2	70379	8419	8339	8379	8215	-1.96%
3	62142	2413	2560	2486	2694	5.35%
4	64156	5244	5253	5248	5465	4.12%
5	65970	5643	5649	5646	5676	0.53%
6	65444	4554	4553	4554	4782	5.02%
7	66932	4899	4878	4888	4792	-1.96%
8	60781	4772	4747	4759	4791	0.66%
9	65825	5371	5352	5361	5602	4.49%
10	64990	4481	4514	4498	4795	4.61%

ESTIMATION AND ANALYSIS

Fuel Consumption Distribution
in Latitude and Longitude Grid

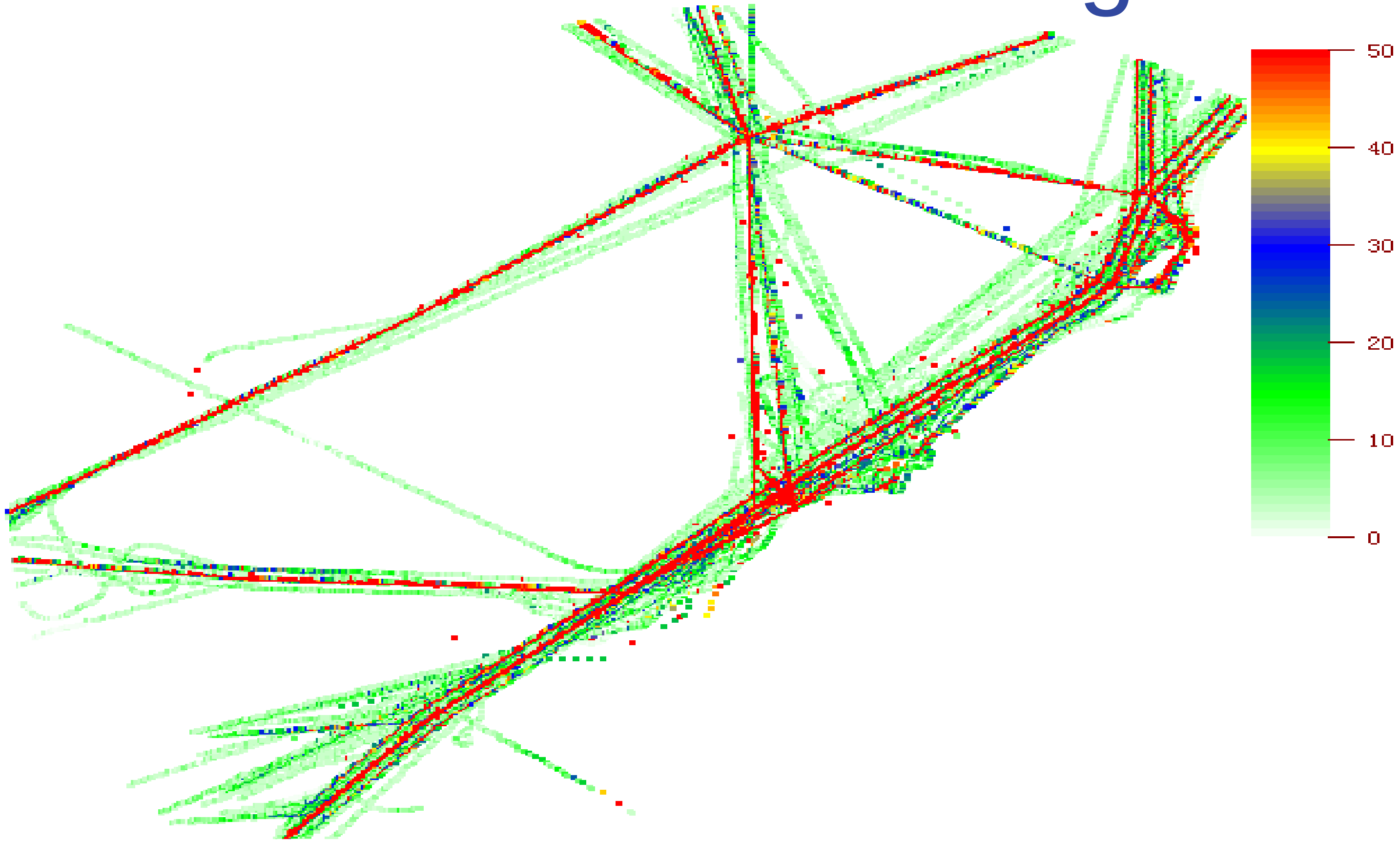
Fuel Consumption Estimation
for Different Time Periods

Fuel consumption Distribution
in Different Altitude Zones

Evaluate ATC Group Performance

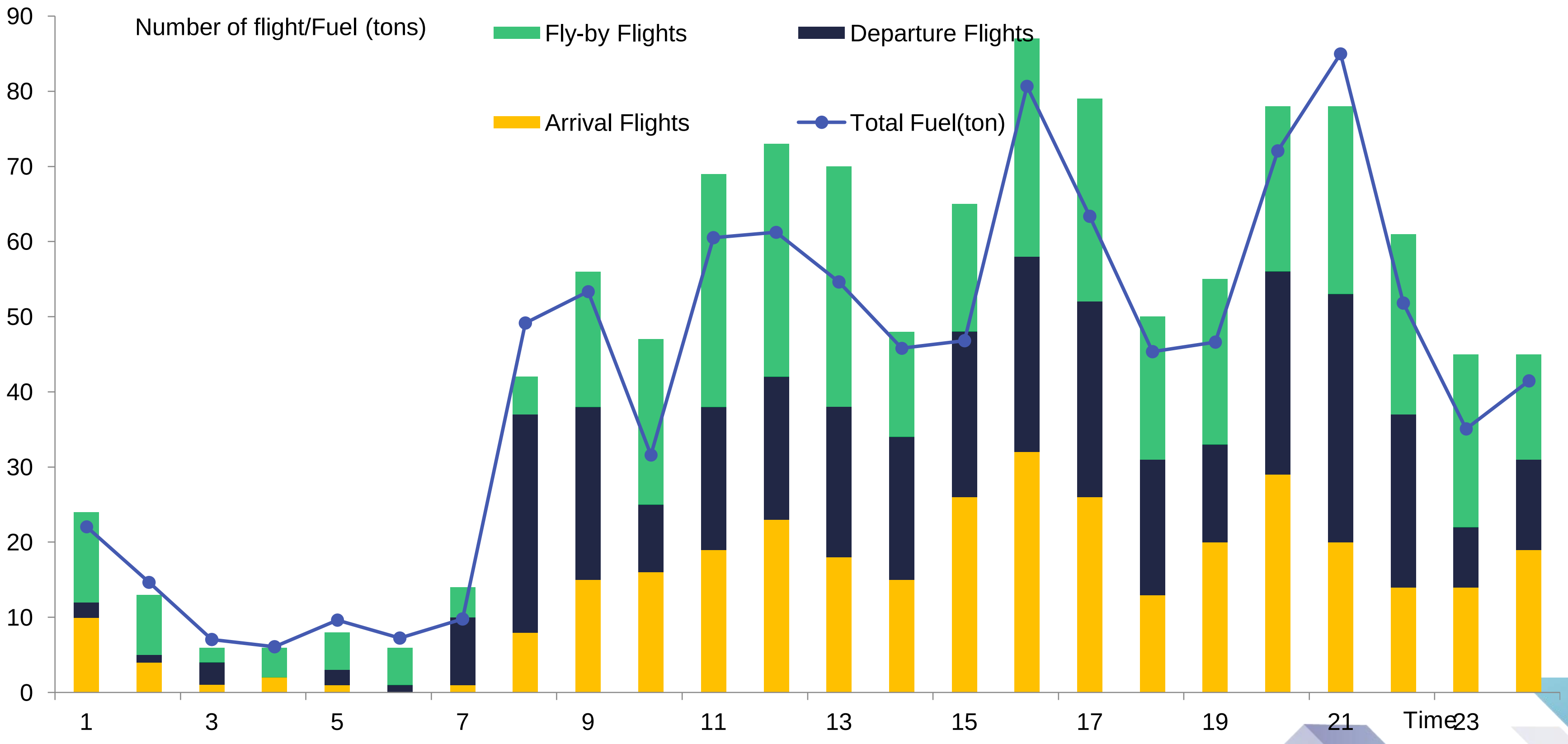
ESTIMATION AND ANALYSIS

1. in Latitude and Longitude Grid



Red routes or points should be paid attention to and some improvement can be made for airspace planning.

2. for Different Time Periods



The peak hours in this airspace are three periods: 11:00-13:00, 16:00-17:00, and 20:00-22:00..

ESTIMATION AND ANALYSIS

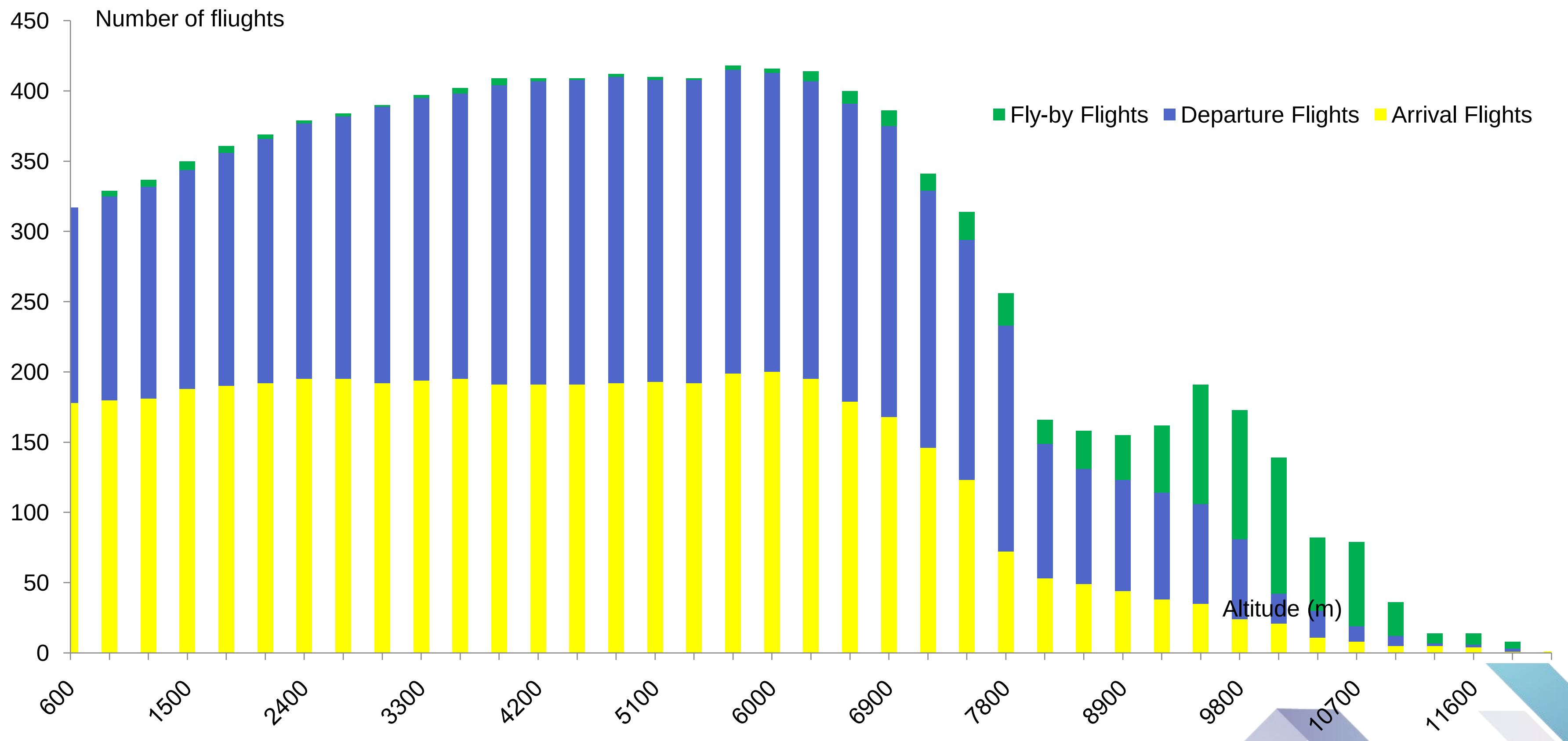
2. for Different Time Periods

	Percentage of Departure flight	Percentage of fly-by flight	Percentage of Arrival flight	Total flight
Average fuel consumption	0.014	0.284	-0.436	-0.480
Average flight time	-0.602	0.647	-0.030	-0.395
Average flight distance	-0.569	0.740	-0.217	-0.483

Fly-by flights percentage has significant positive correlation with the average flight time and average distance.

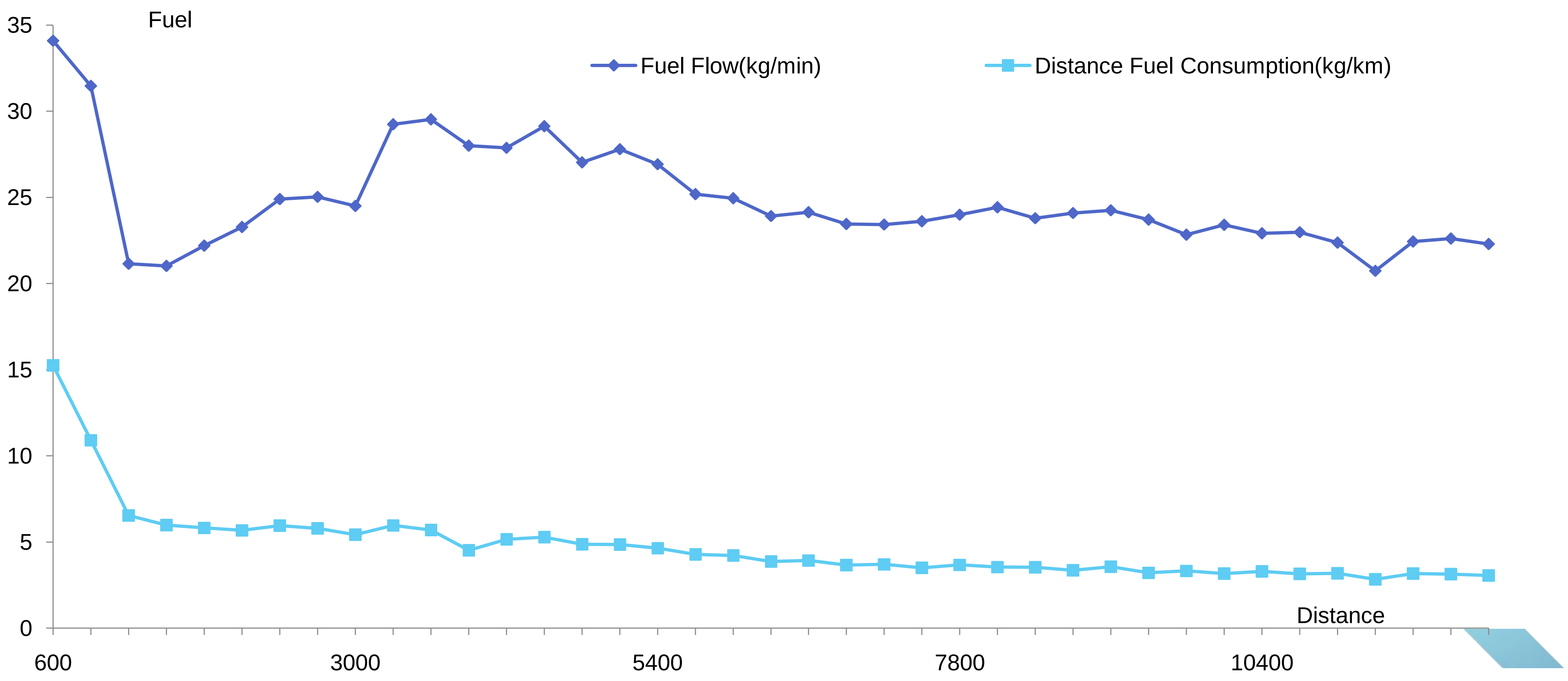
ESTIMATION AND ANALYSIS

3. in Different Altitude Zones



The vast majority of flights occur at mid and low altitude of 7800 meters and below.

3. in Different Altitude Zones



With the increase of altitude, both the fuel consumption per unit time and the fuel consumption per unit distance show a downward trend.

4. Evaluate ATC Group Performance

Date	Amount of Flight	Total Flight Time (sec)	Total Fuel Consumption (kg)	Average Flight Time (sec)	Average Fuel Consumption (kg)	Fuel Consumption per Unit Time (kg/sec)
10-19	780	1245422	1029906	1597	1320	0.827
10-20	781	1241776	1009697	1590	1293	0.813
10-21	774	1209151	971200	1562	1255	0.803
10-22	788	1229770	1008686	1561	1280	0.820
10-23	796	1266331	1035709	1591	1301	0.818
10-24	752	1178552	956782	1567	1272	0.812
10-25	795	1324457	1079655	1666	1358	0.815
10-26	788	1229697	1014074	1561	1287	0.825
10-27	805	1256956	1017973	1561	1265	0.810
10-28	819	1333919	1104473	1629	1349	0.828

4. Evaluate Controller Performance Based on Simulators

Controllers	Average fuel consumption (kg)	Average flight time (s)	Average flight distance (km)
01	2612	1542	236
02	2713	1639	241
03	2547	1522	223
04	2458	1491	221
05	2616	1562	233
06	2623	1579	230
07	2698	1594	245
08	2489	1511	223
09	2429	1488	218

5. The Effect of Flight Parameters

Factors	Correlation Coefficient
Average Speed	-0.341
Flight Amount	0.506
Average Time	0.940
Average Distance	0.915
Flight Time Percentage on Altitudes <= 3000m	0.341
Flight Time Percentage on Altitudes > 3000m	-0.341

The average flight time, average flight distance and the number of flight are the primary factors.

Conclusion

- When there is no accurate fuel burn data available, the model presented can be used to estimate the fuel consumption based on 4D trajectory data.
- The estimation can be used to evaluate the effects of air traffic control and operations in the airspace on energy-saving and emission-reduction of aviation.
- The average flight time, average flight distance and the number of flight in a given ATC airspace are the primary factors that affect the fuel consumption of the aircraft within that airspace.
- With a given number of flights and a certain defined airspace environment, the skills of air traffic controllers have a great bearing on the fuel consumption of the aircraft in that airspace.

Thanks for Listening!

Questions?