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

LIU Fei, ZHUANG Nanjian, REN Qiang, WEI Zhiqiang
College of Air Traffic Management, CAUC
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How to assess the effects?
Quick Access Recorder system (QAR)

Available & Easy
Lack of fuel consumption parameters

Hard & Impossible

ATC surveillance data
ATC surveillance data

Easy & Available
Lack of fuel consumption parameters

Estimation Method
Estimation Method

- What is it?
- How accurate is it?
- What can we do with it?
1. Classifying Flight Phases

- **Takeoff**
- **Climb**
  \[ S_i = \begin{cases} 
  1, & (z_{i+1} - z_i) > Bar \\
  0, & |z_{i+1} - z_i| \leq Bar \\
  -1, & (z_i - z_{i+1}) > Bar 
  \end{cases} \]
- **Cruise**
- **Descent**
- **Landing**

\( Z \) 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

\[
\begin{align*}
\nu_i &= \sqrt{(y_i - y_{i-1})^2 + (x_i - x_{i-1})^2} / (t_i - t_{i-1}) \\
\phi_i &= \arcsin\left(\frac{x_i - x_{i-1}}{\sqrt{(y_i - y_{i-1})^2 + (x_i - x_{i-1})^2}}\right) \\
\theta_i &= \arctan\left(\frac{z_i - z_{i-1}}{\sqrt{(y_i - y_{i-1})^2 + (x_i - x_{i-1})^2}}\right)
\end{align*}
\]

\((x, y)\) is the aircraft position coordinates (in meters), \(t\) is time (in seconds).
2. Calculating Flight Speed and Attitude

\[
\begin{align*}
L_i \sin(\beta_i) &= M_i v_i \frac{d\varphi_i}{dt_i} \\
L_i \cos(\beta_i) - M_i g \cos(\theta_i) &= M_i v_i \frac{d\theta_i}{dt_i}
\end{align*}
\]

$L_i$ is lift (N), $M_i$ is aircraft mass, $\beta_i$ is bank angle (radian)

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

Bank Angle
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

\[ T_i = D_i + M_i g \sin(\theta_i) + M_i \frac{dv_i}{dt_i} \]

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

\( D_i \) is drag (N).
Estimation Method

4. Calculating Fuel Flow during Cruise

\[ D_i = \frac{\rho_i v_i^2 s_w (C_{D0} + C_{D2} C_{Li}^2)}{2} \]

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

\( \rho_i \) 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.
4. Calculating Fuel Flow during Cruise

**Thrust**

\[
T_i = a M_i^2 + b M_i + c
\]

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

\[
b = \left[ g \sin(\theta_i) + \frac{(v_i - v_{i-1})}{(t_i - t_{i-1})} \right]
\]

\[
c = \frac{\rho_i v_i^2 s_w C_{D0}}{2}
\]

**Fuel Flow & Mass**

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

\[
M_i = M_{i-1} - FF_i \left( t_i - t_{i-1} \right)
\]
5. Calculating Fuel Flow during Descent

Based on **DABA MODEL**, $C_6$ and $C_7$ are descent fuel flow coefficients and $h$ (ft) is the altitude above sea level.
Flow chart to estimate aircraft performance parameters
Software Development

Aircraft Pollution Emission Analysis Tools

Calculation of Aircraft Pollution Emissions Based on 4D Data

Aircraft Basic Data File: D:\my projects\emission_analysis\emission_analysis\bin\Debug\aircraft_basic_data.inp

Engine Basic Data File: D:\my projects\emission_analysis\emission_analysis\bin\Debug\engine_emission_basic.inp

Select Data File Type: 
- Radar 4D Data File:
- ADB-B 4D File:
- Simulator's 4D File:

Input 4D Data File: D:\my projects\emission_analysis\emission_analysis\bin\Debug\radar_data.rec

Select Flight Callsign: CDG4886 RADAR@1037

Calculate Emissions
Batch Calculate
Hide Results
Save Results Data
Close

<table>
<thead>
<tr>
<th>CallSign</th>
<th>Time</th>
<th>Altitude</th>
<th>Fuel_Burnt</th>
<th>CO2_Emission</th>
<th>NOX_Emission</th>
<th>CO_Emission</th>
<th>HC_Emission</th>
<th>SO2</th>
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<tbody>
<tr>
<td>CDG4...</td>
<td>64.00</td>
<td>0.00</td>
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<td>1.39934</td>
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<td>0.00837</td>
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<td>1870.83</td>
<td>7.59292</td>
<td>3.80668</td>
<td>0.39096</td>
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<td>AHK7...</td>
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<td>9750.00</td>
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<td>4056.12</td>
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<td>3.08519</td>
<td>0.35655</td>
<td>1.23</td>
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<td>0.00</td>
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<td>6.69595</td>
<td>0.64429</td>
<td>0.05133</td>
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<td>CKK2...</td>
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<td>9720.00</td>
<td>3141.07</td>
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</table>

Aircraft Pollution Emission Analysis Tools (APEAT) 1.0, Developed by WEI of CAUC, 20141201
Accuracy of the Estimation Model

Estimation Method

ATC surveillance data

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

<table>
<thead>
<tr>
<th>QAR No.</th>
<th>Takeoff Mass (KG)</th>
<th>Fuel Consumption (KG)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Direct Calculation</td>
<td>Integration Calculation</td>
<td>Reference Fuel Consumption</td>
</tr>
<tr>
<td>1</td>
<td>64772</td>
<td>4898</td>
<td>4833</td>
</tr>
<tr>
<td>2</td>
<td>70379</td>
<td>8419</td>
<td>8339</td>
</tr>
<tr>
<td>3</td>
<td>62142</td>
<td>2413</td>
<td>2560</td>
</tr>
<tr>
<td>4</td>
<td>64156</td>
<td>5244</td>
<td>5253</td>
</tr>
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<td>5</td>
<td>65970</td>
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<td>6</td>
<td>65444</td>
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<td>9</td>
<td>65825</td>
<td>5371</td>
<td>5352</td>
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<tr>
<td>10</td>
<td>64990</td>
<td>4481</td>
<td>4514</td>
</tr>
</tbody>
</table>
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
Red routes or points should be paid attention to and some improvement can be made for airspace planning.
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

<table>
<thead>
<tr>
<th></th>
<th>Percentage of Departure flight</th>
<th>Percentage of fly-by flight</th>
<th>Percentage of Arrival flight</th>
<th>Total flight</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average fuel consumption</strong></td>
<td>0.014</td>
<td>0.284</td>
<td>-0.436</td>
<td>-0.480</td>
</tr>
<tr>
<td><strong>Average flight time</strong></td>
<td>-0.602</td>
<td>0.647</td>
<td>-0.030</td>
<td>-0.395</td>
</tr>
<tr>
<td><strong>Average flight distance</strong></td>
<td>-0.569</td>
<td>0.740</td>
<td>-0.217</td>
<td>-0.483</td>
</tr>
</tbody>
</table>

Fly-by flights percentage has significant positive correlation with the average flight time and average distance.
The vast majority of flights occur at mid and low altitude of 7800 meters and below.
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

<table>
<thead>
<tr>
<th>Date</th>
<th>Amount of Flight</th>
<th>Total Flight Time (sec)</th>
<th>Total Fuel Consumption (kg)</th>
<th>Average Flight Time (sec)</th>
<th>Average Fuel Consumption (kg)</th>
<th>Fuel Consumption per Unit Time (kg/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-19</td>
<td>780</td>
<td>1245422</td>
<td>1029906</td>
<td>1597</td>
<td>1320</td>
<td>0.827</td>
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<tr>
<td>10-20</td>
<td>781</td>
<td>1241776</td>
<td>1009697</td>
<td>1590</td>
<td>1293</td>
<td>0.813</td>
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<td>10-21</td>
<td>774</td>
<td>1209151</td>
<td>971200</td>
<td>1562</td>
<td>1255</td>
<td>0.803</td>
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<tr>
<td>10-22</td>
<td>788</td>
<td>1229770</td>
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<td>1280</td>
<td>0.820</td>
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<td>10-24</td>
<td>752</td>
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<td>1666</td>
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<td>1333919</td>
<td>1104473</td>
<td>1629</td>
<td>1349</td>
<td>0.828</td>
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</table>
## 4. Evaluate Controller Performance Based on Simulators

<table>
<thead>
<tr>
<th>Controllers</th>
<th>Average fuel consumption (kg)</th>
<th>Average flight time (s)</th>
<th>Average flight distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>2612</td>
<td>1542</td>
<td>236</td>
</tr>
<tr>
<td>02</td>
<td>2713</td>
<td>1639</td>
<td>241</td>
</tr>
<tr>
<td>03</td>
<td>2547</td>
<td>1522</td>
<td>223</td>
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<td>04</td>
<td>2458</td>
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<td>05</td>
<td>2616</td>
<td>1562</td>
<td>233</td>
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<td>06</td>
<td>2623</td>
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<td>07</td>
<td>2698</td>
<td>1594</td>
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<td>1511</td>
<td>223</td>
</tr>
<tr>
<td>09</td>
<td>2429</td>
<td>1488</td>
<td>218</td>
</tr>
</tbody>
</table>
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?