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

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Abstract—Objective and numerical estimation of fuel burn is a critical technology to evaluate the efficiency of air traffic operations. In this paper, the models are constructed to calculate aircraft performance parameters based on 4D flight trajectories. We developed software within Visual Studio C# environment to compute fuel consumption data on the basis of recorded Radar track data. By comparing with QAR data, it is found that the error of the models constructed is no more than 5%. The models and software proposed in this paper are used to estimate and analyze the aircraft fuel consumption in different latitude and longitudinal grids, in different time periods and at different altitudes. They can also be applied to evaluate the efficiency of different air traffic control groups or the performance of individual controller. Based on the evaluation results, controllers can improve their control decision to ensure flight safety and improve airspace capability. The research results can be used to quantify and analyze the impact of new technologies and air traffic controllers’ skill differences on Civil Aviation energy saving and emission reduction.

Keywords: fuel consumption estimation; aircraft performance; flight trajectory data; correlation analysis

1. INTRODUCTION

As one of the main focuses of aviation industry, aircraft fuel consumption has a great impact on airlines’ efficiency. Meantime, the problem of global warming has drawn the world’s attention to aviation emissions including fuel pollutants such as CO2, NOx, SOx, UHC, etc. And many projects have been established to improve the emission status and aviation operation efficiency as well, such as NextGen in the United States [1], SESAR in Europe [2] and the Australian Air Traffic Management Plan (AATMP) in Australia [3]. Many studies have been conducted on aircraft load management, flight mode improvement and flight parameters optimization, so as to reduce the fuel cost which is the primary controllable cost in flight operation [4][5]. There is evidence that air traffic operation modes and air traffic control (ATC) command modes affect fuel consumption significantly. And there is a potential to improve these aspects for energy-saving and emission-reduction, which has drawn attention of the industry. Recent years has witnessed a great progress in the new ATC technologies popularization and application, e.g. Reduced Vertical Separation Minimum (RVSM), Performance Based Navigation (PBN), parallel routes, Multi-airport Collaborative Decision Making (CDM), Continuous Descent Approach (CDA), System Wide Information Management (SWIM), etc.[6][7]. These technologies increase airspace capacity and operation efficiency, and decrease fuel consumption to some extent. However, lack of scientific and quantitative analysis of fuel consumption parameters, the assessment of the effects of new technologies on fuel conservation is vague and uncertain.

There are no fuel consumption parameters in the available ATC surveillance data (e.g. data of Secondary Surveillance Radar (SSR) and ADS-B), so it is difficult for controllers to concern the fuel consumption conditions or to conduct statistics and analysis of the total fuel burning within the airspace [8][9]. Airborne Quick Access Recorder system (QAR) makes real-time storage of parameters such as fuel flow, aircraft weight, engine RPM, airspeed, which can be used to calculate and analyze fuel consumption. But it is impossible for the air traffic management departments to collect all the flights’ QAR data at the same time to evaluate fuel consumption, especially the data of overseas airlines flight. In order to use the great amount of data from these sources, Junzi Sun et al. use different data mining methods to generate parametric models for calculating the aircraft performance parameters in [10]. And Sun et al., have provided some efficient ways to process the loosely connected data points into organized segments based on trajectory and respective flight phases [11].

Trani et al. have explored the application of neural networks algorithms to fuel consumption estimation modeling in [12]. The method of estimating fuel consumption based on ATC surveillance data can support the evaluation of air traffic control command effect and the assessment of new technology application, and can help to improve the quality of ATC service and airspace operation efficiency [4][13][14]. Aircraft fuel consumption and emission estimation tool has been developed by EUROCONTROL based on base of aircraft data (BADA), which estimates the fuel consumption and pollutant emission conditions of air traffic activities according to radar-recorded data. And this tool has become the important basis to evaluate ATC operation efficiency [15][16][17]. Chatterji also studied the fuel burn estimation model used the EUROCONTROL Base of Aircraft Data (BADA) 3 equations [18]. Since cruise is the main flight phase of civil aircraft, WEI and DIAO established the cruise pollutants emission models for calculating pollution emissions during different cruise conditions. The results show that the sequence of pollutants quantity from high to low is as follows: CO2, NOx, CO, SO2 and HC. Meanwhile, the influence of cruise patterns, altitude, weight of aircraft and temperature deviation on pollutants emission is analyzed based on the results [19].

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In this paper, firstly, the effect of Air Traffic Control on aircraft fuel consumption is outlined. Then an estimation method is presented to evaluate the influence of ATC work on fuel burn. In this method, the matching models are constructed for calculating aircraft performance parameters based on ATC surveillance data. The trajectory data recorded by SSR and ADS-B are used to compute the parameters including aircraft fuel flow, Mach number, aircraft mass, thrust and aerodynamic forces. The QAR data collected are studied to analyze the estimation accuracy. Then the data collected by SSR within a specific airspace are used to calculate and contrast the total fuel consumption. Finally, the estimation model is applied to evaluate the performance and effects of air traffic control. It is shown that air traffic operation condition has a great bearing on aircraft fuel consumption. Flight economy and efficiency can be increased by improving ATC command technology and methods. And this estimation can be further used to assess the air traffic management operation strategies or policies.

II. MODEL FOR ESTIMATING AIRCRAFT FUEL CONSUMPTION AND PERFORMANCE PARAMETERS

Aircraft performance parameters, such as aircraft mass, thrust and fuel flow, have a direct bearing on the pollutant emission. But the current ATC 4D trajectory data only contain such parameters as aircraft type, flight number, position, speed and altitude, and exclude the performance parameters above. That’s why the current ATC 4D trajectory data cannot be used to calculate fuel consumption directly. Therefore, it is necessary to construct a model for calculating performance parameters based on 4D trajectory data, which is the basis to estimate fuel consumption and to evaluate ATC efficiency.

A. Method of Classifying Flight Phases

Different flight phases have various impacts on aircraft thrust and fuel flow. The model of classifying flight phases can be constructed based on aircraft altitude data of 4D trajectory before and after a certain moment.

\[
S_i = \begin{cases} 
1, & (z_{i+1} - z_i) > \text{Bar} \\
0, & |z_{i+1} - z_i| \leq \text{Bar} \\
-1, & (z_i - z_{i+1}) > \text{Bar} 
\end{cases}
\]

(1)

Here, \( Z \) is flight altitude (m), \( \text{Bar} \) is the tolerance which is assumed to be 1 meter to neglect the error and interference of 4D trajectory data, \( i \) is flight time series, and \( S_i \) is flight phases (1-climb, 0-cruise/holding, -1-descent). Since the fuel burn of takeoff and landing is not significant for the whole flight, so these two phases are not accounted for. In order to eliminate the fluctuation interference of acquired data, the altitude data of five current and following moments are used to determine and validate the current flight phase. And the flow chart is as shown in Fig. 1.

B. Models for Calculating Performance Parameters

1) Model for Calculating Flight Speed and Attitude

Such parameters as airspeed, Mach number, pitch angle and bank angle are not or partially included by 4D trajectory data, so the calculation model of flight Speed and attitude based on 4D trajectory data are established as following.

\[
\begin{align*}
    v_i &= \sqrt{(y_{i} - y_{i-1})^2 + (x_i - x_{i-1})^2} \\
    \varphi_i &= \arcsin \left( \frac{x_i - x_{i-1}}{\sqrt{(y_{i} - y_{i-1})^2 + (x_i - x_{i-1})^2}} \right) \\
    \theta_i &= \arctan \left( \frac{z_i - z_{i-1}}{\sqrt{(y_{i} - y_{i-1})^2 + (x_i - x_{i-1})^2}} \right)
\end{align*}
\]

(2)

In the equation, \((x, y)\) is the aircraft position coordinates (in meters, \( x \) to the East for the positive, and \( y \) to the north for the positive), \( i \) is time (s), \( V_i \) is groundspeed (m/s) which is specified as the resultant of airspeed and wind speed, and it is considered to be the same as airspeed if without sufficient weather data, \( \varphi_i \) is true heading (radian), \( \theta_i \) is pitch angle (radian). Bank angle can be found by constructing the flight aerodynamic model in lateral and longitudinal projection planes, which is shown below.

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

(3)
In the equation (3) [20], \( L_i \) is lift (N), \( \beta_i \) is bank angle (radian) that affects drag and fuel consumption, \( M_i \) is aircraft mass. The first equation shows that the lateral component of lift results in the change of heading (\( d\theta_i/dt \)), which occurs in lateral turn of aircraft. And the second equation shows that the vertical component of lift affects the change of pitch attitude (\( db_i/dt \)), which occurs in climb and descent of aircraft.

Equation (4) is derived from (2) and (3) to find the bank angle.

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

(4)

2) Model for Calculating Fuel Flow during Climb/Descent

Engine thrust varies with different flight phases. During Climb, engines work with the normal rated thrust which is a function of speed, altitude and temperature. Meteorological parameters are seldom included in ATC trajectory data, so it is assumed the environment is International Standard Atmosphere (ISA). Then the following equation can be obtained based on BADA models [20].

\[
T_i = C_i1 \left( \frac{1}{C_2} + C_3 z_i^2 \right)
\]  

(5)

Where \( C_i, C_2 \) and \( C_3 \) are constants relative to engine type, \( T_i \) is the thrust during climb (N). Fuel flow is directly related to thrust, and can be computed by following equation (6) [20].

\[
FF_i = TC_i \left( 1 + \frac{v_i}{C_3} \right)
\]  

(6)

In the equation, \( C_2 \) and \( C_3 \) are constants relative to engine type, \( FF_i \) is fuel flow (kg/min).

During descent, if the engines work with idle thrust, the fuel flow is defined as Minimum fuel flow \( FF_{\text{min}} \), which is described as Equation (7) below.

\[
FF_{\text{min}} = C_g \left( 1 - \frac{\Delta}{C_7} \right)
\]  

(7)

Where \( C_g \) and \( C_7 \) are descent fuel flow coefficients and \( \Delta \) (ft) is the altitude above sea level.

3) Model for Calculating Aircraft Mass

During Climb, fuel flow is independent of aircraft mass. But in cruise, mass affects fuel flow greatly, while aircraft mass data us not contained by ATC trajectory data. Because climb rate is relative to aircraft mass, which can be deduced by the variation of flight altitudes, mass can be found based on climb rate and be used to compute fuel consumption. To do so, acceleration and deceleration dynamic equation shall be defined firstly.

\[
T_i - \dot{M}_i g \sin(\theta) = M_i \frac{dv_i}{dt}
\]  

(8)

In the equation above [20], \( D_i \) is drag (N) which is relative to air density, airspeed and aircraft aerodynamic characteristics, which can be calculated by the following equation.

\[
D_i = \frac{\rho v_i^2 s(C_{L0} + C_{D2} \phi)}{2}
\]  

(9)

Here, \( \rho \) is air density, \( S_w \) is wing area, \( C_{L0} \) and \( C_{D2} \) are aerodynamic constants determined by aircraft type, \( C_L \) is lift coefficient. Equation (10) can be derived by substituting (3) into (9).

\[
D_i = \frac{\rho v_i^2 s C_{L0} + 2C_{L0} M^2}{2} \left( \frac{\theta - \theta_{i-1}}{v_i - v_{i-1}} \right) v_i + g \cos(\theta)
\]  

(10)

Model for calculating aircraft mass can be obtained according to (5), (8) and (10). In flight, aircraft mass decreases with the fuel burning, then mass should be corrected by following method.

\[
M_i = M_{i-1} - FF_i (t_i - t_{i-1})
\]  

(11)

4) Model for Calculating Fuel Flow in Cruise

In the phases of cruise and descent, engines produce thrust as required to ensure the balance shown by (8). The required thrust can be found by substituting (10) into (8).

\[
\begin{align*}
T_i &= a M_i^2 + b M_i + c \\
2C_{D2} &\left( \frac{\theta - \theta_{i-1}}{v_i - v_{i-1}} \right) v_i + g \cos(\theta) \\
a &= \frac{v_i^2 \rho s \cos(\beta)}{2} \\
b &= \left[ g \sin(\theta) \right] + \left( \frac{v_i - v_{i-1}}{v_i - v_{i-1}} \right) \\
c &= \frac{\rho v_i^2 s C_{L0}}{2}
\end{align*}
\]  

(12)

According to the thrust calculated, the fuel flow in cruise and descent can be acquired by using equation (6).

C. Process of Estimating Aircraft Performance Parameters

ATC radar data have been analyzed in the paper to pick up such information as flight number, groundspeed, altitude, climb rate/descent rate. Aircraft performance parameters can be real time estimated based on equations above, and the process is illustrated in Fig. 2.
D. Software Development for Estimating Aircraft Fuel Consumption

On the basis of models for calculating aircraft performance parameters, visual studio C# is used to develop a software for estimating aircraft fuel consumption. When the software starts, the menu or hotkey can be used to select “Emission@4D data” to activate the page of “Fuel consumption calculation based on 4D trajectory data”. The primary functions of the software include data loading, performance parameters calculation and result display. And before the computation, aircraft type data, engine data and trajectory data should be imported through user actions. Currently, three kinds of trajectory data are available, i.e. radar recorded data, ADS-B data and radar simulator recorded data.

E. Accuracy of the Estimation Model

To analyze the accuracy of estimation model, QAR data of certain types of aircraft are collected to define the accuracy of the performance parameters matching model. Firstly, flight trajectory data are drawn from QAR data, which include time, aircraft type, latitude, longitude, pressure altitude, ground speed, heading, etc.. Based on these data, the performance parameters matching model is called to calculate flight parameters at each time. Then numerical integration is applied to obtain the fuel consumption of whole flight.

In order to examine the accuracy of the model and the method, a comparison with the actual QAR data should be made. There are two ways to find fuel consumption based on QAR recorded data:

a. finding the mass differential between takeoff mass and landing mass, which is usually inaccurate;

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

In this paper, the weighted average of the two methods mentioned above is found, and the acquired reference fuel consumption is used to evaluate the accuracy of the estimation model. In this research, QAR data from a certain airline company are used to validate the accuracy of estimation through the methods mentioned, and the results are shown below.

It is shown that the deviation of the estimated fuel consumption by the model and the reference value is mainly less than 5%. Under the condition without actual fuel consumption data, the model proposed in this paper can obtain relatively accurate flight performance parameters, which satisfying the needs of researches and analysis of energy-saving and emission-reducing.
TABLE I. ACCURACY OF ESTIMATED FUEL CONSUMPTION FOR DIFFERENT FLIGHTS

<table>
<thead>
<tr>
<th>No.</th>
<th>Takeoff Mass (KG)</th>
<th>Fuel Consumption (KG)</th>
<th>Relative Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>64772</td>
<td>4898</td>
<td>4865</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>
<tr>
<td>5</td>
<td>65970</td>
<td>5643</td>
<td>5649</td>
</tr>
<tr>
<td>6</td>
<td>65444</td>
<td>4554</td>
<td>4553</td>
</tr>
<tr>
<td>7</td>
<td>66932</td>
<td>4899</td>
<td>4878</td>
</tr>
<tr>
<td>8</td>
<td>60781</td>
<td>4772</td>
<td>4747</td>
</tr>
<tr>
<td>9</td>
<td>65825</td>
<td>5371</td>
<td>5352</td>
</tr>
<tr>
<td>10</td>
<td>64990</td>
<td>4481</td>
<td>4514</td>
</tr>
</tbody>
</table>

III. ESTIMATION AND ANALYSIS OF AIRCRAFT FUEL CONSUMPTION BASED ON 4D TRAJECTORY

The prescribed estimation models above can find wide applications in the actual flight operations. The estimated results reveal the key factors that affect fuel consumption. Furthermore, those results can help to improve the airspace planning and performance of air traffic controllers.

A. Fuel Consumption Distribution in Latitude and Longitude Grid

Firstly, secondary radar trajectory data are collected, which have already been resolved by some air traffic control unit. And the trajectory data for ten consecutive days are chosen for the calculation and analysis of fuel consumption. The information in the field of trajectory data includes time, radar transponder codes, call sign, aircraft type, longitude, latitude, altitude, ground speed and heading. On the basis of these data, the fuel burn distribution of total 798 flights on each latitude and longitude grid is calculated by the software developed, the result of which is shown in Fig. 4. In the chart, the accuracy of both longitude and latitude is 0.01 degrees. It is easy to find that on some routes the fuel burn is significantly higher than others, then these routes or points should be paid attention to and some improvement can be made for airspace planning.

B. Fuel Consumption Estimation for Different Time Periods

4-D trajectory data in different time periods are extracted from radar records, then the data is used to compute the aircraft fuel burn in different time periods by using the estimation models in this paper. The flight amount and fuel consumption calculated for different time periods are illustrated in Fig. 5, in which the abscissa is time (Beijing time), and the ordinate is the number of flights and fuel consumption (in tons).

![Figure 4. Distribution of fuel consumption in latitude and longitude grid within a given airspace](image)

![Figure 5. Flight amount and fuel consumption for different time periods within a given airspace](image)
different colors in the figure. The relevance coefficients between flight parameters and the proportions of each flight type are obtained so as to find the influence of flight type (departure, arrival or fly-by) on the average fuel consumption. The relevance coefficients are shown in Table. 2.

Table 2 shows that the percentage of total amount of incoming flights and the average fuel consumption are negatively correlated to a certain extent, which means that the incoming arrival flights have relatively small fuel consumption. The reason is that the arrival aircraft usually use Idle thrust setting during approach, so the fuel consumption is much lower than that of departure flights and fly-by flights. The arrival routes and flight mode of approach flights are basically similar for each flight, so the percentage of arrival flights in total flight volume is not related to average flight time and average flight distance. Fly-by flights percentage has significant positive correlation with the average flight time and average distance. The reason is that the fly-by aircraft usually need to cross the entire given airspace, i.e. from one side to the other side of the airspace. So the fly-by aircraft have longer flight distance and flight time than arrival aircraft which only fly from the airspace boundary to a certain airport. And the flight distance and flight time of fly-by aircraft are also longer than those of departure aircraft which fly from a certain airport to the airspace boundary.

C. Fuel consumption Distribution in Different Altitude Zones

In order to estimate the fuel consumption of aircraft on different altitude zones, the altitude zones must be determined at first. In this research, the altitude zones are defined as the altitude regions, each of which has the median of the flight level based on the RVSM airspace flight level standard. Then the 4D trajectory data of each flight are distributed to the respective altitude zone. Finally, the aircraft fuel consumptions in each altitude zone are calculated by using the software developed, and the computed results are discussed below.
low altitude shall be avoided as much as possible; for fly-by-aircraft, the flights at a higher flight level shall be maintained as much as possible. Combined with Fig. 6 and Fig. 7, it can be seen that the vast majority of flights in the control airspace occur at middle and low altitude of 7800 meters and below, and there is a certain potential for fuel saving.

IV. ATC EVALUATION BASED ON FUEL CONSUMPTION ESTIMATION

The fuel consumption of aircraft is one of the important evaluating indicators to evaluate ATM operation efficiency and quality. The estimation of fuel consumption can be applied to the evaluation of post ATM operational changes and can support the design, implementation and review of ATM performance improvement initiative or airspace change. Here, the estimation model is used to evaluate the performance of ATM operation in two ways. The fuel burn result based on SSR Data shows the performance of the whole controller group, and the fuel burn result based on simulators shows the performance of each controller.

A. Fuel Consumption Estimation Based on SSR Data to Evaluate ATC Group Performance

The trajectory data of SSR are collected as binary data from the ATC unit, then the data are decoded into the data of CSV format. The model above is adopted to estimate the fuel consumption based on the 4D trajectory data recorded by the simulation terminal area is originated from the actual condition of Xiamen Gaoqi International Airport airspace in China, in which the wind is not accounted for and the arrival time of each flights are predefined before the simulation.

When the controllers are conducting flight control, the trajectory data of the simulation process is recorded by the simulators, then the data is transformed and stored in the CSV format. The model above is adopted to estimate the fuel consumption based on the 4D trajectory data recorded by the simulators.

<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 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>
</tr>
<tr>
<td>10-20</td>
<td>781</td>
<td>1241776</td>
<td>1009697</td>
<td>1590</td>
<td>1293</td>
</tr>
<tr>
<td>10-21</td>
<td>774</td>
<td>1209151</td>
<td>971200</td>
<td>1562</td>
<td>1255</td>
</tr>
<tr>
<td>10-22</td>
<td>788</td>
<td>1229770</td>
<td>1008686</td>
<td>1561</td>
<td>1280</td>
</tr>
<tr>
<td>10-23</td>
<td>796</td>
<td>1266331</td>
<td>1035709</td>
<td>1591</td>
<td>1301</td>
</tr>
<tr>
<td>10-24</td>
<td>752</td>
<td>1178552</td>
<td>956782</td>
<td>1567</td>
<td>1272</td>
</tr>
<tr>
<td>10-25</td>
<td>795</td>
<td>1324457</td>
<td>1079655</td>
<td>1666</td>
<td>1358</td>
</tr>
</tbody>
</table>

It is shown that the fuel consumptions in ten consecutive days are different although the flights numbers are similar. For example, the flight amounts of October 23rd and October 25th are almost the same, but the difference of fuel consumptions is 57kg.

B. Fuel Consumption Estimation Based on Simulators to Evaluate Controller Performance

In the Radar Control Simulator Lab of Civil Aviation University of China, in order to evaluate the performance of controller, nine controllers are invited to conduct air traffic control respectively in the same simulation environment.

A certain terminal area is simulated with 13 arrival aircraft and 7 departure aircraft, which results in a heavier workload for the controllers than ordinary air traffic control conditions. And the conditions are exactly the same for each controller. The simulation terminal area is originated from the actual condition of Xiamen Gaoqi International Airport airspace in China, in which the wind is not accounted for and the arrival time of each flights are predefined before the simulation.

When the controllers are conducting flight control, the trajectory data of the simulation process is recorded by the simulators, then the data is transformed and stored in the CSV format. The model above is adopted to estimate the fuel consumption based on the 4D trajectory data recorded by the 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>
</tr>
<tr>
<td>04</td>
<td>2458</td>
<td>1491</td>
<td>221</td>
</tr>
<tr>
<td>05</td>
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<td>1562</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>2489</td>
<td>1511</td>
<td>223</td>
</tr>
<tr>
<td>09</td>
<td>2429</td>
<td>1488</td>
<td>218</td>
</tr>
</tbody>
</table>

On the basis of the data shown in the table, a quantitative analysis of the influence of controllers’ performance on fuel consumption is completed.
burn is made. Within the same airspace and for a given number of aircraft, the average fuel consumption is minimum for the aircraft controlled by the Controller 09, and the average fuel consumption is maximum for the Controller 02. The difference between the two is 284 kg. Meantime, it is shown that there is a linear correlation between the fuel consumption and flight time/distance. And the calculated linear correlation coefficient between flight time and fuel consumption is 0.957, while the coefficient between flight distance and fuel consumption is 0.953. If controllers intentionally attempt to reduce the flight time and flight distance within the airspace, the fuel consumption can be decreased significantly so as to improve the operation efficiency.

C. The Effect of Flight Parameters on Fuel Consumption

Statistical interpretation of the data in these ten days has been conducted by the developed software, thus to find out the factors affecting fuel consumption. For the trajectory data of a certain day, the flowing formulas can be applied to calculate the factors affecting fuel consumption. Based on the statistic flight parameters above, the linear correlation coefficient between various factors and average fuel consumption can be computed, and the results are as following.

\[
\overline{v} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{a} s_{i,j} / \sum_{i=1}^{n} t_{i}}{a}
\]

(12)

\[
\overline{s} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{a} s_{i,j}}{n}
\]

(13)

\[
\overline{t} = \frac{\sum_{j=1}^{a} t_{j}}{n}
\]

(14)

In these equations, \(n\) is the flight amount of one day, \(i\) is the flight sequence number, \(t_{i}\) is flight time in the airspace of flight \(i\) (s), \(s_{i,j}\) is the distance in the airspace from time \(j\) to \(j+1\) (m), \(v\) is the total average speed in the airspace (m/s), \(s\) is the average flight distance in the airspace (m), \(\overline{t}\) the average flight time in the airspace (s). The statistic flight parameters are shown below.

<table>
<thead>
<tr>
<th>Date</th>
<th>Flight Amount</th>
<th>Average Speed (m/s)</th>
<th>Average Distance (m)</th>
<th>Flight Time Percentage &lt;=3000m</th>
<th>Flight Time Percentage &gt;3000m</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-19</td>
<td>780</td>
<td>202</td>
<td>322144</td>
<td>16.08%</td>
<td>83.92%</td>
</tr>
<tr>
<td>10-20</td>
<td>781</td>
<td>203</td>
<td>322361</td>
<td>15.31%</td>
<td>84.69%</td>
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<tr>
<td>10-21</td>
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<td>202</td>
<td>315046</td>
<td>16.68%</td>
<td>83.32%</td>
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<tr>
<td>10-22</td>
<td>788</td>
<td>204</td>
<td>317682</td>
<td>16.11%</td>
<td>83.89%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Factors</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Speed</td>
<td>-0.341</td>
</tr>
<tr>
<td>Flight Amount</td>
<td>0.506</td>
</tr>
<tr>
<td>Average Time</td>
<td>0.940</td>
</tr>
<tr>
<td>Average Distance</td>
<td>0.915</td>
</tr>
<tr>
<td>Flight Time Percentage on Altitudes &lt;=3000m</td>
<td>0.341</td>
</tr>
<tr>
<td>Flight Time Percentage on Altitudes &gt;3000m</td>
<td>-0.341</td>
</tr>
</tbody>
</table>

The correlation coefficients between various factors and fuel data can denote their influence on fuel consumption. The correlation coefficient of flight speed is negative, which means the flight speeds are generally low in the current ATC operation. So increasing the flight speed appropriately will improve aircraft performance and decrease fuel consumption. The correlation coefficients of average flight time and average flight distance are positive, so reducing these two factors will decrease fuel burning through the methods as making air route straight, controlling the amount of flying-around, and reducing holding. Furthermore, the amount of flight is correlated to fuel positively, which means in the airspace total work stress is too heavy for controllers to consider flight economy. The percentages of flight time at different altitudes show that the longer time flying at low altitude the more the fuel consumption. Therefore, if possible, ATC should shorten the flight time of aircraft at low altitude to save fuel.

V. CONCLUSION

The paper focuses on the estimation of aircraft fuel consumption based on 4D trajectory and the estimation models are proposed which are constructed to estimate fuel consumption based on 4D trajectory data. And the estimation...
software is developed to analyze the fuel consumption on the basis of radar recorded data. QAR data collected are used to analyze the accuracy of the model, then the trajectory data recorded by radar and the data of ATC simulators are used to estimate and analyze fuel consumption so as to evaluate the performance of ATC operation.

The paper draws the conclusions as follow. When there is no accurate fuel burn data available, the model presented by the paper can be used to estimate the fuel consumption based on 4D trajectory data, thus to analyze the features of the fuel consumption in different latitude and longitudinal grids, that in different time periods and that at different altitudes. And 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 has a great bearing on the fuel consumption of the aircraft in that airspace.

Therefore, aircraft fuel consumption can be reduced by improving ATC technologies and methods as ATC operations have great impact on aircraft fuel burn. Furthermore, in the future, the calculation models and the software may find applications in evaluating the influence of ATC new technologies on fuel consumption and flight operations and designing future ATM systems and procedures.

References