Fuel Burn Estimation Model

Gano Chatterji
University of California, Santa Cruz

Airspace Systems Program
2011 Technical Interchange Meeting
March 28–31 2011
San Diego, CA

www.nasa.gov
Motivation

- Aircraft weight determines climb trajectory, which affects conflict detection
- Aircraft weight determines descent trajectory, which affects the amount of delay that can be absorbed during descent
- Environmental impact depends on the amount of fuel consumed
- Benefit assessment of proposed concepts in terms of fuel consumption metric
Background

- Closed-Form Takeoff Weight Estimation Model for Air Transportation Simulation – 2010 ATIO
  - Constant-altitude range equation
  - Trajectory simulation and drag coefficients
  - Cruise altitude and airspeed
  - Wind data

- Prototype Implementation and Concept Validation of a 4-D Trajectory Fuel Burn Model Application – 2010 GNC
  - Actual trajectory and wind data
  - Drag and fuel flow models
  - Simplified lift and thrust
Main Points

• Validated the fuel estimation procedure using flight test data

• Error in assumed takeoff weight results in same amount of error in the fuel estimate for long distance flights

• Fuel estimation error bounds can be determined
Outline

- Fuel Burn Estimation
- Models and Estimators
- Flight Test
- Estimation Results
- Conclusions
Fuel Burn Estimation Procedure

- Track & Wind Data
- Aircraft Weight
- Aircraft States
- Wind States
- Lift

Aerodynamic Configuration

- Drag
- Thrust
- Fuel Flow Rate
Fuel Flow Model

- Nominal fuel flow rate for jets is a function of
  - Airspeed
  - Thrust

- Minimum fuel flow rate (idle thrust condition)
  Linear function of altitude

\[ f = \max \left( f_{\min}, f_{\text{nom}} \right) \]
Thrust Estimation

• An expression for thrust is obtained by relating the acceleration to thrust, drag and gravitational forces

• Thrust estimate depends on
  – Drag
  – Mass
  – Velocity and acceleration
  – Wind velocity and acceleration
Drag Estimation

- Drag depends on
  - Drag coefficient
  - Density of air
  - Airspeed

- Drag coefficient is a function of
  - Aerodynamic configuration
  - Lift
## Aerodynamic Configuration

<table>
<thead>
<tr>
<th>Aerodynamic Configuration</th>
<th>Takeoff</th>
<th>Initial Climb</th>
<th>Clean</th>
<th>Approach</th>
<th>Landing</th>
</tr>
</thead>
</table>

Aerodynamic configuration depends on
- Stall speed
- Threshold altitude
Lift Estimation

- An expression for lift is obtained using
  - Equations of motion
  - Course is maintained by compensating for wind

- Lift estimate depends on
  - Mass
  - Aircraft velocity and acceleration
  - Wind velocity and acceleration
Wind States

- North and East components of wind velocity obtained from Rapid Update Cycle
- Wind varies with position and time
- Interpolated from hourly data
Aircraft State Estimation

- Position states (latitude, longitude, altitude)
- Velocity states (groundspeed, heading, climb rate)
- Acceleration states (horizontal, vertical, heading rate)
4/17/2009 Flight Test

- Atlantic City International in New Jersey to Los Angeles International in California
- Dry weight: 23,509 kg
- Initial fuel weight: 15,853 kg
- Fuel consumed: 8,119 kg

FAA owned Bombardier Global 5000 aircraft
Aircraft Position Estimates

- Graphs showing latitude and longitude over time, with measured and estimated data.
- Graphs showing pressure altitude over flight time, with measured and estimated data.
Aircraft Speed Estimates

Graphs showing groundspeed and airspeed variations over time.
Fuel Estimate

Fuel Consumed (kg)

Flight time (hours)

- Measured
- Estimated
Estimated takeoff weight = Maximum zero-fuel weight 
+ 90 minute reserve fuel 
+ fuel consumed
## Summary Validation Results

<table>
<thead>
<tr>
<th>Initial Weight</th>
<th>% Weight Error</th>
<th>Measured fuel consumption</th>
<th>Estimated fuel consumption</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>34,667 kg</td>
<td>-11.9</td>
<td>7,395 kg</td>
<td>-8.9</td>
<td></td>
</tr>
<tr>
<td>39,362 kg</td>
<td>0</td>
<td>8,119 kg</td>
<td>8,111 kg</td>
<td>-0.10</td>
</tr>
<tr>
<td>41,957 kg</td>
<td>6.6</td>
<td>8,542 kg</td>
<td>5.2</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

- Validated the fuel estimation procedure using flight test data
- A good fuel model can be created if weight and fuel data are available
- Error in assumed takeoff weight results in similar amount of error in the fuel estimate
- Fuel estimation error bounds can be determined
Recommendations

- Weight and fuel consumption data should be obtained for aircraft types to improve fuel and weight estimation models.

- Trajectories with different takeoff weights should be tested for conflict detection to improve safety.

- Impact of weight uncertainty should be studied for efficient descent operations.

- Environmental impact studies should consider fuel consumption uncertainty.