Fuel Burn Estimation Model

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

\[ f = \max (f_{\text{min}}, f_{\text{nom}}) \]
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 aircraft position estimates.]

- **Latitude** vs. **Longitude**
  - Measured and Estimated positions for LAX and ACY

- **Pressure Altitude** vs. **Flight Time**
  - Comparison of Measured and Estimated altitudes over 6 hours
Aircraft Speed Estimates

- Groundspeed (knots) vs Flight time (hours)
  - Measured
  - Estimated

- Airspeed (KCAS) vs Flight time (hours)
  - Indicated Airspeed
  - Estimated Airspeed
Fuel Estimate

![Graph showing fuel consumption over flight time](image)

- **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></td>
<td>7,395 kg</td>
<td>-8.9</td>
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<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></td>
<td>8,542 kg</td>
<td>5.2</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.