Fuel Burn Estimation Model

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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

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

- Takeoff
- Initial Climb
- Clean
- Approach
- Landing

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

- [Diagram]:
  - **Latitude (deg)** vs **Longitude (deg)**
  - **Pressure Altitude (ft/100)** vs **Flight time (hours)**
  - Black line: Measured
  - Dotted line: Estimated
Aircraft Speed Estimates

- **Graph 1:**
  - Title: Groundspeed (knots)
  - X-axis: Flight time (hours)
  - Y-axis: Groundspeed
  - Lines: Measured, Estimated

- **Graph 2:**
  - Title: Airspeed (KCAS)
  - X-axis: Flight time (hours)
  - Y-axis: Airspeed
  - Lines: Indicated Airspeed, Estimated Airspeed
Fuel Estimate

![Graph showing fuel consumption over flight time]

- **Fuel Consumed (kg)**
- **Flight time (hours)**

- **Measured**
- **Estimated**

The graph illustrates the comparison between measured and estimated fuel consumption over time during flight.
Weight Estimate

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>
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<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.