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
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

\[ f = \max ( f_{\text{min}}, f_{\text{nom}} ) \]
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 depends on
- Stall speed
- Threshold altitude
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](image-url)
Aircraft Speed Estimates

- Groundspeed (knots)
  - Measured
  - Estimated

- Airspeed (KCAS)
  - Indicated Airspeed
  - Estimated Airspeed
Fuel Estimate

![Graph showing fuel consumption over flight time]

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

- **Measured**
- **Estimated**
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>7,395 kg</td>
<td>-8.9</td>
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<tr>
<td>39,362 kg</td>
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<td>8,111 kg</td>
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<td>41,957 kg</td>
<td>6.6</td>
<td>8,542 kg</td>
<td>5.2</td>
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</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.