National Aeronautics and Space Administration

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

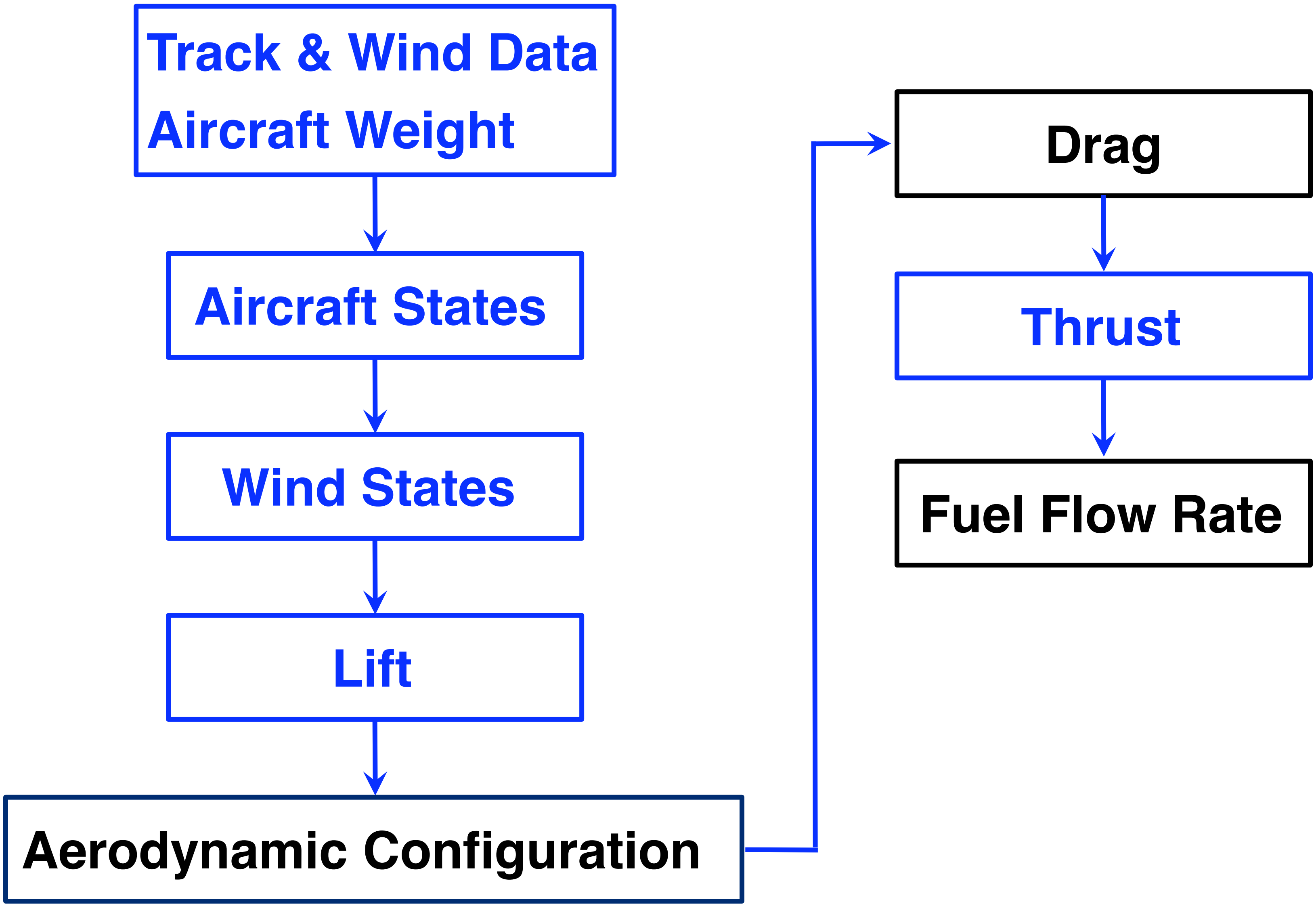
Main Points

- 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



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

$$\boxed{f = \max\left(f_{\min}, f_{nom}\right)}$$

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

Aerodynamic Configuration
Takeoff
Initial Climb
Clean
Approach
Landing

Aerodynamic configuration depends on

- Stall speed
- Threshold altitude

Lift Estimation

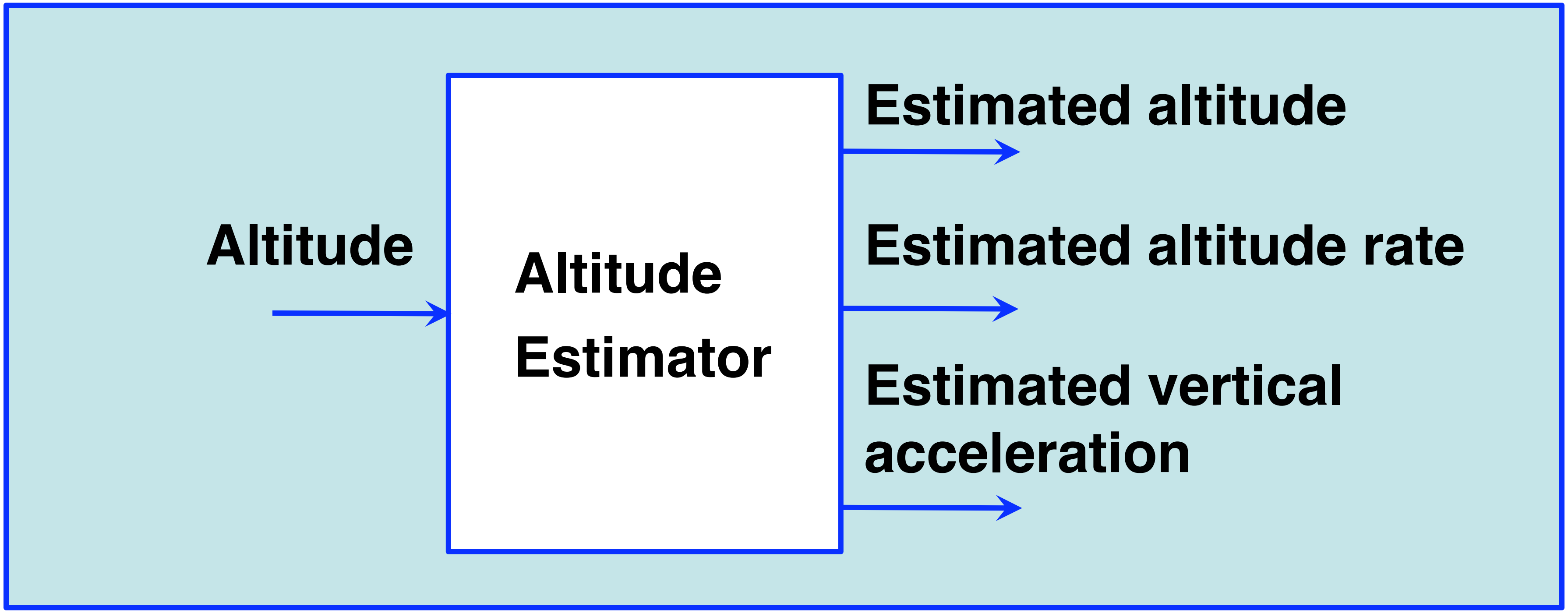
- An expression for lift is obtained using
  - Equations of motion
  - Course is maintained by compensating for wind
- Lift estimate depends on
  - Mass
  - Aircraft velocity and acceleration
  - Wind velocity and acceleration

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)

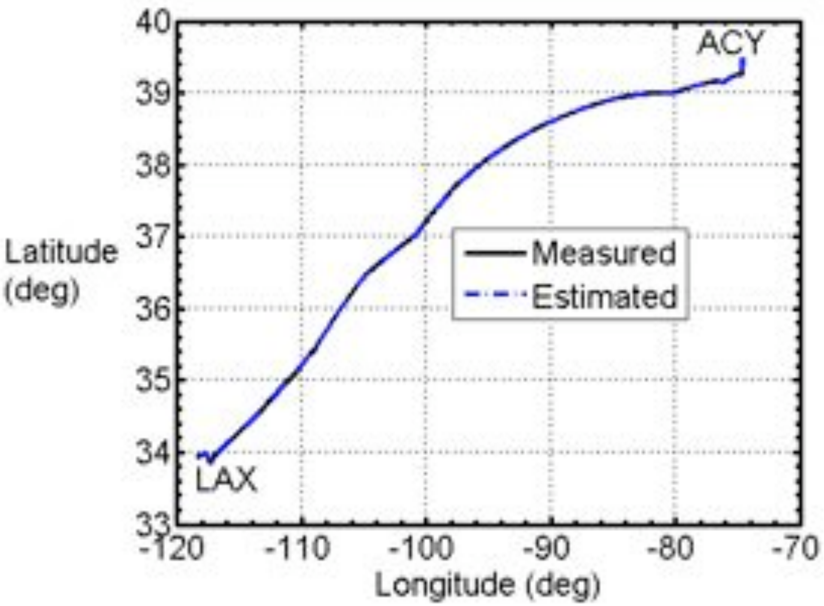


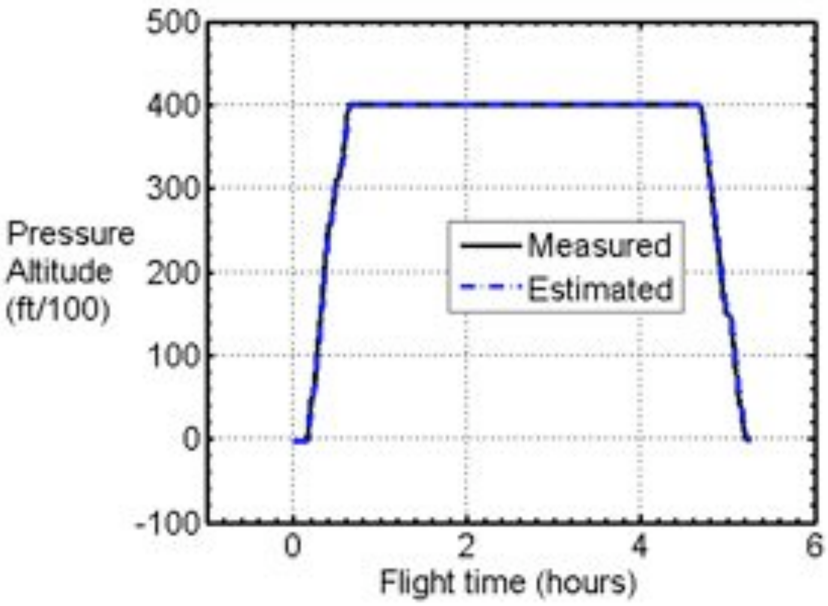
4/17/2009 Flight Test

- 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

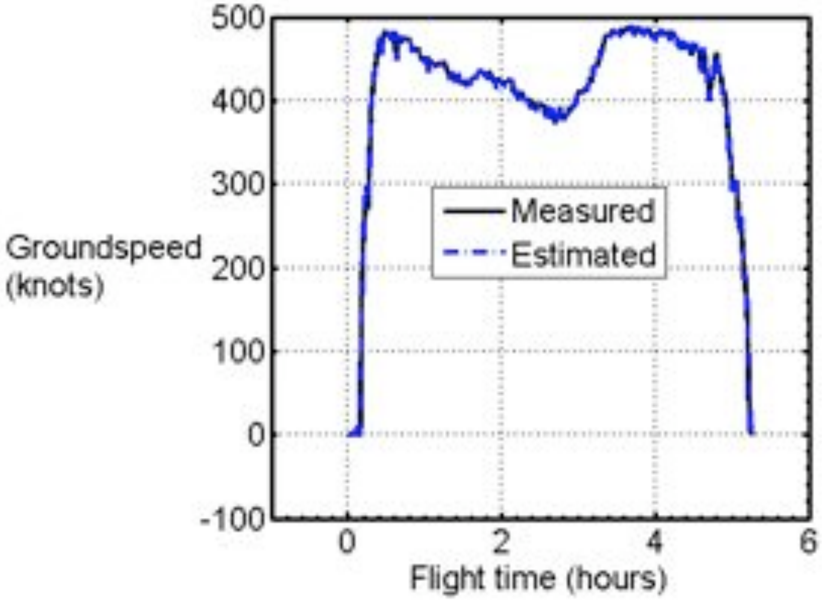
FAA owned Bombardier Global 5000 aircraft

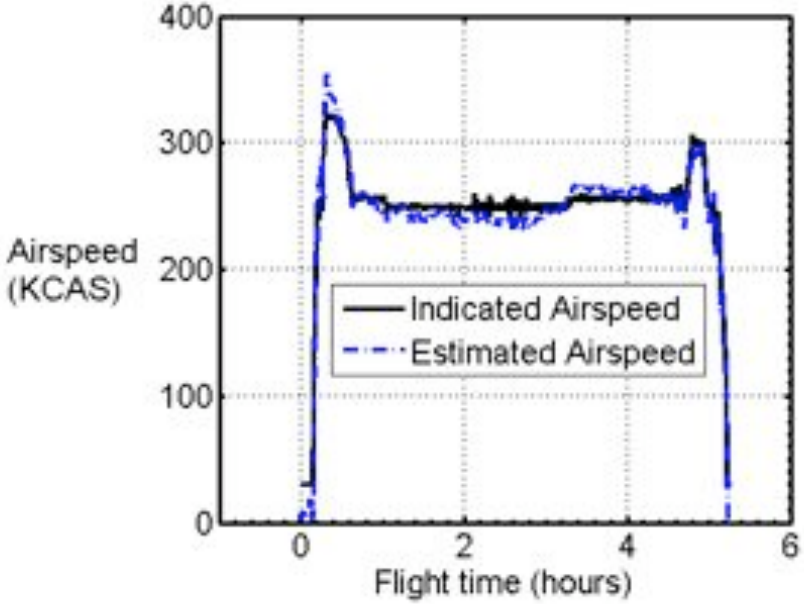
Aircraft Position Estimates



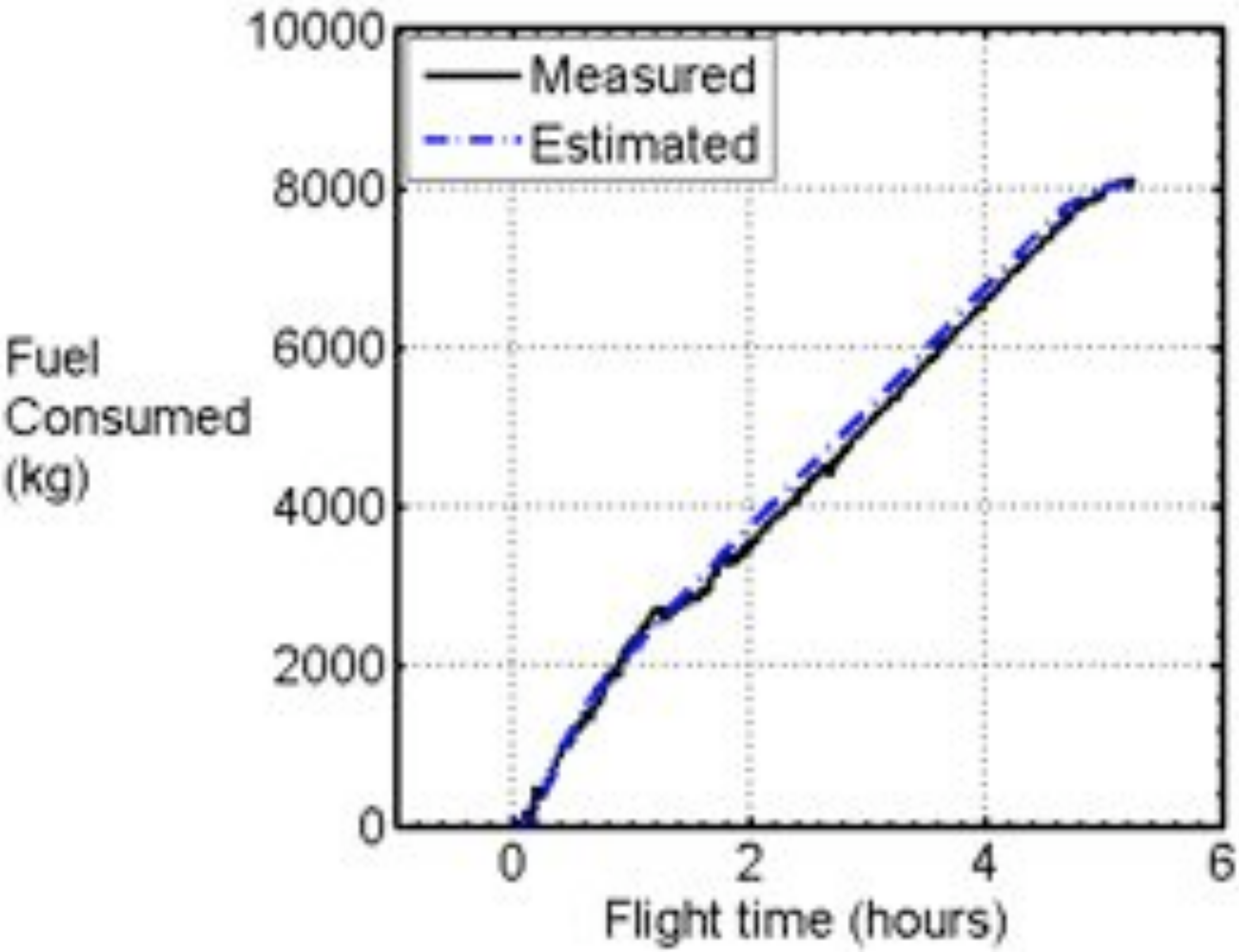


Aircraft Speed Estimates

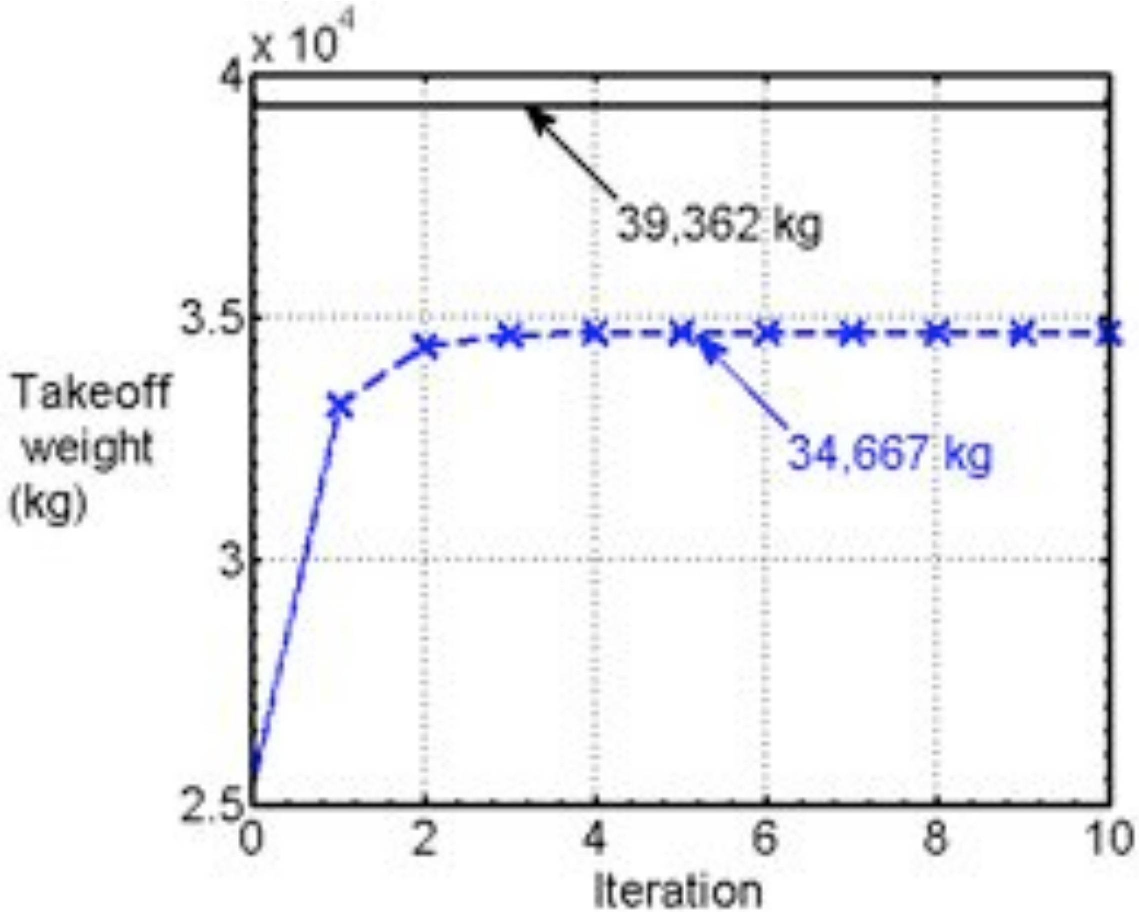




Fuel Estimate



Weight Estimate



Estimated takeoff weight = Maximum zero-fuel weight

+ 90 minute reserve fuel

+ fuel consumed

Summary Validation Results

Initial Weight	% Weight Error	Measured fuel consumption	Estimated fuel consumption	% Error
34,667 kg	-11.9		7,395 kg	-8.9
39,362 kg	0	8,119 kg	8,111 kg	-0.10
41,957 kg	6.6		8,542 kg	5.2

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