Terminal Area Fuel Burn Analyses for Environmental Models

Presented to: Environmental Working Group

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Status of FAA fuel burn modeling

- Historically, we have used a combination of SAE1845 thrust and EUROCONTROL’s Base of Aircraft Data (BADA) Thrust Specific Fuel Consumption (TSFC) to predict fuel burn.
- BADA is intended as an Air Traffic Management tool.
- Flight Data Recorder (FDR) analyses showed that this method did not well model terminal area fuel burn for some aircraft.
- Incorrect fuel burns potentially lead to incorrect emissions calculations and decisions based on erroneous data.
- Other tools (such as APMT) will also be affected by the accuracy of these models.
BADA under-prediction of fuel burn

757-200 Fuel consumption to 3000’ AFE

BADA Perfect fit
Why the differences with FDR?

• BADA TSFC values are not intended to be used in the terminal area
  – Some aircraft have BADA TSFC coefficients that don’t extrapolate well to the speeds used in the terminal area
  – These extrapolations issues appear uncorrelated to airframe or engine type
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BADA TSFC variation

BADA 737-500/-300/-400 TSFC curves
A proposed improvement

• Boeing and the FAA recently exchanged software tools – the Boeing Climb-Out Program (BCOP) and the FAA’s Integrated Noise Model (INM).
  – FAA provided Boeing an executable version of the INM for inclusion in the next version of BCOP and in next generation performance tools
  – Boeing provided the FAA a copy of BCOP

• BCOP contains terminal area fuel burn data, for both departure and arrival
TSFC as a function of Mach and Thrust

- Example at Sea Level
  - Independent axis is Mach
  - Ordinate is Thrust
  - Curves are TSFC
The proposed fuel burn models

Departure:

\[
\frac{TSFC}{\sqrt{\theta}} = k_1 + k_2 M + k_3 h_{\text{MSL}} + k_4 \frac{F}{\delta}
\]

Arrival:

\[
\frac{TSFC}{\sqrt{\theta}} = \alpha + \beta_1 M + \beta_2 e^{-\beta_3 \left( \frac{F}{\delta} / F_0 \right)}
\]
The AEDT fuel burn model process

• Run BCOP with the closest match possible between the FDR aircraft and the AEDT aircraft
  – These BCOP runs are ICAO B procedures at S.L., 4K, and 6K up to 10,000 AFE.
  – The outputs are post-processed to collect the important performance parameters into a single text file
The AEDT fuel burn model process (cont.)

• Run statistical program on post-processed BCOP data to determine the coefficients for the model
• Add these coefficients to the AEDT database
• Quality test by comparing the results of the model to the FDR data.
  – Aircraft weight
  – Airport elevation and temperature
  – AEDT departure procedure based on weight
The AEDT fuel burn model process (cont.)

- Departures are modeled as AEDT (SAE-1845) procedure steps using the thrust calculated internally – we use the AEDT thrust applied to the modeled TSFC to calculate fuel flow

- Arrivals are modeled as fixed point profiles using the thrust from the FDR – we use the FDR thrust applied to the modeled TSFC to calculate fuel flow
The AEDT fuel burn model process (cont.)

Using this process, we have generated fuel burn data for a number of Boeing aircraft:

<table>
<thead>
<tr>
<th>Aircraft 1</th>
<th>Aircraft 2</th>
<th>Aircraft 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>717-200</td>
<td>747-400</td>
<td>MD-11</td>
</tr>
<tr>
<td>737-300</td>
<td>757-200</td>
<td>MD-81</td>
</tr>
<tr>
<td>737-400</td>
<td>757-300</td>
<td>MD-82</td>
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<td>737-500</td>
<td>767-300</td>
<td>MD-83</td>
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<td>777-200</td>
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<tr>
<td>737-800</td>
<td>777-300</td>
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</tr>
</tbody>
</table>
AEDT TSFC variation

AEDT 737-500/-300/-400 TSFC curves
Modeling results – 757 departure

757-200 Fuel consumption to 3000’ AFE

- Fuel consumption - FDR (kg)
- Fuel consumption - modeled (kg)

BADA
AEDT
- Perfect fit
Modeling results – 747-400 departure

747-400 Fuel consumption to 10,000’ AFE

Fuel consumption - Modeled (kg)

Fuel consumption - FDR (kg)

AEDT

perfect fit
Modeling results – 757 arrival

757-200 arrival fuel consumption from 3000' AFE

- BADA
- AEDT
- perfect fit
Summary

• We have a process in place to generate airplane performance data which in turn can be processed to create TSFC methods in the FAA’s environmental models.

• These airplane performance tools-derived methods match the FDR data better than the existing BADA-based methods in the terminal area.

• We have added the new fuel burn data for the current generation of Boeing airplanes into the AEDT database.
Next steps

• Continue analyses of recently received U.S. carrier FDR data (expected completion: Dec. 08)
  – Goal: Determine impact of using standard arrival procedures in lieu of actual procedures

• Re-run existing CDA data at Miami after the new method is integrated with the AEDT radar track processing tools (expected completion: Jan. 09)
  – Goal: Determine impact of improved operations on fuel burn

• Acquire other manufacturers’ aircraft performance tools (long term)
  – Goal: Improve terminal area fuel burn for all major in-production aircraft
Comments and Questions…

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Back-ups
Intermediate fuel burn models

Equation 1 (Original BADA): \[ TSFC = C_{f1} \left(1 + \frac{V_{TAS}}{C_{f2}}\right) \]

Equation 2 (Modified BADA w/BCOP): \[ TSFC = C_{f1} \left(1 + \frac{V_{TAS}}{C_{f2}}\right) \]

Equation 3 (Volpe TSFC): \[ TSFC = k_1 + k_2 V_{TAS} + k_3 h_{MSL} + k_4 \frac{F}{\delta} \]

Equation 4 (Yoder TSFC): \[ TSFC \sqrt{\theta} = \left[ \alpha + \beta_1 M + \beta_2 e^{-\beta_3 \left(\frac{F}{\delta}\right)^{0.3}} \right] \]

Equation 5 (Modified Yoder TSFC): \[ TSFC \sqrt{\theta} = \left[ \alpha + \beta_1 M + \beta_2 e^{-\beta_3 \left(\frac{F}{\delta}\right)^{0.5}} \right] \]
## FDR v. BADA Fuel burn to 3000’ AFE (average)

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Measured (FDR)</th>
<th>Modeled (BADA)</th>
<th>Difference</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>757-200</td>
<td>328 kg</td>
<td>262 kg</td>
<td>-66 kg</td>
<td>-20%</td>
</tr>
<tr>
<td>767-300ER</td>
<td>464</td>
<td>552</td>
<td>+88</td>
<td>+19%</td>
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<tr>
<td>777-300ER</td>
<td>736</td>
<td>1131</td>
<td>+395</td>
<td>+54%</td>
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<tr>
<td>A319</td>
<td>181</td>
<td>189</td>
<td>+8</td>
<td>+5%</td>
</tr>
<tr>
<td>A320</td>
<td>198</td>
<td>278</td>
<td>+80</td>
<td>+40%</td>
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<tr>
<td>A321</td>
<td>241</td>
<td>268</td>
<td>+27</td>
<td>+11%</td>
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<tr>
<td>A330-202</td>
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<td>769</td>
<td>+130</td>
<td>+20%</td>
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<tr>
<td>A330-223</td>
<td>680</td>
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<td>+196</td>
<td>+29%</td>
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<tr>
<td>A330-243</td>
<td>539</td>
<td>741</td>
<td>+202</td>
<td>+37%</td>
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<tr>
<td>A340-313</td>
<td>956</td>
<td>1104</td>
<td>+148</td>
<td>+16%</td>
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<tr>
<td>A340-541</td>
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<td>1258</td>
<td>+245</td>
<td>+24%</td>
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<tr>
<td>BAe-146</td>
<td>170</td>
<td>388</td>
<td>+218</td>
<td>+128%</td>
</tr>
</tbody>
</table>
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TSFC and By-pass ratio, departure powers, CFM56 family

By-pass ratio

TSFC (lbm/hr/lbf)

-5A, 4CM035
-5B, 3CM021
-5C, 1CM010
-5C, 2CM015
-7B, 4CM041
-7B, 3CM034
The proposed fuel burn models (details)

- Preliminaries: Sensitivity runs to determine parameters of interest
  - Multiple runs with different parameters held constant
  - Primary focus was 757-200/RB211-535 since we had a three-way match with FDR/AEDT/BCOP
  - Determine which of seven proposed fuel burn methods would most closely mimic BCOP
The proposed fuel burn models (details)

757-200RR Original BADA; 3000' AFE

BCOP (kg) vs Modeled (kg) graph
The proposed fuel burn models (details)

757-200RR Volpe; 3000' AFE

Modeled (kg) vs. BCOP (kg) chart for different altitudes and fuel loads.

- 0', 184K
- 0', 215K
- 0', 255K
- 2000', 184K
- 2000', 215K
- 2000', 255K
- 6000', 184K
- 6000', 215K
- 6000', 255K
- Perfect Fit
Flight 119033, example of ATC hold

Time from CFDR start (sec)

Altitude (ft MSL)

Thrust (lb)

Altitude (ft)

Thrust (lb)
757-200 Arrival TSFC

Net Corrected Thrust (lb) vs Mach

- Mach values: 0.7, 0.8, 0.9, 1.0, 1.1, 1.2
- Net Corrected Thrust values range from 0 to 20,000 lb