Analytical Approach for Quantifying Noise from Advanced Operational Procedures

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Motivation

RNAV SID Deployment at Boston

2010

2015
Motivation

• Advanced operational procedures may have the potential to reduce aircraft noise and associated population exposure
  – RNAV/RNP, Continuous Descent Approaches, Delayed Deceleration Approaches, Climb Thrust Scheduling, etc.

• Traditional aircraft noise analysis assumes that engine noise dominates aerodynamic noise
  – Assumption may have been valid for earlier generation jet engines

• Current analytical approach does not fully capture noise impacts from aircraft configuration or other operational techniques which may have noise benefits
• Noise modeling capabilities have been developed with support from FAA Office of Environment and Energy (AEE)

• Limitations of industry-standard Noise-Power-Distance (NPD) based computations
  – Noise is calculated using **engine thrust** and **observer distance**
    • Reasonable simplification for older, louder aircraft types
  – Contribution from speed changes and aerodynamic sources not fully accounted for

• **New modeling capabilities** capture noise changes due to speed, flaps, and landing gear configuration
Noise Modeling Background
Two Approaches to Noise Modeling

Aviation Environmental Design Tool (AEDT)

• Current industry standard model to evaluate aircraft noise impacts
• Noise-Power-Distance (NPD) based computations
  – Interpolation from flight test data
• Assumes engine noise dominates aerodynamic noise on approach
  – Effects of configuration and speed not captured
  – Simple directivity assumptions

Aircraft NOise Prediction Program (ANOPP v1)

• NASA-developed software incorporating physics-based methods
• Computes far-field engine and airframe noise at an observer grid given various flight profile and configuration metrics
  – Semi-empirical calculations require detailed engine/aircraft performance inputs
  • e.g., Engine mass flow, areas, and temperatures, airframe geometry, etc.
Physics-Based Noise Analysis Framework

Performance Parameters:
- Mission
- Aircraft
- Engine

Aircraft Type

TASOPT

BADA4

Performance Model Outputs:
Performance & geometry

Procedure Definition:
- Lateral Path
- Speeds
- Configuration

Flight Profile Generator

Flight Profile:
Thrust, velocity, position, configuration

Atmospheric Model Observer Grid

AEDT/ANOPP

Output to Population Impact Modeling

Single-Event Noise Grids
Current Validation Results

- Within -2.24/+3.71dB agreement between ANOPP results & FAA data for all aircraft & observers
  - Within the range of error typically seen in aircraft noise measurement campaigns
- Magnitude of error across all aircraft lowest for Approach, followed by Flyover then Lateral
# Noise Metrics Used for Evaluation

<table>
<thead>
<tr>
<th>Single-Event Metrics</th>
<th>Integrated Metrics</th>
<th>Population Exposure</th>
</tr>
</thead>
</table>
| • $L_{A,\text{MAX}}$  
• Sound Exposure Level (SEL) | • $N_{\text{ABOVE}}$  
• Day-Night Average Level (DNL) | • $N_{\text{ABOVE}}$  
• $L_{A,\text{MAX}}$  
• DNL |

### Sound Pressure Level (SPL, dB) at One Microphone Location

![Sound Pressure Level Graph](image)

*Graphic Adapted from Environmental Science Associates*
Analysis of Boston Procedures
Noise Complaints at BOS: One Dot per Address

Each dot represents an address that registered at least one complaint during period

Complaint Data: August 2015 – July 2016
Track Data: ASDE-X from 12 days of operation, 2015-2016
Noise Complaints at BOS:
Dots Weighted by Complaint Frequency

Each dot represents an address that registered at least one complaint during period
Marker size corresponds to number of complaints registered by address

Departures

Arrivals

Complaint Data: August 2015–July 2016
Track Data: ASDE-X from 12 days of operation, 2015-2016
Procedural Concepts for Reducing Noise

**Departure Procedure Modifications**
- Modified climbs
  - Reduced speed
  - Delayed thrust cutback
  - Thrust scheduling
- Noise-preferential lateral paths
  - Early turns after takeoff
  - SID waypoint relocation
  - Overflight of high ambient noise areas
- Dispersion of departure routes
  - Open-SID
  - Vectors/headings

**Arrival Procedure Modifications**
- Steep approaches
  - 1-segment steep approaches
  - 2-segment steep approaches
- Noise-preferential lateral paths
  - Overflight of areas with high ambient noise or low population
  - Late turn to final using RNAV or RNP
- Speed/configuration management
Departure Concept: Modified Climb Procedures
Standard Departure Definition

- Standard departure procedures vary by airline and location
- Typical profile includes thrust reduction at 1,000’ AGL followed by an **acceleration to climb speed** and **flap retraction**
Potential Modifications to Climb Profiles

Climb Speed Reduction

- Initial climb speed
  • $V_2 + 15$

- Thrust reduction height
  • Select climb thrust (as needed)

- VR
  • Rotate

- Acceleration height
  • Retract flaps on schedule

- Positive rate of climb
  • Retract gear

Maximum Performance Climb

- Initial climb speed
  • $V_2 + 15$
  • Use maximum thrust

- VR
  • Rotate

- Thrust set

- V1

- Positive rate of climb
  • Retract gear

- Initial climb speed
  • $V_2 + 15$
  • Use derated takeoff thrust
**737-800: Maximum Thrust, Reduced-Speed Climb**

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>B737-800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metric</td>
<td>$L_{A,\text{MAX}}$</td>
</tr>
<tr>
<td>Noise Model</td>
<td>ANOPP</td>
</tr>
<tr>
<td>Notes</td>
<td>Runway 33L: Maintain Maximum Climb Thrust &amp; $V_2$ to 10,000'</td>
</tr>
</tbody>
</table>

### Population Exposure

<table>
<thead>
<tr>
<th>Distance from takeoff (nmi)</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
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<tbody>
<tr>
<td>Radar matched</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Climb</td>
<td></td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Population Exposition</th>
<th>60dB</th>
<th>65dB</th>
<th>70dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Departure</td>
<td>237,952</td>
<td>105,869</td>
<td>38,599</td>
</tr>
<tr>
<td>Maximum Thrust</td>
<td>288,653</td>
<td>101,127</td>
<td>44,001</td>
</tr>
<tr>
<td>Difference</td>
<td>-50,701</td>
<td>4,743</td>
<td>-5,402</td>
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</table>

**Preliminary**
Increasing Speed Increases Airframe Noise

- **DEPARTURES**
  - Boeing 737-800

<table>
<thead>
<tr>
<th>Speed</th>
<th>Contours</th>
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<tbody>
<tr>
<td>160 KTAS</td>
<td><img src="image1" alt="160 KTAS Contours" /></td>
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<tr>
<td>190 KTAS</td>
<td><img src="image2" alt="190 KTAS Contours" /></td>
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<td>220 KTAS</td>
<td><img src="image3" alt="220 KTAS Contours" /></td>
</tr>
<tr>
<td>250 KTAS</td>
<td><img src="image4" alt="250 KTAS Contours" /></td>
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</table>
737-800: Delayed Acceleration Climb – 180 knots

<table>
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<tr>
<th>Aircraft</th>
<th>B737-800</th>
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<tr>
<td>Metric</td>
<td>( L_{A,\text{MAX}} )</td>
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<td>Noise Model</td>
<td>ANOPP</td>
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<td>Notes</td>
<td>Runway 33L: Maintain Standard Climb Thrust &amp; 180 KIAS to 10,000'</td>
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### Population Exposure

<table>
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<th>65dB</th>
<th>70dB</th>
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</thead>
<tbody>
<tr>
<td>Standard Departure</td>
<td>237,952</td>
<td>105,869</td>
<td>38,599</td>
</tr>
<tr>
<td>Delayed Acceleration</td>
<td>172,598</td>
<td>59,392</td>
<td>24,025</td>
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<tr>
<td>Difference</td>
<td>65,354</td>
<td>46,477</td>
<td>14,574</td>
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</table>
737-800: Delayed Acceleration Climb – 200 knots

**Aircraft**
B737-800

**Metric**
$L_{A,\text{MAX}}$

**Noise Model**
ANOPP

**Notes**
Runway 33L: Maintain Standard Climb Thrust & 200 KIAS to 10,000'

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**Population Exposure**

<table>
<thead>
<tr>
<th></th>
<th>60dB</th>
<th>65dB</th>
<th>70dB</th>
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</thead>
<tbody>
<tr>
<td>Standard Departure</td>
<td>237,952</td>
<td>105,869</td>
<td>38,599</td>
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<tr>
<td>Delayed Acceleration</td>
<td>169,124</td>
<td>66,585</td>
<td>26,811</td>
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<td>Difference</td>
<td>68,828</td>
<td>39,285</td>
<td>11,788</td>
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</table>

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*Preliminary*
737-800: Delayed Acceleration Climb – 220 knots

**Aircraft**
- B737-800

**Metric**
- $L_{A,\text{MAX}}$

**Noise Model**
- ANOPP

**Notes**
- Runway 33L: Maintain Standard Climb Thrust & 220 KIAS to 10,000'

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### Population Exposure

<table>
<thead>
<tr>
<th>60dB</th>
<th>65dB</th>
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</tr>
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<tbody>
<tr>
<td>Standard Departure</td>
<td>237,952</td>
<td>105,869</td>
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<tr>
<td>Delayed Acceleration</td>
<td>190,128</td>
<td>75,469</td>
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<td>Difference</td>
<td>47,824</td>
<td>30,401</td>
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</table>
737-800: Delayed Acceleration Climb – 240 knots

**Aircraft**
B737-800

**Metric**
$L_{A,\text{MAX}}$

**Noise Model**
ANOPP

**Notes**
Runway 33L: Maintain Standard Climb Thrust & 240 KIAS to 10,000'

---

### Population Exposure

<table>
<thead>
<tr>
<th>Level (dB)</th>
<th>Standard Departure</th>
<th>Delayed Acceleration</th>
<th>Difference</th>
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<tr>
<td>60</td>
<td>237,952</td>
<td>220,781</td>
<td>17,171</td>
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<td>65</td>
<td>105,869</td>
<td>91,525</td>
<td>14,345</td>
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<tr>
<td>70</td>
<td>38,599</td>
<td>31,007</td>
<td>7,592</td>
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</table>
777-300: Delayed Acceleration Climb – 220 knots

<table>
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<th>B777-300</th>
</tr>
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<tbody>
<tr>
<td>Metric</td>
<td>$L_{A,\text{MAX}}$</td>
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<td>Noise Model</td>
<td>ANOPP</td>
</tr>
<tr>
<td>Notes</td>
<td>Runway 33L: Maintain Standard Climb Thrust &amp; 220 KIAS to 10,000'</td>
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### Population Exposure

<table>
<thead>
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<th></th>
<th>60dB</th>
<th>65dB</th>
<th>70dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Departure</td>
<td>455,746</td>
<td>275,879</td>
<td>118,685</td>
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<tr>
<td>Delayed Acceleration</td>
<td>437,415</td>
<td>262,310</td>
<td>105,182</td>
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<tr>
<td>Difference</td>
<td>18,331</td>
<td>13,569</td>
<td>13,502</td>
</tr>
</tbody>
</table>

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**Altitude (feet)**

- Baseline
- Hold at 220 kts

**Indicated airspeed (kts)**

- Gear up
- Clean
- Flaps 1

**Population Exposure Map**

- B773 Baseline Flight Track
- B773 Baseline Flight Track 5nm Increment Markers
- B773 Baseline Noise Contours
- B773 220 KIAS to 10000 ft Flight Track
- B773 220 KIAS to 10000 ft Flight Track 5nm Increment Markers
- B773 220 KIAS to 10000 ft Noise Contours

---

Preliminary
E-170: Delayed Acceleration Climb – 220 knots

### Aircraft
- E-170

### Metric
- \( L_{A,\text{MAX}} \)

### Noise Model
- ANOPP

### Notes
- Runway 33L: Maintain Standard Climb Thrust & 220 KIAS to 10,000'

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### Population Exposure

<table>
<thead>
<tr>
<th></th>
<th>60dB</th>
<th>65dB</th>
<th>70dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Departure</td>
<td>147,222</td>
<td>58,441</td>
<td>10,437</td>
</tr>
<tr>
<td>Delayed Acceleration</td>
<td>97,728</td>
<td>33,306</td>
<td>9,298</td>
</tr>
<tr>
<td>Difference</td>
<td>49,493</td>
<td>25,135</td>
<td>1,139</td>
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</tbody>
</table>

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**Preliminary**
• Reduced speed climb profiles impact total trip fuel burn and flight time
• Magnitude varies by speed and aircraft type (generally small)

<table>
<thead>
<tr>
<th>Climb Speed</th>
<th>B738</th>
<th>E170</th>
<th>B773</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel Burn Increase (kg)</td>
<td>Time Increase (s)</td>
<td>Fuel Burn Increase (kg)</td>
</tr>
<tr>
<td>180 kts</td>
<td>141</td>
<td>121</td>
<td>55</td>
</tr>
<tr>
<td>200 kts</td>
<td>54</td>
<td>65</td>
<td>12</td>
</tr>
<tr>
<td>220 kts</td>
<td>21</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>240 kts</td>
<td>4</td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>
Departure Concept: Lateral Track Modification
Example: 2010 BOS Runway 22R Departures

Flight Track Density Plot
January 1, 2010 to December 31, 2010
Runway 22R Jet Departures
(46,446 Flight Tracks)

- Airport Runway
- Roads
- River or Stream
- Municipal Boundary
- Water

Flight Track Density
Low  Medium  High
Example: 2015 BOS Runway 22R Departures

Flight Track Density Plot
January 1, 2015 to December 31, 2015
Runway 22R Jet Departures
(49,991 Flight Tracks)

- Airport Runway
- Roads
- River or Stream
- Municipal Boundary
- Water

Flight Track Density
Low
Medium
High
Detailed BOS Rwy 22R, 22L, and 15R Departure Tracks

* Lowest Observed A320 Departure at FOXXX
† Median A320 Departure at FOXXX

Track Data: ASDE-X from 12 days of operation, 2015-2016
1. Reduced separation with Rwy 27 arrival flow

2. Early turn after takeoff to reduce noise at Castle Island and surrounding areas
• **22R Early turn:**
  – Initial turn at 500’ AGL
  – Direct-to initial waypoint located on target departure corridor

• **Runway 15R Departure Fix:**
  – Current procedure uses same departure fix as 22R departures (FOXXX)
  – Potential benefit from changing departures to use fix offset from Hull

Example plot shows turn location for B737-800 at a medium-range typical takeoff weight
Noise Exposure: 22R/22L Early Turn

- 22R/22L Early Turn and Waypoint Relocation
- Aircraft: B737-800
- Metric: LAMAX
- Noise Model: AEDT

### Population Exposure

<table>
<thead>
<tr>
<th></th>
<th>60dB</th>
<th>65dB</th>
<th>70dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>36,807</td>
<td>11,698</td>
<td>2,649</td>
</tr>
<tr>
<td>Early Turn</td>
<td>26,821</td>
<td>6,517</td>
<td>510</td>
</tr>
<tr>
<td>Difference</td>
<td>9,986</td>
<td>5,181</td>
<td>2,139</td>
</tr>
</tbody>
</table>
15 Waypoint Relocation

- 15R Departure Waypoint Relocation
- Aircraft: B737-800
- Metric: LAMAX
- Noise Model: AEDT

### Population Exposure

<table>
<thead>
<tr>
<th></th>
<th>60dB</th>
<th>65dB</th>
<th>70dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>14,367</td>
<td>1,765</td>
<td>84</td>
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<tr>
<td>Early Turn</td>
<td>13,140</td>
<td>1,781</td>
<td>147</td>
</tr>
<tr>
<td>Difference</td>
<td>1,227</td>
<td>-16</td>
<td>-63</td>
</tr>
</tbody>
</table>

2.5 nmi
Departure Concept: Departure Route Dispersion
Example: 2010 BOS Runway 33L Departures
Example: 2015 BOS Runway 33L Departures
Open SIDs are RNAV departure procedures that allow for embedded ATC radar vector segments.

- Authorized by FAA in 2015
- Dispersion may be introduced by direct ATC instruction or based on aircraft altitude
Arrival Concept:
Steep Approach Profiles
• According to TERPS, the following are the standard maximum approach angles authorized on a final approach segment:

<table>
<thead>
<tr>
<th>Precision Approach:</th>
<th>Non-Precision Approach:</th>
</tr>
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<tbody>
<tr>
<td>Aircraft Approach Category</td>
<td>Maximum Angle</td>
</tr>
<tr>
<td>C</td>
<td>3.60°</td>
</tr>
<tr>
<td>D</td>
<td>3.10°</td>
</tr>
</tbody>
</table>

• Feedback from operators: Some aircraft in planned descent autoflight mode cannot exceed 3.77° glideslope angle
Steep Approach Concept

- BADA-4 model indicates that steeper glideslopes may be feasible for some aircraft types
- Regulatory limit: Approach Category C aircraft on non-precision approaches cannot exceed 3.77° glideslope angle

Significant Concerns from Airline Technical Pilots and ATC for Operational Feasibility
Significant Concerns from Airline Technical Pilots and ATC for Operational Feasibility
Safety Concerns - High-Energy Approaches

Fatalities by CICTT Aviation Occurrence Categories

Runway Excursions

Note: Principal categories as assigned by CAST.

For a complete description of CAST/CAO Common Taxonomy Team (CICTT) Aviation Occurrence Categories, go to www.intlaviationstandards.org.

Figure source: The Boeing Company http://www.boeing.com/resources/boeingdotcom/company/about_bca/pdf/statsum.pdf
Arrival Concept: Noise-Preferential Lateral Paths
Example: 2010 BOS Runway 4R Arrivals
Example: 2015 BOS Runway 4R Arrivals
RNAV (GPS) Rwy 33L approach under development based on current JetBlue RNAV special procedure

- Minor modifications required to meet public procedure design specifications
Impact of Proposed RNAV (GPS) to 33L
RNAV (GPS) Approach: 4R

Transposing Lighthouse RNAV from 33L directly to 4R:

Removing intermediate waypoints over land:
RNAV (GPS) Approach: 4R

• Modified RNAV to 4R:
Canarsie-Like RNAV (RNP) Special

Figure: Honeywell
Canarsie-Like RNAV (RNP) Special
Notional Noise-Driven RNP: BOS Rwy 4R

- 0.95 nmi final
- 2.1 nmi radius RF
- 10° bank at 160 KTAS
- 40% Standard Rate
Noise Exposure: 4R Noise-Driven RNP Approach

- 4R Noise-Driven RNP Approach
- Aircraft: B737-800
- Metric: LAMAX
- Noise Model: AEDT

Population Exposure

<table>
<thead>
<tr>
<th></th>
<th>60dB</th>
<th>65dB</th>
<th>70dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>46,039</td>
<td>21,207</td>
<td>5,159</td>
</tr>
<tr>
<td>Noise-Driven RNP</td>
<td>7,137</td>
<td>3,155</td>
<td>946</td>
</tr>
<tr>
<td>Difference</td>
<td>38,902</td>
<td>18,052</td>
<td>4,213</td>
</tr>
</tbody>
</table>
Example of Noise-Preferential Lateral Path: Overflight of High Ambient Noise Area

- Concept: move arrival flows over areas with compatible land use
  - Highways
  - Industrial areas
- Currently developing prototype arrival profile definitions
- When overflying low-population areas is not possible, background noise levels may drive procedure placement

Notional 4R Expressway Approach Path

- Concept: move arrival flows over regions of higher ambient noise
  - Highways
  - Industrial areas
- Currently developing prototype arrival profile definitions

### Noise Exposure: 4R Expressway Approach

- **4R Expressway Approach**
- **Aircraft:** B737-800
- **Metric:** LAMAX
- **Noise Model:** AEDT

#### Population Exposure

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<td>Expressway</td>
<td>66,417</td>
<td>32,879</td>
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<td>Difference</td>
<td>-20,377</td>
<td>-11,672</td>
<td>-786</td>
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</tbody>
</table>
A noise analysis framework has been developed that allows for evaluation of advanced operational procedures:
- Lateral and vertical track modifications
- Speed effects
- Ambient noise masking

A set of candidate advanced procedures have been evaluated for generic conditions as well as at BOS.

Next steps:
- Continue noise analysis of candidate procedures at other airports in the NAS
- Evaluate potential barriers to implementation for high-benefit procedures
- Incorporate demographic data to evaluate environmental justice concerns arising from modified procedures
Questions?