Accurately estimating aircraft emissions using flight data records

Centre for Transport Studies
Imperial College London

George Koudis
Dr. Marc Stettler

30th June 2016
Presentation outline

• Research context
• Research aim
• Methodology
• Results of analysis
  • Comparison between simple and FDR emissions
  • Reduced thrust takeoff
  • Single-engine taxi
• Further work
Research context: SNAQ Project

- Research in collaboration with Sensor Network for Air Quality (SNAQ) at London Heathrow project
- High-density, low-cost network of air quality sensor nodes
- Aim to evaluate sensor network against high-resolution emission inventory at London Heathrow
Aviation growth is forecast and expansion is required to meet demand.

Aircraft at airports emit pollutants which cause harm to human health.

Mass of pollutants is expected to increase alongside expansion.

Therefore, pollutant emission mitigation strategies are adopted.

Benefits are not well understood due to the regular use of simplified modelling approaches.
Research context: Aircraft emissions modelling

Individual flight data records (FDRs)
Research context: Calculate emissions

- The relationship between thrust setting and fuel flow rate is given by:

\[ \frac{F}{F_{00}} = A \cdot \dot{m}_f^2 + B \cdot \dot{m}_f + C \]

- Where the components are taken from the ICAO EEDB
- Consequently, emissions are calculated, as given by:

\[ E_i = \dot{m}_f \cdot EI \cdot t \]

Emissions  Fuel flow rate  Emission index  Time-in-mode
Research aim

• Accurately estimate aircraft emissions using flight data records

• Objectives:

1. Compare simplified approach emissions estimate to FDR estimate

2. Quantify the impact of reduced thrust takeoff on pollutant emissions and investigate optimisation based on aircraft takeoff weight and thrust setting

3. Quantify the impact of single-engine taxiing (SET) on pollutant emissions and investigate optimisation based on time before initiation of SET and thrust setting
Data

- Activity summary (BOSS)
- 8331 (high-resolution) landing and takeoff flight data records (FDRs)
- Aircraft emissions modelling
- High-resolution spatial and temporal emission rates
- BUCHair
- 4D trajectory (10m/1s) Fuel flow rate (kg/s)
- ICAO EEDB
- BADA
- Enable reliable operations analysis
Aircraft emissions modelling

- FDR data
- Cleaned FDR data
- 4D trajectory (x, y, z, t)
- QA/QC

Boeing Fuel Flow Method II (BFFM2)
- Fuel flow (kg/s)
- Thrust setting (% of maximum)
- Emission rate (g/s)
- Emission time series/spatial distribution

Analysis

- Double quadratic interpolation
- Linear interpolation of log-log plot

ICAO EEDB
Objective 1.

Compare simplified approach emissions estimate to FDR estimate
Compare FDR data to simple model assumptions

- For any single aircraft phase, using simplified modelling consistently overestimates fuel consumption from FDR data.
- Considerable variability exists when comparing the estimate to the 5th and 95th percentile of fuel consumption from FDR data.
Compare FDR data to simple model assumptions

- For all activities for each aircraft type, using simplified modelling considerably overestimates fuel consumption and NO\textsubscript{X} emissions, compared to estimates from FDR data.
Objective 2.

Quantify the impact of reduced thrust takeoff on pollutant emissions and investigate optimisation based on aircraft takeoff weight and thrust setting
Reduced thrust takeoff: Operation definition

• Reduced thrust takeoff is used at LHR with benefits for:
  • Engine wear
  • Fuel consumption
  • Pollutant emissions
• The aircraft operators compute and select the minimum thrust required to achieve a safe takeoff based on aircraft TOW (and other limiting conditions)
• Trade-off between thrust (acceleration) and TIM
• The takeoff roll is a high-emitting mode, therefore reduced thrust takeoff has the potential to significantly reduce airport emissions
Reduced thrust setting: Comparison to ICAO thrust

- Fuel consumption of activities in the current sample are compared to the estimated masses if activities had occurred at 100% and 85% thrust.
Reduced thrust setting: Comparison to ICAO thrust

- NO\textsubscript{X} emissions of activities in the current sample are compared to the estimated masses if activities had occurred at 100% and 85% thrust.
Reduced thrust takeoff: TOW estimation

Fundamental equation:

\[ TOW = \frac{\left( F_{00} \cdot \frac{F}{F_{00}} \cdot \alpha_{age} \cdot \alpha_{bleed} \right) - (F_D + F_{RR})}{a} \]

\[ F_D = \frac{C_D \cdot \rho \cdot V^2 \cdot S}{2} \]

Rolling resistance

\[ F_{RR} = C_{RR}(TOW \cdot g - F_L) \]

Lift

\[ F_L \]

Thrust

\[ F = \left( F_{00} \cdot \frac{F}{F_{00}} \cdot \alpha_{age} \cdot \alpha_{bleed} \right) \]

Aircraft takeoff weight

TOW

Koudis et al. (in review), Transportation Research Part D
Reduced thrust takeoff: Thrust setting variability

- Thrust setting increases as TOW increases
- A range of thrust settings are used for any given relative TOW

Koudis et al. (in review), Transportation Research Part D
Reduced thrust setting: Impact on NO\textsubscript{X} emissions

![Graph showing the impact of reduced thrust setting on NO\textsubscript{X} emissions. The x-axis represents Relative Takeoff Weight, the y-axis represents Average thrust setting (% of max.), and the color gradient represents Total NO\textsubscript{X} emissions (g). There are lines of constant TOW (see next slide).]
Reduced thrust setting: Impact on NO$_X$ emissions

- Varying the takeoff roll thrust setting for constant TOW causes variation in fuel consumption, NO$_X$ and BC

Koudis et al. (in review), Transportation Research Part D
Reduced thrust setting: ‘Optimum’

- Quadratic equations are fitted to the ‘optimal’ thrust setting versus takeoff weight relationship, for the use of aircraft operators.

Koudis et al. (in review), Transportation Research Part D
Reduced thrust takeoff: Potential additional reductions

- Further reductions in fuel consumption, $\text{NO}_x$ (see below) and BC emissions may be possible.
Reduced thrust takeoff: Caveats

- The ability to conduct reduced thrust takeoff is limited by several factors including:
  - Runway contamination
  - Heavy rain/snow
  - Runway obstacles
  - Wind speed/direction
  - Atmospheric pressure
  - Temperature
  - Aircraft ‘acceptable defects’

- These factors may explain the variability identified in the reduced thrust takeoff operations
Objective 3.

Quantify the impact of single-engine taxiing (SET) on pollutant emissions and investigate optimisation based on time before initiation of SET and thrust setting.
Single-engine taxi: Operation definition

- In the current dataset, SET operations are used at LHR during taxi-in operations
- This consists of deactivating one engine (two for four-engine aircraft) as soon as safely possible following landing
- The time before one engine is deactivated during SET operations is variable based on pilot preference and satisfactory completion of post-landing checks

Koudis et al. (in review), Transportation Research Part D
Single-engine taxi: Operation definition

- Empirical evidence of SET operations during Heathrow taxi-in
Single-engine taxi: Comparison to estimates

![Graph showing fuel consumption for different aircraft-engine combinations]
Single-engine taxi: Model development

Thrust setting

\[ f_c = f_f \cdot n \cdot (t_{TET} + \frac{1}{2} (t_T - t_{TET})) \]

Taxi duration

Time before SET initiation

Koudis et al. (in review), Transportation Research Part D
Single-engine taxi: Estimation of pollutant emissions

- In total, 3 scenarios were analysed:
  - Scenario 1: SET – time before SET initiation = 25\(^{th}\) percentile
  - Scenario 2: TET – thrust settings used = 25\(^{th}\) percentile
  - Scenario 3: Combination of 1 and 2

![Graph showing fuel consumption for different aircraft-engine combinations]

<table>
<thead>
<tr>
<th>Aircraft-engine combination</th>
<th>Observed Fuel (kg)</th>
<th>Scenario 1 (kg)</th>
<th>Scenario 2 (kg)</th>
<th>Scenario 3 (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>319 V2522-A5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>320 V2527-A5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>321 V2533-A5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>744 RB211-524G</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>744 RB211-524G-T</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>77A GE90-85B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In total, 3 scenarios were analysed:

- Scenario 1: SET – time before SET initiation = 25\textsuperscript{th} percentile
- Scenario 2: TET – thrust settings used = 25\textsuperscript{th} percentile
- Scenario 3: Combination of 1 and 2

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel change</td>
<td>-3 to -12%</td>
<td>+18 to +58%</td>
<td>-8 to -15%</td>
</tr>
<tr>
<td>NO\textsubscript{X} change</td>
<td>-6 to -13%</td>
<td>+16 to +45%</td>
<td>-11 to -17%</td>
</tr>
<tr>
<td>CO change</td>
<td>-8 to -18%</td>
<td>+20 to +55%</td>
<td>+6 to +14%</td>
</tr>
</tbody>
</table>
Single-engine taxi: Caveats

- The ability to increase usage of SET, and reduce time before SET is initiation is subject to several limiting factors. Including:
  - Aircraft engine (jet) blast considerations
  - Busy traffic conditions
  - Compliance with safety factors
  - Crew workload considerations
  - Implications on aircraft systems
  - Breakaway thrust levels
  - Weather conditions
  - Taxiway contamination
  - Airport restrictions

- The utilisation of SET requires consideration of all the above aspects before attempting operational optimisation
Further work: Measured/modelled EI comparisons

- Compare modelled and measured aircraft emission indices (EIs)
- Measured NO\textsubscript{\text{X}} and CO concentrations can be divided by CO\textsubscript{2} concentration (multiplied by EI(CO\textsubscript{2})) to give EI(NO\textsubscript{X}, CO)
- Values are compared to modelled EI(NO\textsubscript{X}) and EI(CO)
- This will present a valuable contribution in the cross-validation of the ICAO EEDB and SNAQ network
Further work: Measured/modelled EI comparisons

- Isolation of aircraft takeoff emission source using upstream and downstream sensor nodes
Further work: Measured/modelled EI comparisons

- Differences in upstream and downstream measured NO\textsubscript{X}, CO and CO\textsubscript{2} concentrations
- Red = upstream
- Black = downstream
Further work: Measured/modelled EI comparisons

- Plotting measured and modelled NO\textsubscript{X} and EI(CO) against each other shows moderately strong correlation (both r and R\textsuperscript{2})
- However, for both pollutants, extreme low and high measured EIs are not captured in the modelled data
Summary

- Simple approach overestimates fuel consumption by between 21 – 41% and NO\textsubscript{X} emissions by between 35 – 68%, relative to FDR estimates.
- Reduced thrust takeoff implemented at LHR reduces fuel consumption and emissions (e.g. NO\textsubscript{X} by up to 50%).
- Fuel consumption and NO\textsubscript{X} emissions may be further reduced if thrust settings are optimised based on aircraft TOW (e.g. NO\textsubscript{X} by up to an additional 3 - 9%).
- Single-engine taxiing implemented at LHR reduces fuel consumption, NO\textsubscript{X} and CO emissions (e.g. NO\textsubscript{X} by up to 50%).
- Reduction of time before SET initiation further reduces fuel consumption and NO\textsubscript{X} emissions (e.g. NO\textsubscript{X} by between 6 – 13%).
Any questions?