Aircraft emissions and airport air quality monitoring

Klaus Schäfer, Gregor Schürmann, Carsten Jahn, Edgar Flores-Jardines, Herbert Hoffmann, Stefan Emeis

Institute for Meteorology and Climate Research (IMK-IFU), Forschungszentrum Karlsruhe GmbH, Garmisch-Partenkirchen

Motivation, background and problems
Methodology of measurements and inverse dispersion modelling
Measurement results
Conclusions

International Colloquium “Safeguarding Airport Air Quality: Angles of Approach”, Manchester, April 12th, 2007
Motivation

For the execution of the European Air Quality Framework Directive 96/62/EC and its daughter directives it is required from the EU member states to submit 12-monthly air pollution maps that show the spatial distribution of air pollutants

- for the member state in total,

- for conurbations with more than 250,000 inhabitants and

- for micro environments as, e.g., city districts subject to high pollutant concentrations: spatial resolution of 200 m²
Motivation

• Airport air quality is not well known because emission inventories are estimated only

• On airports, aircraft engines are one of the major sources for air pollutants

• Emission indices for NO\textsubscript{x} and CO (UHC, smoke number) of ICAO* are used to calculate aircraft main engines emissions: 4 different thrust levels – Idle, approach, climb out, take off (LTO cycle)

=> Applicability of ICAO data from certification measurements must be shown with measured data at airports

*ICAO: International Civil Aviation Organization
Motivation

• APU are running during all services

• Emission indices of APU are not listed by ICAO

• Initiatives within the EU-Network of Excellence ECATS (Environmentally Compatible Air Transport System)

• Road traffic and ground support equipment have a significant influence on airport air quality also
Motivation

Due to ongoing improvement of air quality regulations and steadily growing air traffic it is possible that also airport authorities must decide about emission reduction measures.

Long-term strategic framework to reduce specific emissions from air traffic in the context of airport expansion plans required to meet future demands of air traffic: Operation ability of air pollution modelling necessary - data requirements, forecasting.

As many metropolitan areas include airports this would be a contribution to enhance urban air quality.
Background and problems

Determination of strengths of all emission sources at airports is required:
• emission indices of aircraft exhaust emissions and
• diffuse or heterogeneous emissions

Interaction between exhaust plume and ambient air is not well understood but important for small-scale chemistry-transport models

Where are the “hot spots” of airport air quality?

Which interactions between airport air pollution and air pollutions in the surroundings e.g. urban areas exist?
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Methods

• Passive remote sensing using FTIR-spectroscopy (K300, SIGIS) for determination of exhaust composition at aircraft engine nozzle exit

• Concentration measurement across the plume with FTIR & DOAS

• Determination of emission indices

• Inverse modelling to estimate multiple sources from heterogeneous emissions
Measurement – Set up

- Detailed observations of aircraft movements
- Application of other measurement devices for Inverse Dispersion Modelling
Average emission index $EI$ of a molecule $X$ in g/kg kerosene:

$$EI(X) = EI(CO_2) \times \frac{M(X)}{M(CO_2)} \times \frac{Q(X)}{Q(CO_2)}$$

$M$: molecular weight

$Q$: concentrations (mixing ratios, column densities etc.), difference to background

Theoretical emission index of $CO_2$: calculated from stoichiometric combustion of kerosene to be 3,159 g/kg

$EI\ (NO_x) = EI\ (NO^*\ and\ NO_2)$ is related to the mass of $NO_2$:

$EI\ (NO^*) = EI\ (NO) \times 46/30$
Measurement – Instrumentation

FTIR spectrometry with a spectrometer from Kayser Threde or Bruker and the use of glowbars as IR-source

DOAS from Opsi in monostatic configuration with retroreflectors
Measurement Locations

Airport Zurich (ZRH)  
Airport Paris Charles de Gaulle (CDG)

Vienna  
London-Heathrow
Airport Mexico City

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The present:
Airport Mexico City

RAMA
FTIR and DOAS

SIGIS
IFU

UNAM

MOBILE UNIT
FTIR and DOAS

80 m

FTIR, DOAS and mobile unit

MOBILE UNIT
FTIR, DOAS

FTIR, DOAS and mobile unit

FTIR, DOAS and mobile unit
Measurement principle

\[
I = I_b \tau_p \tau_f + I_p \tau_f + I_f
\]

\[
\tau_{\Delta \nu}(L) = \left\{ \int \prod_{i=1}^{N} \exp\left[-k_i(\nu) n_i L\right] d\nu \right\} \exp\left[-k_a(\Delta \nu) n_a L\right]
\]
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Measured spectra

Simulated spectra
Measurement results

![Graph showing CO₂ and CO concentrations over time]

- **CO₂-Concentration [mg m⁻³]**
- **CO-Concentration [mg m⁻³]**

03-07-2004 [CET]

- HBIQA
- HBIOH
- HBIOL
- HBIQP
- HBJMB
Measurement results

![Graph showing NO-concentration in µg/m³ for Taxiway and Parking place on 06.07.2004 in CET time.]
Measurement results

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06.07.2004 [CET]
## Measured Pollutants by FTIR and DOAS

<table>
<thead>
<tr>
<th>Name</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>Carbon monoxide very good, passive and active</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide very good, passive and active</td>
</tr>
<tr>
<td>H₂O</td>
<td>Water high background, passive/active</td>
</tr>
<tr>
<td>HCOH</td>
<td>Formaldehyde good</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>Ethene very good</td>
</tr>
<tr>
<td>C₂H₂</td>
<td>Ethine good, interferences to CO₂ &amp; H₂O</td>
</tr>
<tr>
<td>CH₄</td>
<td>Methane difficult, passive and active</td>
</tr>
<tr>
<td>C₃H₆</td>
<td>Propene good, low concentrations</td>
</tr>
<tr>
<td>C₄H₆</td>
<td>Butadiene good, low concentrations</td>
</tr>
<tr>
<td>N₂O</td>
<td>Nitrous oxide difficult, passive and active</td>
</tr>
<tr>
<td>NO</td>
<td>Nitrogen oxide very good, passive and active</td>
</tr>
<tr>
<td>NO₂</td>
<td>Nitrogen dioxide very good</td>
</tr>
</tbody>
</table>
Measured emission indices

Measured compounds:

- FTIR passive: CO, NO, CO₂ – simultaneous
- FTIR active: CO, CO₂ – simultaneous
- DOAS: NO, NO₂ – one after another

Averaging temporal interval: ~ 1 - 3 minutes
<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Nozzle diameter</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-3B1</td>
<td>115 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>CFM56-3B2</td>
<td>115 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>CFM56-5A1</td>
<td>65 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>CFM56-5B1P</td>
<td>66 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>CFM56-5B1/2</td>
<td>66 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>CFM56-5B2</td>
<td>66 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>CFM56-5B3P</td>
<td>66 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>CFM56-5B4/2</td>
<td>66 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>CFM56-5B4/2P</td>
<td>66 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>CFM56-5C2</td>
<td>140 cm</td>
<td>Civil, long range</td>
</tr>
<tr>
<td>CFM56-7B22/2</td>
<td>68 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>CFM56-7B27</td>
<td>68 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>GE CF 34-3A</td>
<td>43 cm</td>
<td>Civil, short range</td>
</tr>
<tr>
<td>GE CF 34-3A1</td>
<td>43 cm</td>
<td>Civil, short range</td>
</tr>
<tr>
<td>GE CF 34-3B</td>
<td>43 cm</td>
<td>Civil, short range</td>
</tr>
<tr>
<td>GE CF 700-2D2</td>
<td>44 cm</td>
<td>Civil bus. jets</td>
</tr>
<tr>
<td>GE90-85B</td>
<td>150 cm</td>
<td>Civil, long range</td>
</tr>
<tr>
<td>JT8D-15</td>
<td>108 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>JT8D-217C</td>
<td>95 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>PW123B</td>
<td>43 cm</td>
<td>Civil, short range</td>
</tr>
<tr>
<td>PW150A</td>
<td>45 cm</td>
<td>Civil, short range</td>
</tr>
<tr>
<td>RB211-524D4</td>
<td>90 cm</td>
<td>Civil, long range</td>
</tr>
<tr>
<td>RB211-524D4X</td>
<td>90 cm</td>
<td>Civil, long range</td>
</tr>
<tr>
<td>RB211-524H2</td>
<td>170 cm</td>
<td>Civil, long range</td>
</tr>
<tr>
<td>RB211-535C</td>
<td>84 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>RB211-535C-37</td>
<td>84 cm</td>
<td>Civil, med. range</td>
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<tr>
<td>RB211-535E4</td>
<td>145 cm</td>
<td>Civil, med. range</td>
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<tr>
<td>RB211-535E4-37</td>
<td>145 cm</td>
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</tr>
<tr>
<td>RR M45H</td>
<td>50 cm</td>
<td>Civil bus. jets</td>
</tr>
<tr>
<td>RR-TAY MK 620</td>
<td>90 cm</td>
<td>Civil, short range</td>
</tr>
<tr>
<td>PW4168A</td>
<td>99 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>V2500-A1</td>
<td>124 cm</td>
<td>Civil, med. range</td>
</tr>
<tr>
<td>APS2000</td>
<td>35 cm</td>
<td>APU</td>
</tr>
<tr>
<td>APS3200</td>
<td>35 cm</td>
<td>APU</td>
</tr>
<tr>
<td>GT CP85-98DHF</td>
<td>35 cm</td>
<td>APU</td>
</tr>
<tr>
<td>GT CP331-200/250</td>
<td>55 cm</td>
<td>APU</td>
</tr>
<tr>
<td>GT CP331-500</td>
<td>55 cm</td>
<td>APU</td>
</tr>
<tr>
<td>GT CP660-4</td>
<td>55 cm</td>
<td>APU</td>
</tr>
<tr>
<td>PW901A</td>
<td>55 cm</td>
<td>APU</td>
</tr>
</tbody>
</table>

**Measured engines up to now**
### Mean values of emission indices of APU

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Number of aircraft</th>
<th>APU type</th>
<th>El CO [g/kg]</th>
<th>El NO [g/kg]</th>
<th>El NOx [g/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A320-200</td>
<td>1</td>
<td>APS3200</td>
<td>2.9 ± 0.30 (2.5 -3.1)</td>
<td>0.3 (bdl - 0.8)</td>
<td>0.4 (bdl - 1.3)</td>
</tr>
<tr>
<td>B737-406</td>
<td>1</td>
<td>APS2000</td>
<td>2.7 ± 0.29 (2.5 - 3.1)</td>
<td>1.7 ± 0.34 (1.4 - 2.2)</td>
<td>2.5 ± 0.53 (2.3 - 3.3)</td>
</tr>
<tr>
<td>B737-800</td>
<td>1</td>
<td>GTCP85-98DHF</td>
<td>13.9 ± 1.07 (12.4 - 15.1)</td>
<td>0.8 ± 0.07 (0.7 - 0.8)</td>
<td>1.2 ± 0.11 (1.0 - 1.3)</td>
</tr>
<tr>
<td>B747-236</td>
<td>1</td>
<td>GTCP660-4</td>
<td>2.2 ± 0.32 (1.9 - 2.4)</td>
<td>0.1 (bdl - 0.3)</td>
<td>0.2 (bdl - 0.4)</td>
</tr>
<tr>
<td>B747-400</td>
<td>3</td>
<td>PW901A</td>
<td>11.6 ± 3.98 (5.5 - 18.0)</td>
<td>1.1 ± 0.37 (0.6 - 1.8)</td>
<td>1.7 ± 0.56 (0.8 - 2.7)</td>
</tr>
<tr>
<td>B747-436</td>
<td>8</td>
<td>PW901A</td>
<td>12.4 ± 5.26 (0.5 - 31.3)</td>
<td>0.6 ± 0.75 (bdl - 2.7)</td>
<td>1.0 ± 1.14 (bdl - 4.2)</td>
</tr>
<tr>
<td>B757-236</td>
<td>3</td>
<td>GTCP331-200/250</td>
<td>1.1 ± 0.41 (0.2 - 1.7)</td>
<td>2.6 ± 0.79 (0.4 - 3.6)</td>
<td>3.9 ± 1.21 (0.6 - 5.5)</td>
</tr>
<tr>
<td>B777-236</td>
<td>3</td>
<td>GTCP331-500</td>
<td>1.3 ± 0.63 (0.5 - 2.2)</td>
<td>3.0 ± 0.87 (bdl - 4.5)</td>
<td>4.6 ± 1.33 (bdl - 6.9)</td>
</tr>
</tbody>
</table>

bdl: below detection limit i.e. a signature in the measured spectra cannot be inverted. Extrema as minimum and maximum value of all measured data are given in brackets.
Comparison of measurement results in different parts of the exhaust plume and with ICAO databank

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>No for CO</th>
<th>EI CO [g/kg]</th>
<th>EI NO\textsubscript{x} [g/kg]</th>
<th>No for NO\textsubscript{x}</th>
<th>EI NO\textsubscript{x} [g/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FTIR Em. spectr.</td>
<td>FTIR Abs. spectr.</td>
<td>ICAO</td>
<td>FTIR Em. spectr.</td>
</tr>
<tr>
<td>DHC 8Q</td>
<td>29</td>
<td>8.9</td>
<td>17.27</td>
<td>None</td>
<td>11</td>
</tr>
<tr>
<td>Fokker 70</td>
<td>20</td>
<td>23.1</td>
<td>32.33</td>
<td>24.10</td>
<td>24</td>
</tr>
<tr>
<td>RJ</td>
<td>15</td>
<td>38.27</td>
<td>23.16</td>
<td>42.60</td>
<td>15</td>
</tr>
<tr>
<td>MD80</td>
<td>5</td>
<td>10.3</td>
<td>28.32</td>
<td>17.84</td>
<td>5</td>
</tr>
<tr>
<td>A320</td>
<td>50</td>
<td>41.7</td>
<td>40.72</td>
<td>30.07</td>
<td>40</td>
</tr>
<tr>
<td>A340</td>
<td>3</td>
<td>6.0</td>
<td>17.79</td>
<td>32.98</td>
<td>2</td>
</tr>
<tr>
<td>B737</td>
<td>14</td>
<td>31.46</td>
<td>36.16</td>
<td>26.95</td>
<td>13</td>
</tr>
<tr>
<td>B747</td>
<td>9</td>
<td>23.6</td>
<td>25.45</td>
<td>15.03</td>
<td>7</td>
</tr>
<tr>
<td>B757</td>
<td>15</td>
<td>8.8</td>
<td>15.47</td>
<td>17.90</td>
<td>13</td>
</tr>
<tr>
<td>B767</td>
<td>3</td>
<td>7.3</td>
<td>25.09</td>
<td>11.75</td>
<td>3</td>
</tr>
<tr>
<td>B777</td>
<td>6</td>
<td>24.6</td>
<td>43.34</td>
<td>13.67</td>
<td>5</td>
</tr>
</tbody>
</table>
Conclusions

The presented methods are a tool to determine EI:

EI for idle conditions under in-use conditions in comparison to ICAO data base: EI(CO) higher, EI(NO_x) slightly smaller

Idle during operational conditions unequal to ICAO definition

APU emissions cannot be neglected at airports

For better conclusions, more measurements are necessary for a statistical treatment of the data
Improvement of measurement technique

Passive FTIR emission spectrometry has also the capability to determine the composition of hot exhausts but also the plume behaviour non-intrusively.

Are there inhomogeneous distributions along the plume i.e. temporal variations in the measurement volumes?
SIGIS: Instrumentation improved to detect exhausts composition of aircraft on the ground nearly automatically

Spectrometer OPAG coupled with an IR camera: rapid selection of the hottest exhaust area is possible

Imaging of the scenery behind the turbine with the scanning mirror:

• low-resolution spectra are measured and analysed in a spectral range which is sensitive for plume temperature

• software for real-time visualisation of the plume shape in this spectral range
Aircraft, main engine PW4168A: IR camera picture
Main engine: gas temperature mode
approximated length 11 m, diameter 2.4 m
Aircraft, main engine CFM56-5C2F: gas temperature mode asymmetry, approximated plume length 8.4 m
Main engine: gas radiation mode (absorption / emission)
approximated length of hottest part 3.8 m, diameter 1.4 m
Airport air pollution

Zuerich July 2004

Following the definitions the air quality is good

But during periods of high air traffic at the apron area the air quality is moderate only

Results

- Reactive C$_2$–C$_3$ alkenes in significant amounts in the exhaust of an engine compared to ambient levels

- Also, isoprene, a VOC commonly associated with biogenic emissions, in the exhausts

- Benzene to toluene ratio used to discriminate exhaust from refuelling emission:
  - In refuelling emissions the ratio was well below 1
  - For exhaust this ratio was usually about 1.7
Inverse dispersion modelling

Emission rates for NO on the taxiway 4.4 up to 146 mg/s, parking places 1.6 up to 357 mg/s

CO emission rates for taxiing aircrafts 0.4 up to 7.5 g/s, parking places 0.01 up to 0.35 g/s

NO₂ on the taxiway 13 mg/s up to 90 mg/s, parking places 0.25 mg/s up to 113 mg/s

Dispersion matrix by modelling with the Lagrangian model Austal2000 from Janicke
Meteorological measurement tasks at Paris CDG

Altitude profiles of turbulence and wind were measured by the METEK DSD3x7 monostatic Doppler SODAR: three antennas, each including seven sound transducers.

Averaged every 30 minutes, vertical resolution 20 m, minimum height 40 m and maximum height is 800 m above ground.
Wind speed resolving wind roses for 100 m (left) and 300 m (right) above ground for night-time (0 to 6 hours GMT+1, top) and daytime (12 to 18 hours) bottom.
Mean daily courses
More sources than measurements =>

Use of a-priori knowledge within the inverse procedure

Firestation as background measurement

Meteorological measurements
Detailed observations of aircraft movements and handling activities

NO/NO<sub>2</sub>, DOAS, TE42-95, TE42-96, AC-31M
CO
K300-1, K300-2, AL5001
PM10
FH62 I-R, FH62 I-N
Inverse dispersion modelling

Bayesian statistics is used to solve the inverse problem: on the basis of hourly averaged concentration measurements.

All kind of emissions on the airport Budapest show very high temporal variability.

The traffic itself on the airport is highly variable.
Results

Highest concentrations during low wind speed conditions downwind of the airport

Reliable background measurements are required

3 taxiways, 7 aircraft stands, 1 road, 1 freight area

A-priori dominates results, if no measurement are available

Adjustment of a-priori, if measurements are available
Ground support emissions

Comparison with aircraft emissions:

CO is a factor of 10 lower

NO and NO$_2$ with comparable emission levels

=>

CO originates mainly from aircrafts while NO$_x$ is caused by aircrafts and all other sources
Conclusions

Overall, emissions of taxiing aircrafts were the most important sources for NO$_x$ around Terminal 2 during the measurement campaign.

Freight and car park emissions reach similar emission levels.

But emissions on runways were not considered because they were not located in the measurement area.

It is well known, that NO$_x$ emissions of an aircraft are highest during take-off.
Future activities

• EU-network of excellence ECATS (Environmentally Compatible Air Transport System):
  Capability gap analyses
  Capability enhancement
  Research initiatives
  Education

• Research projects: 7th Framework Program of the EC
Acknowledgements

Measurements at airport Frankfurt/Main, London-Heathrow and Vienna were undertaken within the frame of the EC funded projects AEROJET 2 (BRPR CT-98-0618) and ARTEMIS (1999-RD.10429) as well as at airport Munich with funding by Deutsche Lufthansa AG and airport Paris CDG with funding by ONERA.

During these investigations we worked successfully together with Roland Harig and Peter Rusch (Arbeitsbereich Messtechnik, Technische Universität Hamburg-Harburg, Hamburg), Peter Sturm, Bernhard Lechner and Michael Bacher (Institut für Verbrennungskraftmaschinen und Thermodynamik, Technische Universität Graz, Graz), Szabina Török and Veronika Groma (Health and Environmental Physics, KFKI Atomic Energy Research Institute, Budapest, Hungary) as well as Richard Ramaroson (ONERA).
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Without this co-operation no reliable investigations would have been possible.