The impact of aviation emissions on urban air quality in Europe — an airport/city analysis

The study summarised in this article aims to enhance understanding of the influence of aviation emissions on air quality in cities with large airports nearby, compared with the influence of emissions from other sectors. This article describes the methodology, the types of data and the simulation set-up used, and presents a summary of the results for three of the six European cities studied. The complete analysis can be found in the full Concawe report on this study.[1]

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Introduction

It is well known that fuels burnt by aircraft engines result in emissions of several pollutants such as NO_x, SO_2, soot and particulate matter (PM), etc. that have a negative impact on air quality and are thus harmful to human health and ecosystems.

Despite that, on average in Europe, the aviation sector is not considered a large contributor to the emissions of air pollutants of concern, and has seen an increase in emissions compared to most other sectors. For example, between 2000 and 2018, aviation NO_x emissions showed an increase from 61 kt to 86 kt (41%), while for most of the other sectors emissions generally decreased.[2] That said, the relative contribution of the aviation sector to total emissions remains low for the whole of Europe (< 1.5% for NO_x in 2018). However, locally, in cities with major airports nearby, the effect of emissions from the aviation sector on ambient air quality is expected to be higher due to the proximity of the cities to the airports.

This work aims to provide insights and enhance understanding of the influence of aircraft emissions on ambient air quality in cities with, or near to, a major airport, by addressing the following research question: 'How is the air quality influenced by aviation emissions over Europe and specifically in cities with large airports in comparison to other sectors?'

In this context, the chemical transport model (CTM) LOTOS-EUROS and its source apportionment capabilities were used to assess the contribution of aviation emissions to atmospheric air pollutant concentrations for six cities in Europe (London, Paris, Amsterdam, Frankfurt am Main, Munich and Brussels) with large airports (Heathrow, Charles de Gaulle, Schiphol, Frankfurt am Main, Munich and Zaventem).

The methodology used in the study is described in the following section, which provides details on the model that is used and the data that are utilised as input to the model to perform the simulations of the atmospheric concentrations. The results of the study are presented in the third section of this article on pages 37–43. The CTM provides labelled atmospheric concentrations over the simulation domain. Using the simulation results, the contributions of various sectors to air emissions in airport-cities of interest are computed. The main findings are presented in the *Conclusions* on pages 43–44.

Methods

Model description

LOTOS-EUROS is a 3-D chemical transport model developed by TNO. The offline Eulerian grid model simulates air pollution concentrations in the lower troposphere, solving the advection-diffusion equation on a regular latitude-longitude grid with a variable resolution over Europe.[3]

The vertical transport and diffusion scheme accounts for atmospheric density variations in space and time and for all vertical flux components. The vertical grid is based on terrain following vertical coordinates and, excluding the stacked boundary layers on top, extends to 5 km above sea level. The height of the layers on top of the 25-metre surface layer is determined by heights in the meteorological input data.

Gas-phase chemistry is simulated using the TNO CBM-IV scheme, which is a condensed version of the original scheme.[4] The LOTOS-EUROS model explicitly accounts for cloud chemistry, computing sulphate formation as a function of cloud liquid water content and cloud droplet pH as described in Banzhaf *et al.* (2012).[5] For aerosol chemistry the thermodynamic equilibrium module ISORROPIA II is used.[6] Dry Deposition fluxes are calculated using the resistance approach as implemented in the DEPAC (DEPosition of Acidifying Compounds) module.[7] Furthermore, a compensation point approach for ammonia is included in the dry deposition module.[8] The wet deposition module accounts for droplet saturation following.[9]

The model is part of the Copernicus Atmospheric Monitoring Service (CAMS) regional ensemble providing operational forecasts and analyses over Europe. In this context the model is regularly updated and validated using observations from ground and satellite observations. The model performance is also subject to numerous peer-reviewed publications.[10,11,12]

Source apportionment

TNO has also developed a system to track the impact of emission categories within a LOTOS-EUROS simulation based on a labelling technique.[13] This technique provides more accurate information about the source contributions than using a brute force approach with scenario runs as the chemical regime remains unchanged. Another important advantage is the reduction of computational costs with respect to the brute force approach. The source apportionment module for LOTOS-EUROS provides a source attribution that is valid for current atmospheric conditions as all chemical conversions occur under the same oxidant levels. For details and validation of this source apportionment module, the reader is referred to Kranenburg *et al.*[13] The source apportionment technique has been used extensively in previous studies.[12,14,15]

As well as calculating the total concentrations of each pollutant, the contributions of selected sources to these concentrations are calculated. The labelling routine is implemented for primary, inert aerosol tracers as well as for chemically active tracers containing a C, N (reduced and oxidised) or S atom, as these are conserved and traceable.

Meteorology

The LOTOS-EUROS model is run with ECMWF ERA5 reanalysis meteorological data (2018). ERA5 provides hourly estimates of a large number of atmospheric, land and oceanic climate variables, that are necessary inputs for calculations of atmospheric concentrations. Examples of typical inputs required by LOTOS-EUROS are surface and air temperature, cloud cover, wind speed and direction, precipitation and relative humidity.

Quality-assured monthly updates of ERA5 (1959 to present) are published within three months of real time and are available through the Climate Data Store.[1] Preliminary daily updates of the dataset are available to users within five days of real time.

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[1] https://cds.climate.copernicus.eu/#!/home

Emissions

The CAMS-REG inventory emission data for the year 2018 version 5.1 REF2[16] is used in this study for anthropogenic trace gas emissions. At the time of performing this study, this was the latest available dataset (an update with more recent data was published in December 2023). The inventory uses the official emissions data reported by European countries. The aviation emissions in the national inventories only include the total national emissions during the landing and take-off cycle (LTO). The LTO covers four modes of engine operation, namely idle, approach, climb-out and take-off, each of which is associated with a specific engine thrust setting and a time in mode. The emissions during cruise flights (above 3,000 feet) are not reported in the national inventories. The national aviation emissions (LTOs) in a country are distributed over the contributing airports in that country based on flight statistics per airport on an annual basis. All emissions from an airport are represented as a point source at the location of the airport in the CAMS-REG inventory.

Since this study aims to better assess the local effects and spatial extent of aviation emissions at an airport and the impact they have on air quality in its vicinity, modelling simulations are performed at a 1 x 1 km resolution. Because the CAMS-REG inventory has a 6 x 6 km resolution, it is not suitable for use in the 1 x 1 km resolution simulations, so for this purpose a 1 x 1 km regridded dataset is used that contains CAMS-REG emissions for NO_x at a 1 x 1 km resolution. The regridding is done based on high-resolution proxy data, such as road and rail networks and land use maps, while keeping the annual total emissions per sector unchanged. For SO_2 and PM, this level of detail is not available from the CAMS-REG inventory. However, for the Netherlands and Germany, emissions for all pollutants of interest are available at this resolution from other national datasets, namely the Emission Register (ER) in the Netherlands and GrETA (Gridding Emission Tool for ArcGIS) in Germany,[17] which provide a more detailed representation of airports with runways rather than point sources.

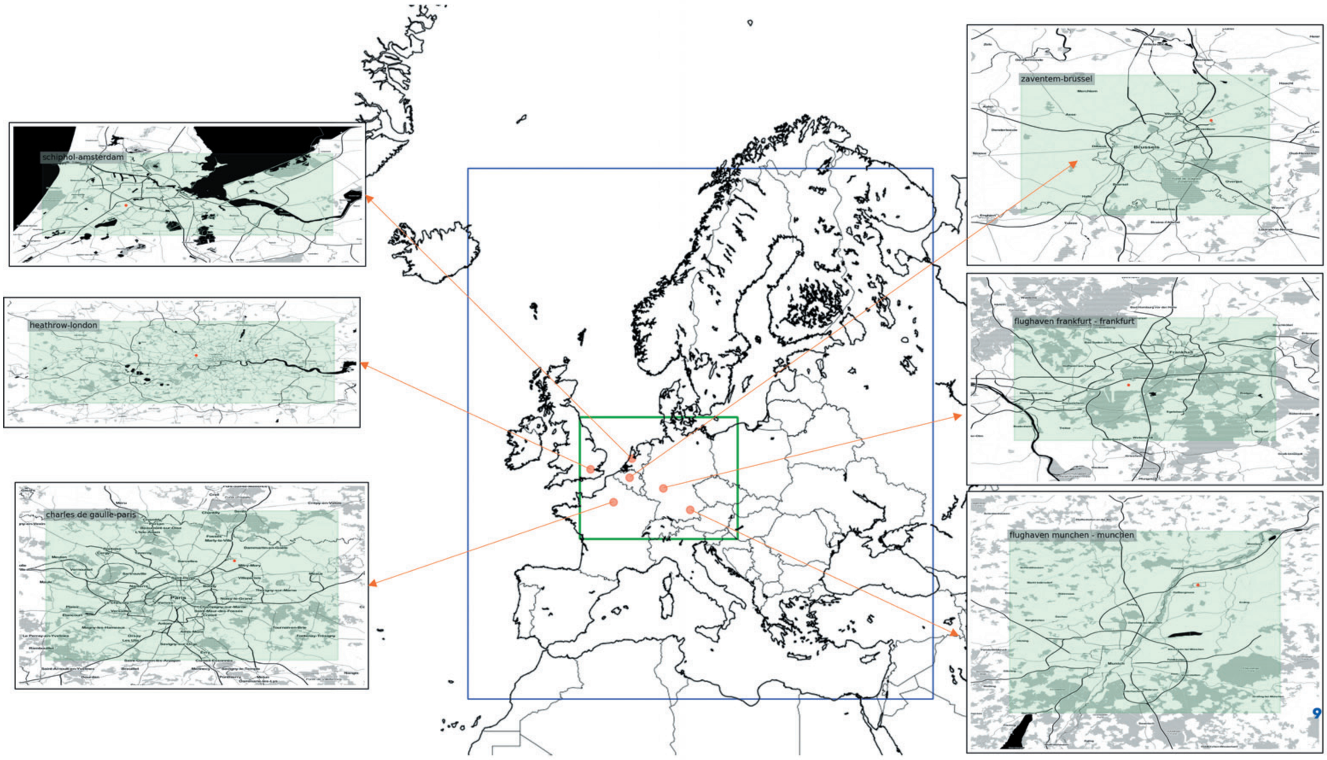
As multiple emissions datasets are available, an exploratory study was undertaken to find the most appropriate option to use in the simulations. For this purpose, the city of Amsterdam was chosen as a test case since all three emissions datasets (CAMS-REG version 5.1 6 x 6, CAMS-REG version 5.1 1 x 1 and ER 1 x 1) are available, and were used as input for the LOTOS-EUROS model for a simulation of the pollutant concentrations in January and July 2018. Details on the analyses can be found in the respective Concawe report.[1] Based on the results, the decision was made to use emissions at the highest available resolution for as many of the relevant pollutants as possible to avoid unrealistic patches in the simulated concentrations. Hence, for the Netherlands and Germany, ER and GrETA emissions data are used because high-resolution data are available for all pollutants of interest. Unfortunately, this dataset does not cover Paris, London or Brussels. For these domains, the CAMS-REG v5.1 1 x 1 dataset was used.

Model set-up

Figure 1 shows the different domains which are part of the LOTOS-EUROS simulations. In the middle of the figure, a coarse resolution (circa 25 x 25 km) simulation performed over Europe (domain edge in purple) is shown. Results from this simulation are used as a boundary condition for the nested simulation over north-western Europe (domain in green) at a higher resolution (circa 6 x 6 km). As a next step, simulations are performed for the cities that are part of this study at higher resolution (circa 1 x 1 km). The chosen cities and domains are shown with orange dots in the centre figure. On the outsides of the figure, the domains of the 1 x 1 km high-resolution zoom runs are shown in more detail. The following major cities are studied in the high-resolution zoom runs:

1. London (UK)
2. Paris (FR)
3. Amsterdam (NL)
4. Frankfurt am Main (DE)
5. Munich (DE)
6. Brussels (BE)

Figure 1: Display of the simulation set-up domains
(the chosen cities and domains are shown by orange dots on the map at the centre)



In order to distinguish emissions sources from different sectors, a set of labels was applied during the source apportionment simulations. The complete set of labels is as follows:

1. Aviation
2. International shipping (all sea-going shipping)[2]
3. Inland shipping (all river-going shipping)
4. Public power/Energy
5. Residential combustion
6. Industry
    a. Solvent use[a]
    b. Fuel production
    c. Refineries[b]
    d. Other industry
7. Mobile machinery[c]
8. Road transport—exhaust
9. Road transport—non-exhaust (only contributes to PM)
10. Waste management
11. Agriculture
    a. Livestock
    b. Manure management
12. Biogenic[3]
13. Wildfires (GFAS,[4] daily[18])
14. Sea salt (only contributes to PM)
15. Saharan dust (only contributes to PM)
16. Boundary[5]

[a] Even though 'Solvent use' is considered a subcategory of industry, domestic solvent use is included here. This is, however, a relatively small contribution.

[b] Oil, gas and petroleum refining is incorporated in this label. The label 'Fuel production' contains emissions that occur during production, distribution, exploration, gas flaring and venting, and oil and coal handling.

[c] 'Mobile machinery' contains emissions from railways, small agricultural, forestry and fishing equipment, compressors, gardening, off-road vehicle usage, etc.

There is a strong variation in the influence of these emission sources on surface concentrations of $PM_{2.5}$, PM_{10}, NO_2 and SO_2. In the analysis of the results, only those sectors that contribute significantly (> 2%) are presented graphically, with the exception of sectors of special interest (aviation) that are always reported if they contribute. The less-contributing sectors are aggregated and labelled as 'Other'.

The results of the study are presented in the following section of this article.

[2] A detailed analysis of the contribution from shipping can be found in Concawe Report no. 2/23, *The impact of shipping emissions to urban air quality in Europe – Detailed port-city analysis.*

[3] Biogenic emissions include isoprene and monoterpene from vegetation and soil NO_x emissions.

[4] Global Fire Assimilation Service, https://atmosphere.copernicus.eu/global-fire-emissions

[5] The label 'Boundary' is used to describe contributions from the CAMS global simulation results that are used as a boundary condition to the simulation over the European domain.

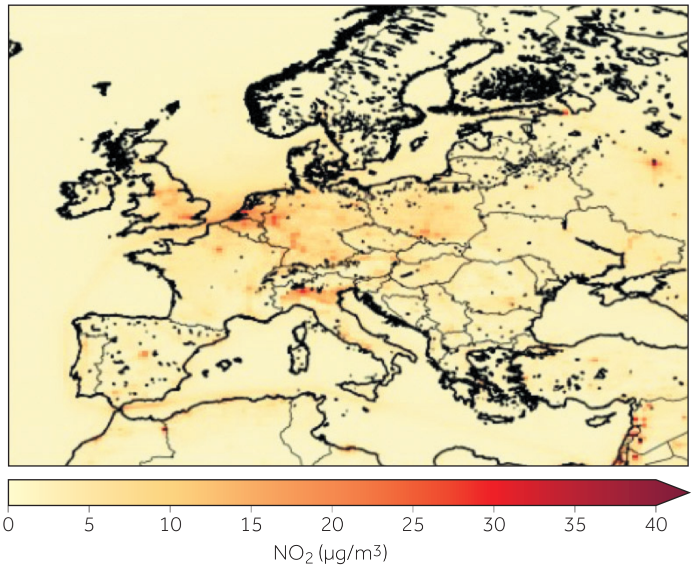
Results

Contribution of aviation emissions to air quality in Europe

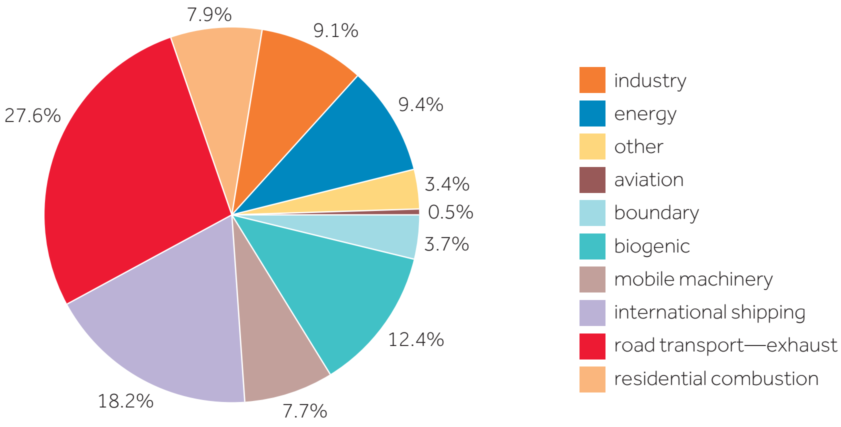
Figure 2 shows the predicted annual average surface concentration of NO_2 in 2018 for the European domain, together with the source apportionment results of the whole domain. High NO_2 concentrations are mainly predicted in the central part of Europe (Benelux, Germany, UK) and in the Po Valley (north of Italy) with 'Road transport—exhaust' and 'International shipping' being the two largest contributors.

Figure 2: The annual average NO_2 surface concentration for 2018 in the simulation domain of the coarse (25 x 25 km) resolution LOTOS-EUROS simulation (a), and the relative contributions from the various labelled sectors to the surface concentration of NO_2 for the entire simulation domain (b)

a) Annual average NO_2 concentration in Europe



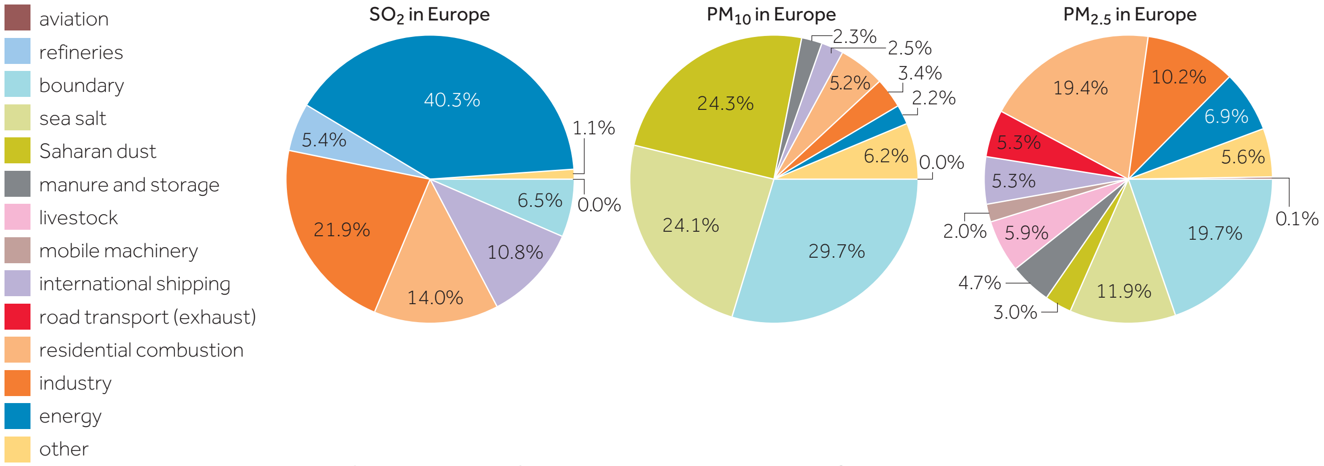
b) Contributions of the various labelled sectors to NO_2 in Europe



In contrast, the aviation sector contribution, averaged over the whole European domain, is relatively small (0.5%), which is to be expected due to its local nature and the short lifetime of NO_2 (this is discussed in more detail in the city/airport analyses results).

Aviation is also predicted to be a negligible contributor to the average surface concentrations of the remaining pollutants examined in the study, as shown in Figure 3. On average over the European domain, the results show that for $PM_{2.5}$, PM_{10} and SO_2 the contributions are 0.14% (a 1.7 ng/m^3 contribution to a domain average of 1.2 µg/m^3), 0.04% (a 2.2 ng/m^3 contribution to a domain average of 5.5 µg/m^3) and 0.03% (a 6.6 ng/m^3 contribution to a domain average of 21 µg/m^3), respectively.

Figure 3: The predicted relative contributions from the various labelled sectors to SO_2, PM_{10} and $PM_{2.5}$ (annual average surface concentrations over Europe in 2018)



Contribution of aviation emissions in cities/airports

Looking at the surface contributions, averaged over the European domain, it would appear that aviation seems to be a sector of limited significance. Aviation activities could nevertheless be relevant, since these are commonly concentrated in densely populated areas. It is therefore worthwhile to take a closer look at the fractional contributions of the various source sectors in the vicinity of large airports.

Because the highest contribution of aviation is found for NO_2, the results of the calculated aviation contribution to NO_2 levels near the cities where airports are located are presented and discussed here in more detail. The cities of London, Paris and Amsterdam are used as illustrative examples while detailed analyses for all cities and pollutants can be found in the full Concawe report on this study.[1] For the analyses, a representative central location for the airport and the city centre was determined for the selected cities. The city centre locations are represented as blue dots and the airport locations as turquoise dots on Figures 4 to 6. For these locations of interest, the concentration fields were calculated as a weighted average of the four nearest grid points in the 1 x 1 km simulation domain (inversely with distance from the grid point to the coordinates of the location of interest).

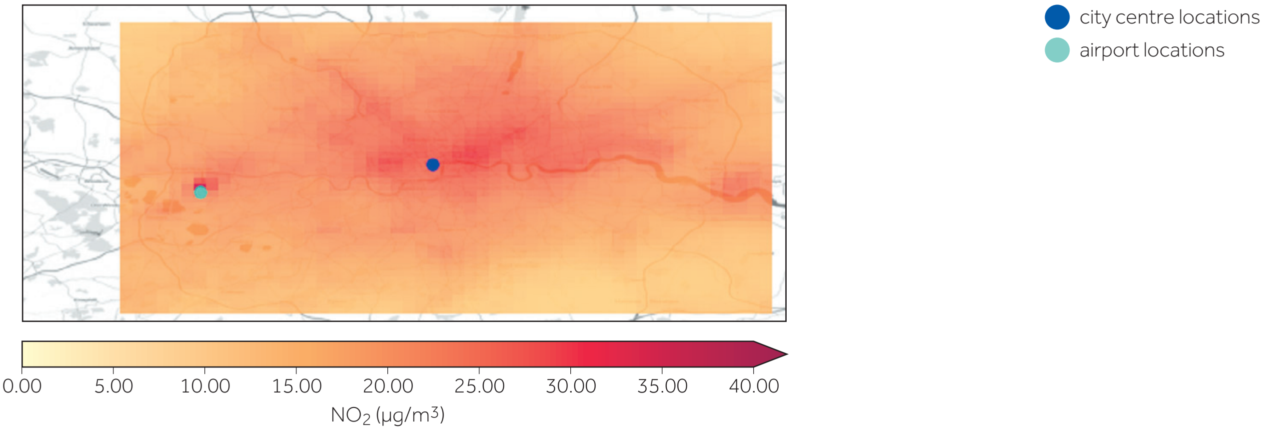
London

London city centre is located 25 km east of Heathrow airport (IATA[6] code: LHR) the busiest airport in Europe with respect to passenger throughput (i.e. more than 80 million passengers passed through Heathrow in 2018). At Heathrow, the predicted elevated NO_2 concentrations can be largely attributed to aviation activities, with a contribution of 54.9% (17.2 µg/m^3) (Figure 4).

[6] International Air Transport Association

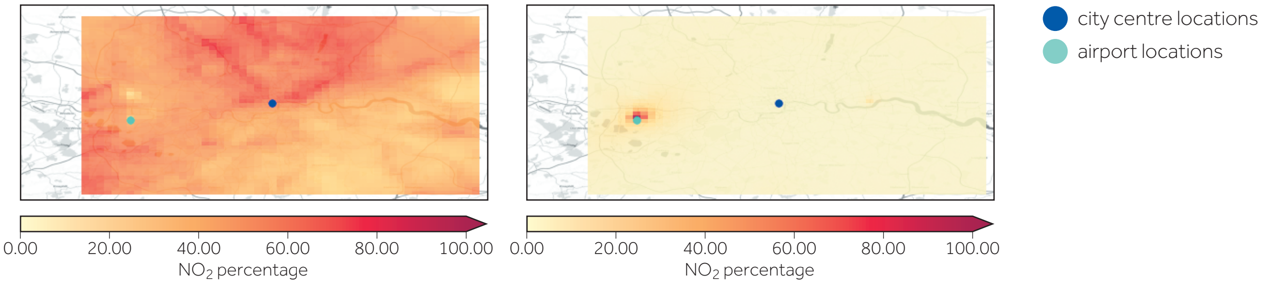
Figure 4: Predicted annual average NO_2 concentration in and around London (a), and the relative contributions of road transport (the largest contributor in the region) (b) and aviation (c) to this concentration. The pie charts show the contributions from various sectors to NO_2 concentrations in the city centre and near Heathrow airport.

a) Predicted annual average NO_2 concentration in London



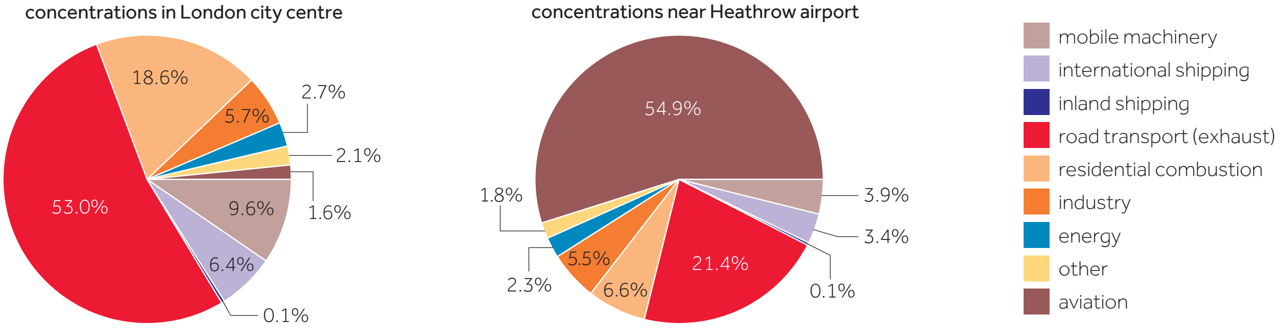
b) Relative contributions of road transport to NO_2 concentrations in the vicinity of London

c) Relative contributions of aviation to NO_2 concentrations in the vicinity of London



d) Relative contributions of various sectors to NO_2 concentrations in London city centre

e) Relative contributions of various sectors to NO_2 concentrations near Heathrow airport



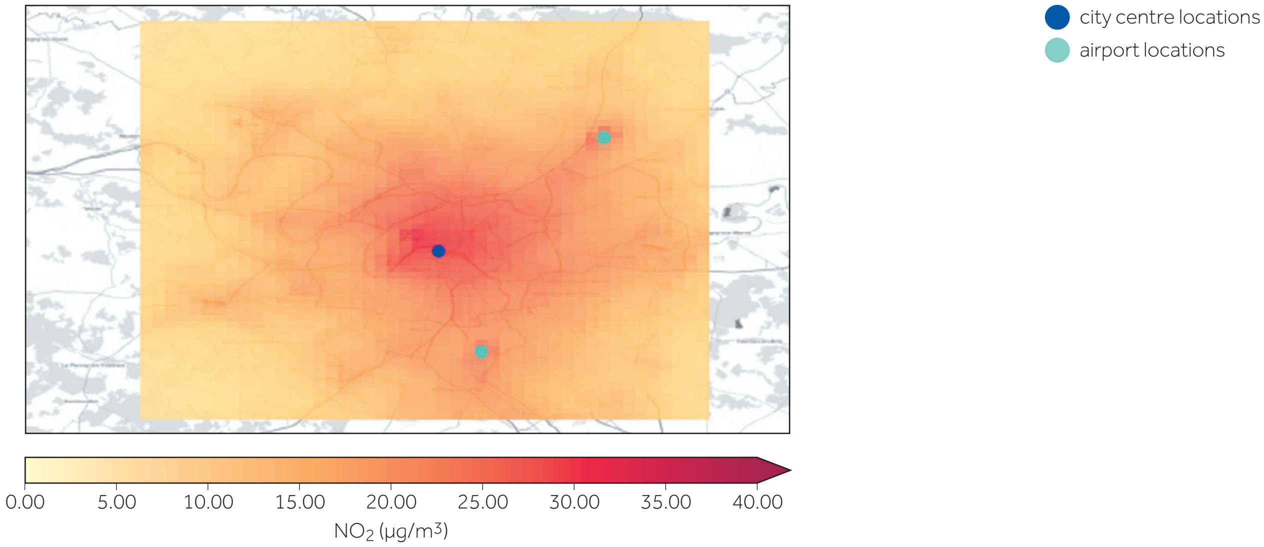
In the city centre, the contribution from aviation diminishes to 1.6% (0.44 µg/m^3) due to dilution upon transport and the lifetime of NO_2 in the atmosphere. If an exponent is fitted to the declining contribution of aviation as a function of distance from the airport, a 63% reduction in the relative contribution can be seen for every 2.8 km separation from the airport toward the city centre. This means that, at 2.8 km from Heathrow airport, aviation contributes 20% of the NO_2 concentration present. More details on this analysis can be found in the Appendix of the full Concawe report on this study.[1] The declining trend as a function of distance is also a result of a larger absolute contribution from other sources in the city of London (e.g. road transport and residential combustion), hence the relative contribution from aviation is reduced.

Paris

Paris has two airports in relatively close proximity to the city centre. Charles de Gaulle airport (IATA code: CDG) is located about 30 km north-east of the city centre and is Europe's second largest airport with a throughput of 72 million passengers, while to the south of Paris is Orly (IATA code: ORY), the second largest French airport with a throughput of 33 million passengers. At Charles de Gaulle airport, aviation is predicted to contribute around 58% (15.5 µg/m^3) of the NO_2 surface concentration. In the city centre, aviation activities at both Orly and Charles de Gaulle airports contribute 2.3% (0.68 µg/m^3) of the NO_2 surface concentration; the dominant sectors contributing to NO_2 emissions in the city centre are road transport and residential combustion activities, which together account for ~80% of the total NO_2 concentration. At 4.3 km from CDG airport, the relative contribution from aviation to the NO_2 concentration is predicted to reduce by 63% with respect to the relevant contribution at the airport (i.e. to 21%). This drop-off is less steep than the one found for London, and can be due to the presence of contributions from the Orly airport, or a smaller relative contribution from other sources. See Figure 5 on page 41.

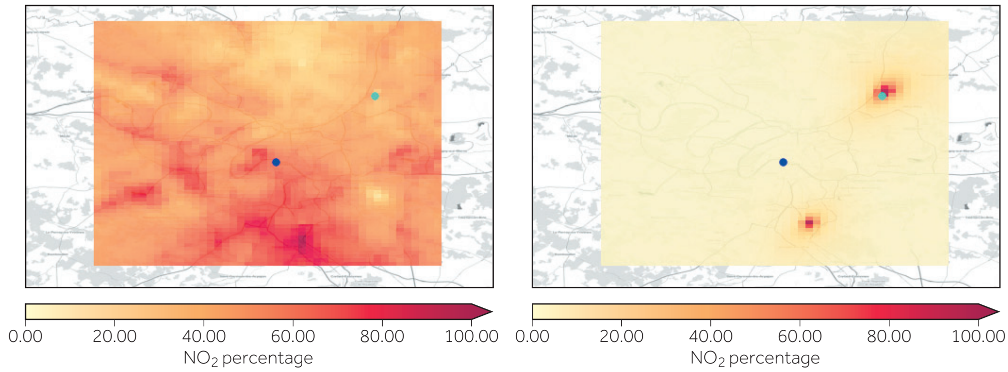
Figure 5: Predicted annual average NO_2 concentration in and around Paris (a), and the relative contributions of road transport (the largest contributor in the region) (b) and aviation (c) to this concentration. The pie charts show the contributions from various sectors to the NO_2 concentration in the city centre and near CDG airport.

a) Predicted annual average NO_2 concentration in Paris



b) Relative contributions of road transport to NO_2 concentrations in the vicinity of Paris

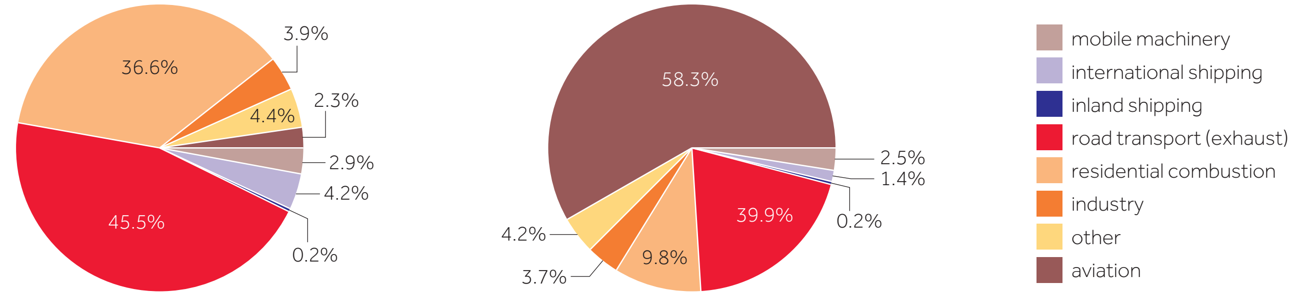
c) Relative contributions of aviation to NO_2 concentrations in the vicinity of Paris



Note:
In the pie charts below, the sector labelled 'aviation' includes emissions from both airports, hence the contribution from Orly airport cannot be distinguished from that of CDG airport; both contributions are incorporated together in the pie charts and represented by the brown slice.

d) Relative contributions of various sectors to NO_2 concentrations in Paris city centre

e) Relative contributions of various sectors to NO_2 concentrations near CDG airport

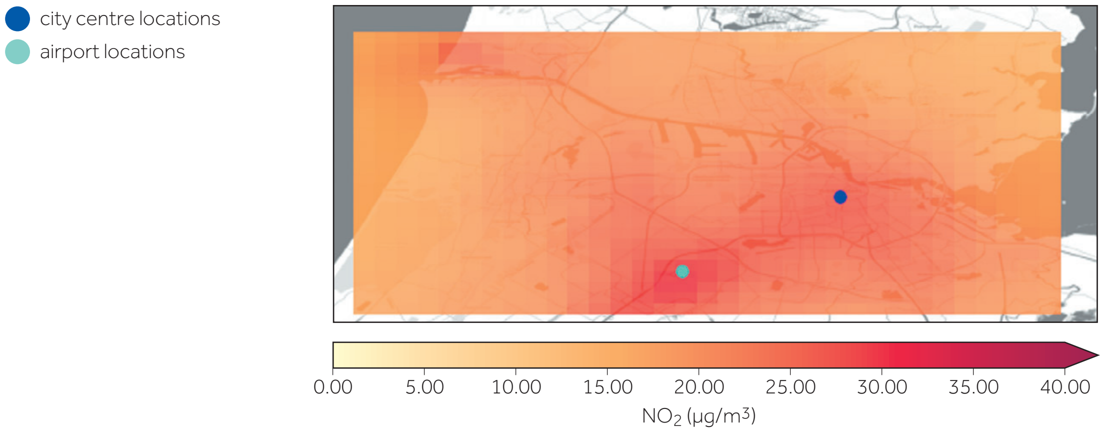


Amsterdam

Schiphol airport (IATA code: AMS) lies approximately 15 km south-west of Amsterdam city centre. It is the largest airport in the Netherlands and the third largest airport in Europe (after Heathrow and Charles de Gaulle) with a throughput of 71 million passengers. The predicted NO_2 concentrations in and around Amsterdam, and the relative contributions of the various sectors are shown in Figure 6.

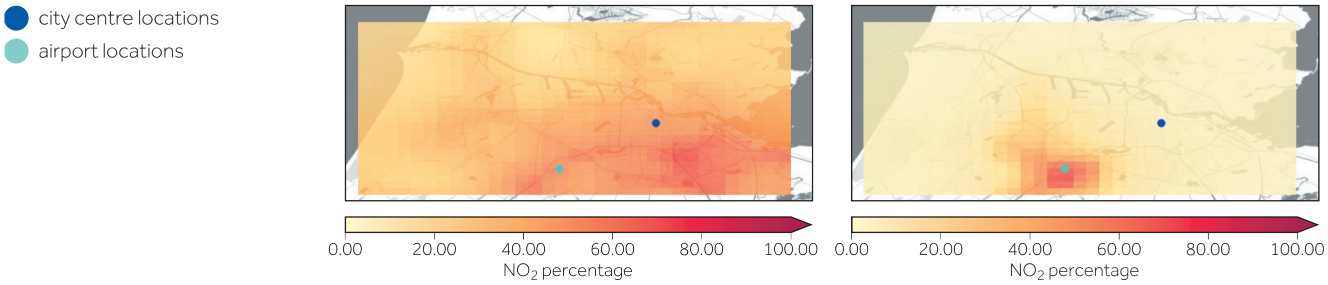
Figure 6: Predicted annual average NO_2 concentration in and around Amsterdam (a), and the relative contributions of road transport (the largest contributor in the region) (b) and aviation (c) to this concentration. The pie charts show the contributions from various sectors to the NO_2 concentration in the city centre and near Schiphol airport.

a) Predicted annual average NO_2 concentration in Amsterdam



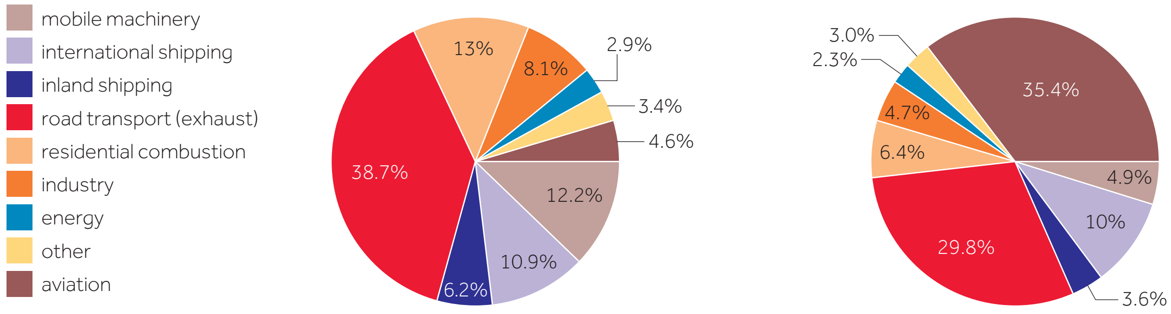
b) Relative contributions of road transport to NO_2 concentrations in the vicinity of Amsterdam

c) Relative contributions of aviation to NO_2 concentrations in the vicinity of Amsterdam



d) Relative contributions of various sectors to NO_2 concentrations in Amsterdam city centre

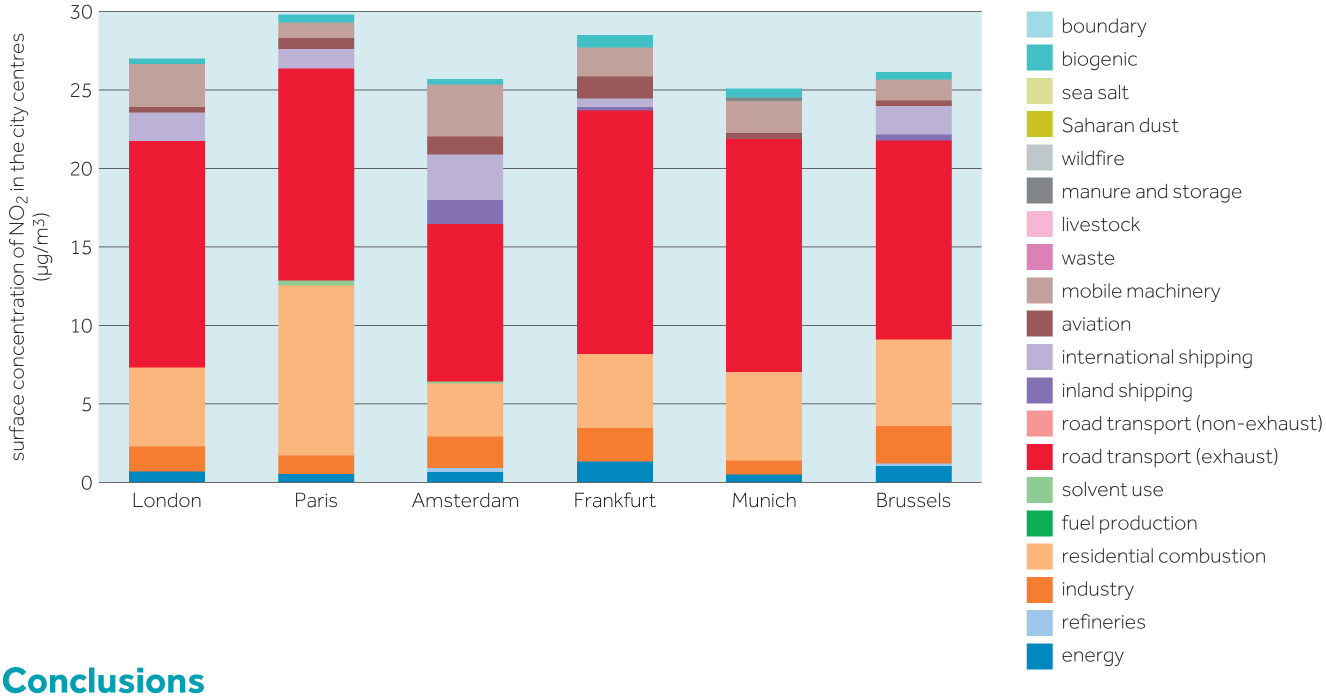
e) Relative contributions of various sectors to NO_2 concentrations near Schiphol airport



The modelling simulations predict that aviation activity at Schiphol airport contributes about 35% (10.9 μg/m^3) of the NO_2 concentration at the airport location and 4.6% (1.19 μg/m^3) of the NO_2 concentration in the city centre. A 63% reduction of the relative contribution is seen for every 4.2 km separation from the airport toward the city centre.

An overview of the total absolute contributions from the labelled sectors to the city centre locations is given in Figure 7.

Figure 7: The predicted absolute contributions from the various labelled sectors to the annual average surface NO_2 concentration in 2018 for the city centres in the vicinity of the airports of interest



Conclusions

The contribution of aviation emissions to atmospheric pollutant concentrations in Europe were assessed using the chemical transport model LOTOS-EUROS and its source apportionment feature that allows tracing of labelled emitted pollutants. In addition to the modelling simulation covering the whole European domain, six European cities (London, Paris, Amsterdam, Frankfurt am Main, Munich and Brussels) with large airports nearby were chosen for additional analyses.

Due to the spatial characteristics of the aviation contribution (i.e. mainly a local issue with respect to ambient air pollutant concentrations), an initial exploration into various emissions datasets was performed from which it was concluded that emissions data at the highest available resolution should be used for as many of the relevant pollutants as possible depending on the data availability.

The main findings from the study can be summarised as follows:

- An average contribution from aviation to the NO_2 concentration in the respective city centres of the six cities examined of 2.5% is predicted, ranging from 0.5% (Munich) to 4.6% (Amsterdam).
- For the other pollutants, the relative contribution is smaller with, respectively, 1.9%, 0.5% and 0.3% for SO_2, $PM_{2.5}$ and PM_{10}. This suggests that aviation is not a significant contributor to pollutant concentrations in the city centres compared to other sources, e.g. road transport and residential combustion.
- Closer to the airports, the average relative contributions from aviation to the NO_2 concentration in the six airports examined is significantly higher at 40%, varying from 26% (Zaventem) to 58% (Charles de Gaulle).
- This is also the case for the other pollutants, with aviation contributing, respectively, 45%, 6.2% and 4.6% to concentrations of SO_2, $PM_{2.5}$ and PM_{10}.
- The relative contribution of aviation declines as a function of distance from the airport. On average over the six airports examined, pollutant concentrations decrease with a reduction rate of 63% for every 3.8 km separation from the airport toward the city centre, ranging from 1.8 km (Brussels) to 4.9 km (Frankfurt am Main and Munich).

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