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URBAN NO_2 ATLAS

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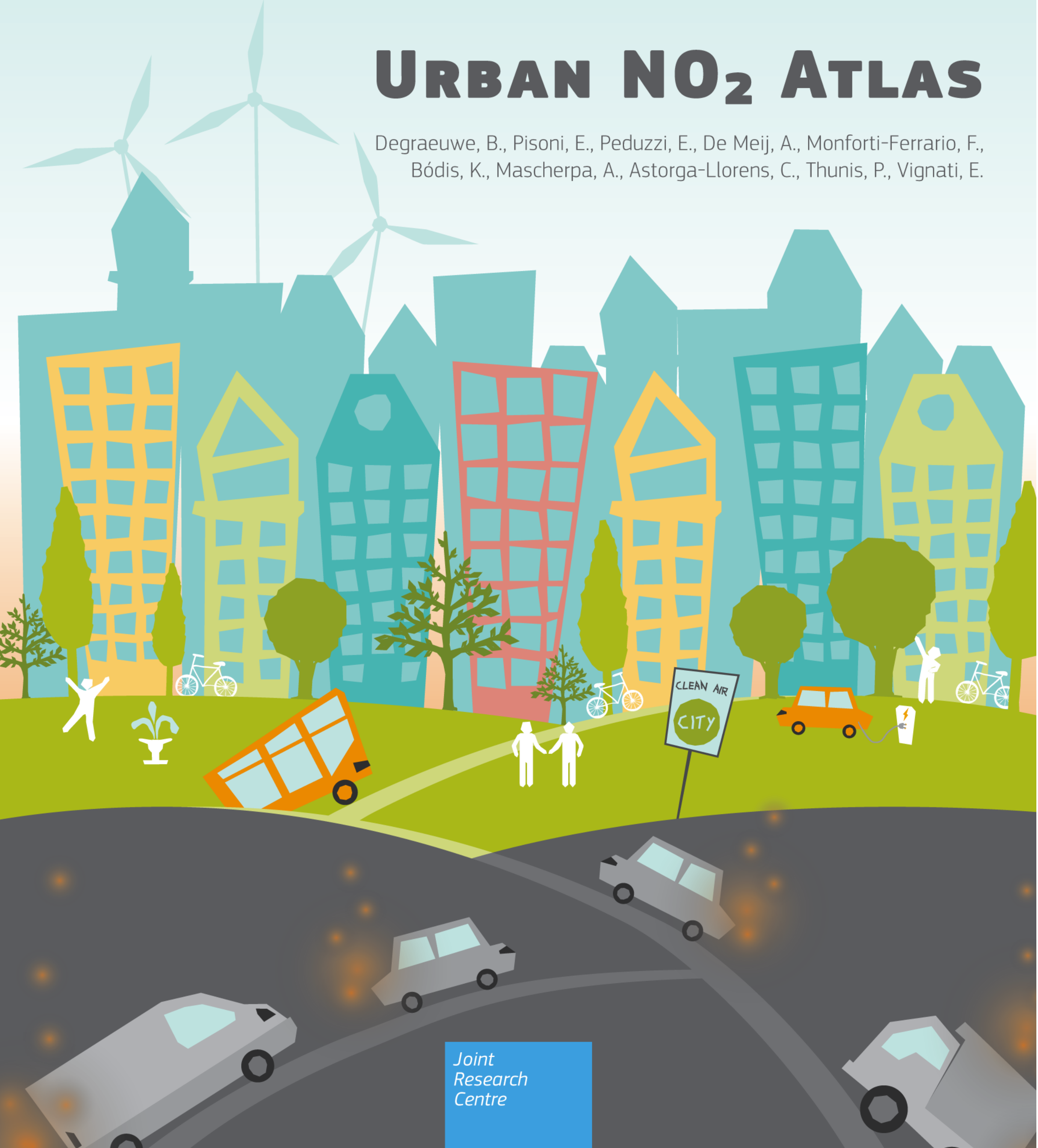

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Contents

Foreword

In this report, the potential of traffic measures to abate NO_2 air pollution in cities is explored. The analysis uses the SHERPA-City web tool (https://integrated-assessment.jrc.ec.europa.eu) developed by the Joint Research Centre. This tool is freely available and allows the user to perform a fast screening of possible NO_2 abatement measures addressing traffic in city of choice.

The methodology relies on a number of assumptions and the results depend strongly on the quality of the default input data. It is therefore important to stress that the underlying traffic flows, emission factors, fleet composition, road network topology, NO_2 pollution from other sources and meteorological data are based on EU-wide datasets that may not always represent perfectly a particular local situation. This is why the SHERPA-City web tool allows the default data to be substituted by local data.

This atlas must be considered as a first step in exploring options to abate NO_2 air pollution through transport measures. The final decisions should be based, wherever possible, on full-scale modelling studies incorporating local knowledge.

Acknowledgements

This report benefitted from discussions with and comments from colleagues at the European Commission — Directorate-General for Environment. The authors also acknowledge: *TerrAria s.r.l.*, contributing to the development of the SHERPA-City Graphical User Interface; *EMISIA*, providing information on fleet composition and emission factors; the *OpenTransportMap* project, providing "annual average daily traffic" for the main road links and *EMEP* air quality model, providing the NO_2 background concentrations for the year 2015.

Map data are copyrighted OpenStreetMap and available from https://www.openstreetmap.org.

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Executive summary

The Atlas shows, for selected cities, the likely effects of the implementation of "Traffic Policies" intended to reduce urban NO_2 concentrations.

As NO_2 pollution in urban areas is mainly caused by traffic, the analysis focuses on assessing the relative contribution to the NO_2 concentration in ambient air from different types of vehicles.

The results, obtained for a selected number of cities in Europe show that, depending on the size of the selected "Inner Area" (by this name, we mean the area over which traffic measures are applied), one could reduce on average up to 40% the NO_2 urban background concentrations. Of this average reduction, roughly 15% is linked to passenger diesel cars, 13% to trucks and 6% to vans (mostly diesel); while the remaining share is associated to other type of vehicles (buses, gasoline cars, etc…).

This Atlas provides a first indication of the relative effectiveness of mobility policies aimed at reducing urban NO_2 pollution concentrations in European cities. However, considering the specific assumptions in the applied approach, as on traffic flows, fleet composition, emission factors, size of the "Inner Area", etc…, the results may not be as accurate as they would be when using detailed local data.

The SHERPA-City methodology and tool applied in this Atlas can be used by local authorities to assess a broad range of air quality measures, including technological (e.g. fleet renewal, new technologies) and soft measures (i.e. promotion of walking and cycling). Such measures can be assessed alone or in combination.

1 Introduction

Air pollution remains the single largest environmental health risk in Europe according to the World Health Organization (WHO, 2018), with many European cities still suffering from poor air quality. Nitrogen Oxides (NO_2) contributes to air pollution and associated negative health outcomes with direct effects, and also with indirect effects through the formation of fine secondary particulate matter ($PM_{2.5}$).

Numerous European cities regularly exceed the European air quality standards prescribed by the Ambient Air Quality Directive (AAQD, 2008) (EEA, 2019) and the Air Quality Guidelines (AQGs, WHO, 2005), for both NO_2 and $PM_{2.5}$ (see Box 1 for details on these two pollutants). The NO_2 annual average ambient concentration limit value (40 μg/m^3) is the same in EU legislation and in the WHO AQGs, and is frequently exceeded in many cities (Figure 1).

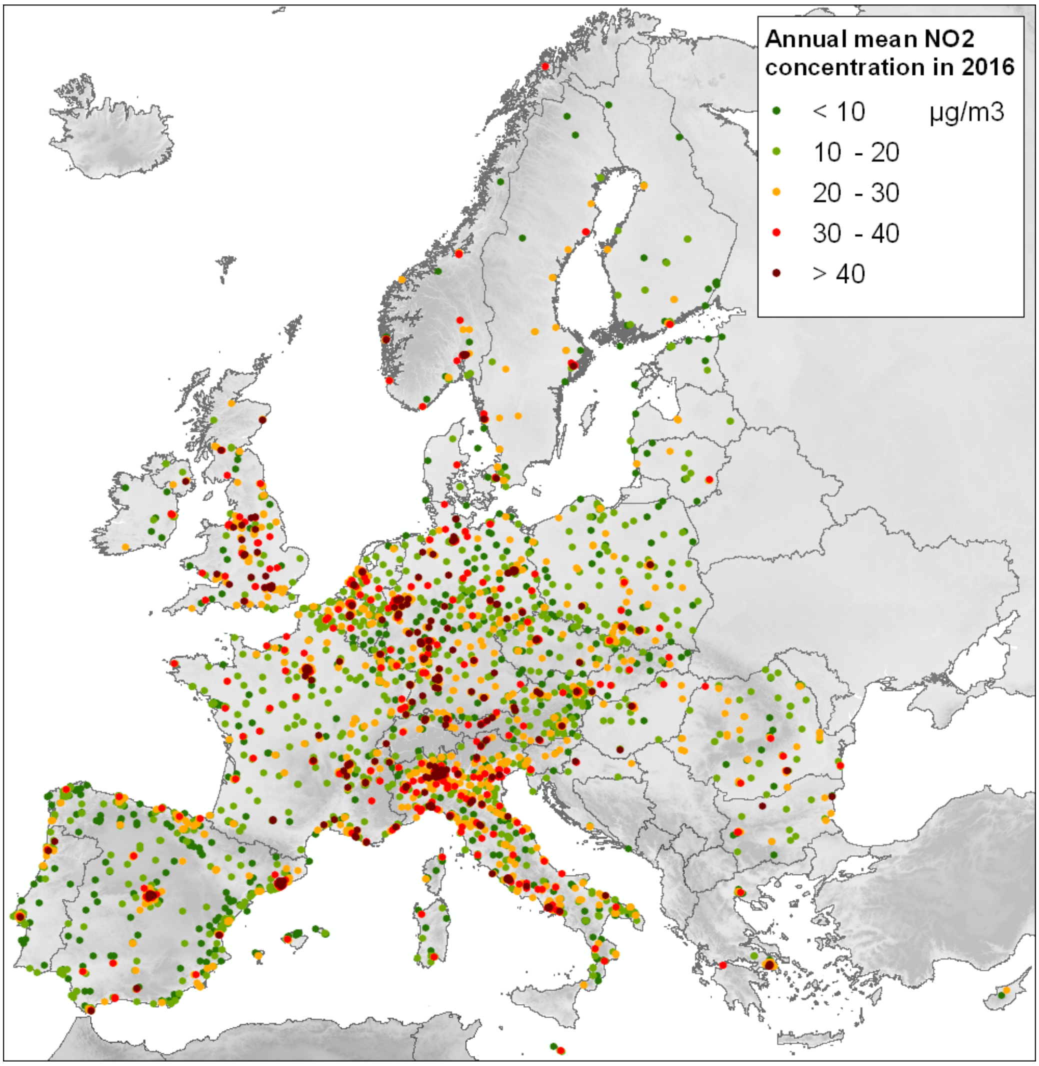

Figure 1: Annual mean NO_2 concentration in European cities. The dark red dots indicate stations reporting concentrations above the EU annual limit value for NO_2 (40 μg/m^3). (Source: JRC based on EEA data, 2018).

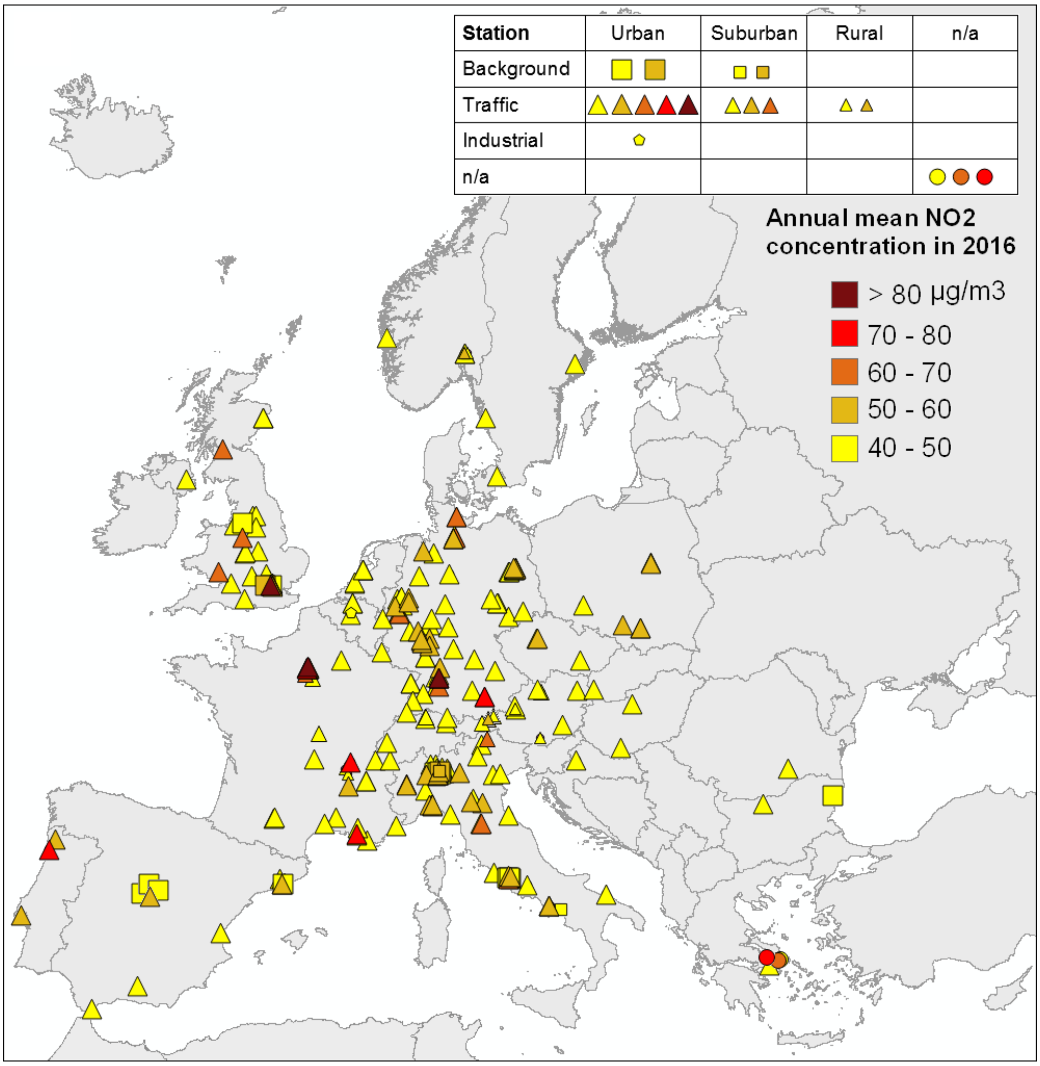

Figure 2: Annual mean observed NO_2 concentrations above the limit value of 40 µg/m^3, by station type. Only stations with > 75% of valid data have been included in the map. (Source: JRC based on EEA data, 2018).

In 2017, around 10% of all the air quality monitoring stations reporting in the EU28 recorded average annual concentrations above the annual limit value (EEA, 2019). About 86% of the concentrations above this limit value were observed at traffic stations, i.e. stations designed to measure traffic pollution (Figure 2). This is to be expected, as traffic is a major source of NO_X, which forms NO_2 when reacting with O_3 in the atmosphere.

Box 1: What are NO_2 and $PM_{2.5}$?

NO_2 is one of the highly reactive nitrogen oxides (NO_X) gases. Its major source in cities is the combustion of fossil fuels. It is generally produced in larger quantities by older vehicles with diesel engines. NO_2 is also a main contributor to the formation of nitrates in the atmosphere and, in the presence of ultraviolet light, to the formation of ozone (WHO 2018).

$PM_{2.5}$ (fine particulate matter with an aerodynamic diameter <2.5 µm) can be of primary or secondary origin. The primary fraction is directly emitted from the source (e.g. from cars, or from boilers). The secondary fraction consists of sulphate, nitrate, ammonium and organic carbonaceous materials formed through chemical reactions of gaseous precursor such as NO_X, SO_2, NH_3 and VOC. For example, ammonium nitrates and sulphates are formed through the reaction of NH_3, originating mostly from agricultural activities, and of respectively NO_X and SO_2 originating from the combustion of fuels.

Furthermore, 8% of the EU28 urban population was exposed to concentrations of $PM_{2.5}$ - partly formed through chemical reactions involving nitrogen oxides (NO_X) - above the EU annual average limit value (25 µg/m^3). About 77% of the urban population was exposed to concentrations above the more stringent AQG set by WHO (of 10 µg/m^3) (EEA, 2019).

The political guidelines of the new "Von der Leyen" Commission supports the goals of climate neutrality for the EU by the year 2050 and a Zero-pollution ambition (EC, 2019). Nevertheless, road vehicles equipped with internal combustion engines are likely to maintain an important presence for the next decade. Also, a vast number of diesel vehicles produced in the past emits considerably more NO_X in real-world driving situations than their type-approval emission limit values would suggest (Ntziachristos et al., 2016). This mismatch between emission limits and real emissions got public attention in 2015 with the "diesel gate" scandal (see Box 2).

Box 2: The Diesel gate scandal

Policy makers expected the NO_X emissions of diesel cars to decrease considerably when introducing more stringent Euro 5 and 6 emission limits in 2009 and 2014. This expectation, however, has not materialized. Tests with Portable Emissions Measurement Systems (PEMS) suggested that, on the road, Euro 5 and 6 diesels emitted several times more NO_X than permitted by the applicable limit (Weiss et al., 2011; Franco et al., 2014; Kadijk et al., 2015). The cause of this discrepancy was believed to be the laboratory test procedure that was not representative for on-road driving.

In October 2015, the US-Environmental Protection Agency (EPA) published a notice of violation of the Clean Air Act by the Volkswagen Group. Researchers of West Virginia University found that Volkswagen diesel cars, certified under the most stringent NO_X emission limit, emitted over ten times more on the road. The cars were equipped with a defeat device that was able to recognize the speed profile of the certification test. When the car detected that it was tested, the Lean NO_X Trap (LNT) or the Selective Catalytic Reduction (SCR) systems were activated. Otherwise they were switched off. In this way the consumption of fuel and urea solution were kept low.

In Europe, tests carried out by the national type approval authorities in the aftermath of the diesel gate have shown that on the road Euro 5 and 6 diesel cars emit on average five times more NO_x than their respective limits of 180 and 80 mg/km (Degraeuwe and Weiss, 2017; Suarez-Bertoa et al., 2018). Some manufactures did software updates but their real effect is yet unclear. The consequence is that these diesel cars with excessive emission remain on the road. Considering that in the EU28 42% of the passenger cars are diesels and 13% are Euro 5, this has a considerable impact on air quality.

In view of the persistent air quality problems, in Europe the so-called Real-Driving Emissions (RDE) on-road test procedure was introduced in 2016, complementing the standard type approval test of passenger cars in the laboratory. NO_X emissions are measured during a trip on the road with a PEMS. An initial monitoring phase was followed by a gradual introduction of the RDE. Since September 2019 all new passenger cars sold in Europe follow the RDE test protocol resulting in ultra-clean vehicles emitting as low as 20-30 mg of NO_X per km in most typical use and only reaching the limits in sever conditions of use. For more information on the RDE application please look at: https://ec.europa.eu/growth/content/new-and-improved-car-emissions-tests-become-mandatory-1-september_en.

To respond to the air pollution challenge, cities often take measures to reduce air pollution in areas with high traffic densities. Such measures are sometimes required to comply with the AQD, including access restrictions to limit transport emissions in the short term. The Commission's (EC, 2014) study on a European City Pass for Low Emission Zones (LEZs) showed that there is a patchwork of LEZ approaches and rules applied throughout the EU. The effectiveness of LEZs depends strongly on the way they are implemented, notably the modulation by Euro emissions class, the type of access control and particularly the number of exemptions granted.

Tools are available (i.e. Jensen et al., 2017) to model yearly, daily and hourly particulate matter, and nitrogen dioxide concentrations at street level, taking into account urban topography, emission performance of vehicles, the composition of the vehicle fleet, the daily activity patterns, and background pollution. These tools can be used to perform *ex ante* evaluations, to understand the impact of a LEZ on air quality. However, they require appropriate IT infrastructure and the input of detailed data. As a result, in many cases, municipalities wishing to put into place access restrictions do not have access to a simple tool to estimate the effects of such measures upon air quality before they are applied. Thus, they have no way to evaluate access restrictions, neither geographically nor as a function of emission performance.

To overcome this limitation, the Joint Research Centre (JRC) developed the SHERPA-City[1] tool (Degraeuwe et al. 2019). This simplified screening tool (see Annex 1 for details) mimics a Gaussian pollutant dispersion model, but with a much shorter calculation time. It can therefore be used to evaluate the impact of traffic management measures leading to reductions of emissions at the source.

In this study, an analysis of 30 urban European areas where many of the current exceedances occur is presented. SHERPA-City is used to identify the most relevant category of vehicles (diesel vs. gasoline? Passenger cars? Euro norms breakdown? etc…) in order to tackle the NO_2 air pollution problems most effectively.

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[1] https://integrated-assessment.jrc.ec.europa.eu

2 Objective and structure of this Air Quality Atlas

The main objective of this Atlas is to support policy makers in designing air quality measures to reduce yearly average concentrations of NO_2 in urban ambient air. This can be implemented through "Traffic Policies", i.e. "Low Emission Zones". We analyse the case of 30 cities in the EU with a focus on urban background levels, at a 20 meter spatial resolution; local or microscale traffic impacts are not explicitly considered, e.g. street canyon effects, accelerating or decelerating traffic at intersections etc... A future extension of this analysis will also include street canyon effects.

Because policymakers require information to prioritise their air quality strategies in terms of transport activities, a breakdown of "sectorial" contributions (i.e. diesel vs. gasoline, Euro norms) to urban NO_2 pollution from road traffic for each city is provided.

This study focuses on the impacts on concentrations of emission abatement measures, but does not assess other aspects such as implementation costs or social acceptability. This means that the emission reductions in terms of sectors and city area identified in this Atlas may not be the most cost-efficient, or the ones with the best social acceptance.

The Atlas is structured as follows. In the next chapter, we give a brief overview of the health impacts of NO_2. Then, the sources of NO_X in Europe are discussed, with transport, as the main source, presented in detail. A closer look at 30 urban areas in Europe follows; these selected urban areas are analysed considering sectorial and spatial source allocation. The SHERPA-city screening methodology followed by a discussion of its assumptions, limitations and associated uncertainties are presented in the Annexes.

3 Health impacts of NO_2 air pollution

According to the European Environmental Agency (EEA) the largest environmental risks to health from ambient air pollution are associated with particulate matter (PM), with an estimated 374000 attributable premature deaths[2] in the EU28 in the year 2016 (EEA, 2019). For NO_2, the estimates are of 68000 attributable premature deaths in the EU28 for the year 2016 (EEA, 2019). In addition to these direct effects, it is important to note that NO_2 also has indirect effects through its contribution to the formation of fine secondary particulate matter (secondary $PM_{2.5}$). 14000 (EEA, 2019) premature deaths are attributed to ground-level ozone (O_3) exposure. It is also possible to estimate the "years of life lost" (YLLs) for a given population, taking into account the age at which death occurs with respect to the standard life expectancy, giving therefore greater weight to deaths occurring at younger ages. The YLL values corresponding to the premature deaths cited earlier are 800, 100 and 30 YLL/10^5 inhabitants for $PM_{2.5}$, NO_2 and O_3 respectively (EEA, 2019).

Estimating the *burden* of air pollution and the *impacts* of emission reduction measures in terms of health is important, to communicate the relevance of air quality effectively to the public and the authorities. It is beyond the scope of this work to carry out a detailed health risk evaluation, nevertheless, it is useful to give a short overview while referring the reader to specific literature.

Adverse health effects of air pollution on both the short-term (occurring shortly after exposure) and the long-term (resulting from exposure over time) have been linked to several mortality and morbidity endpoints as summarised in Costa et al. (2014). More specifically for short-term, adverse effects of air pollution include exacerbation of asthma, effects on lung function, increase in hospital admissions for respiratory and cardiovascular conditions and mortality (Gowers, Miller, and Stedman 2014).

While for $PM_{2.5}$ long-term and short-term exposure and for NO_2 short-term exposure, there is enough data available to "*enable reliable quantification of the effects*", it is not that the case for NO_2 long-term exposure for which there is "more uncertainty about the precision of the data used for the quantification of the effects" (WHO, 2013). The most recent report on NO_2 by COMEAP (Committee on the medical effects of air pollutants (COMEAP) 2018) reviews the available evidence relating NO_2 long-term exposure to mortality. This report, interestingly, documents the full range of views of experts on the subject, both on areas where they reached a consensus and the ones that were most controversial.

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[2] People who die before reaching the standard life expectancy for a given gender and country.

4 NO_X emissions in the EU

4.1 The share of transport

According to the EEA (EEA, 2019), road transport continues to be the largest source of NO_X emissions (39% in the EU28) in 2016, followed by the energy production and distribution sector, and the commercial, institutional and households sector. However, the contribution of the road transport sector to population exposure to ambient NO_2 concentrations, particularly in urban areas, is considerably higher, because its emissions are close to the ground and distributed across densely populated area. For the cities analysed in this Atlas, the contribution of transport to the overall NO_X emissions (Figure 3, transport emissions are shown in yellow) is on average of 47%, with minimum of 20% for Lisbon (where high shipping emissions are reported) and maximum values of more than 70% (i.e. for Athens and Milan)[3].

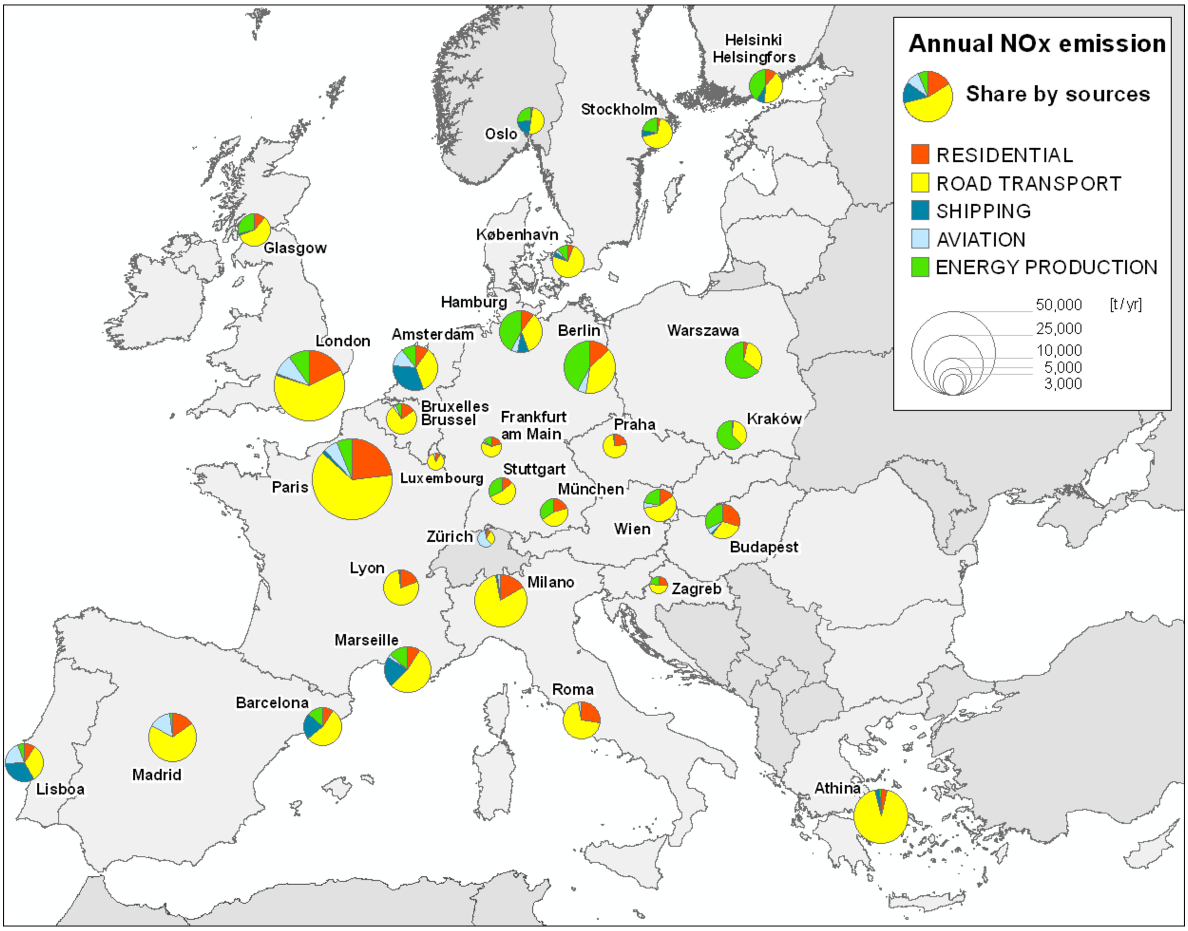

Figure 3: Sector share for NO_X emissions, in 2015. (Source: JRC, analysis based on EMEP gridded emissions).

It is important to note that while NO_2 is currently one of the most critical pollutants originating from the transport sector, it is not the only one. The development of

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[3] Emissions here refer to EMEP gridded emissions. Only the grids related to the urban areas (Functional Urban Areas, as the EC/OECD definition, see https://www.oecd.org/cfe/regional-policy/functionalurbanareasbycountry.htm) have been considered for this analysis.

transport and fuel technologies has been associated through the years to different pollution issues, as summarised in Box 3.

Box 3: Road transport and pollution: a historical perspective

The issues raised by exhaust emissions from the transport sector have always been a concern from various aspects.

Lead (actually tetraethyl lead) was introduced in the 1920s as an additive to gasoline to enhance engine performance. Its use sharply increased after 1950 and spread globally to reach a peak in the early 1970s. Despite early fears on its potential health impacts, no tangible effects could be demonstrated because its effects were too progressive and lead was finally phased out in Europe only around 2000. According to P. Landrigan et al. (The Lancet, 2018), lead was responsible for many more deaths than initially expected because of widespread environmental contamination and population exposure.

Volatile Organic compounds (VOC): In the 1950s, chemical processes leading to ozone formation were identified. As an important emission source of unburned VOC (about 4 times more than the industrial sector at the time), the transport sector was identified as one of the guilty actors. Exhaust emission limits were then imposed for this pollutant while emission limits on NO_X (the second key player responsible for O_3 formation) were set in the 1960s.

Sulphur: With the occurrence of acid rains in the 1970s, progress has been made to reduce the sulphur content from fuels. Sulphur in the fuel not only leads to undesirable sulphur oxide emissions, it also poisons the catalytic material used in the after-treatment system. The sulphur content of fuels have been reduced by a factor of 20 in 20 years.

Particulate matter: Due to incomplete combustion, diesel engines produce a variety of particles generically classified as diesel particulate matter. Diesel particulate filters (DPF) have been in use since 1985. They usually remove 85% or more of the sooty particles and can attain efficiencies approaching 100%. While particulate filters have solved the issue for diesel engines, a problem emerged with the particle number emissions of direct injection gasoline engines (GDI). Therefore since 2009 (Euro 5b) also particle number emissions per kilometre are limited.

Carbon dioxide: Road transport is now the largest and growing source of CO_2 emissions in Europe, accounting for one-fifth of all emissions. To fight climate change, carmakers must produce more efficient, low and zero-emission vehicles. In 2009 and 2014 respectively, the EU introduced legally-binding CO_2 standards.

Nitrogen oxides: Gasoline and diesel engines emit nitrogen oxides, NO and NO_2, generically abbreviated as NO_X. NO_X emissions have been regulated since the 1960s as they have harmful effects on human health, crops and ecosystems. Today it is impossible to comply with the limits without a modern after-treatment system consisting of catalytic converters and filters. Annex 3 provides information on currently available technologies.

For more details, see also “Airvore ou la face obscure des transports”, L. Castagnede, Ecosocietes.

While the direct effects of NO_X on human health can be attributed to a large part to local NO_X emissions, therefore (mostly) to transport, this is not the case with indirect effects (NO_X emissions leading to the formation of particulate matter). Particulate matter, characterised by much longer residence time in the atmosphere, contains contribution of various emission pollutants (PM, NO_X, VOC, NH_3, …). They originate from various sources such as transport, industry, agriculture and heating. Based on the SHERPA tool (Thunis et al., 2016), the contribution from the transport sector (in particular its NO_X emissions) to annual total PM concentrations is shown in Figure 4. For the cities analysed in this Atlas, the contribution of transport NO_X emissions to the overall annual $PM_{2.5}$ concentrations in the so-called "Functional Urban Area" is on average 4% with a minimum value of 1% in Athens and maximum values of 10% in Luxembourg and of 8% in Lyon.

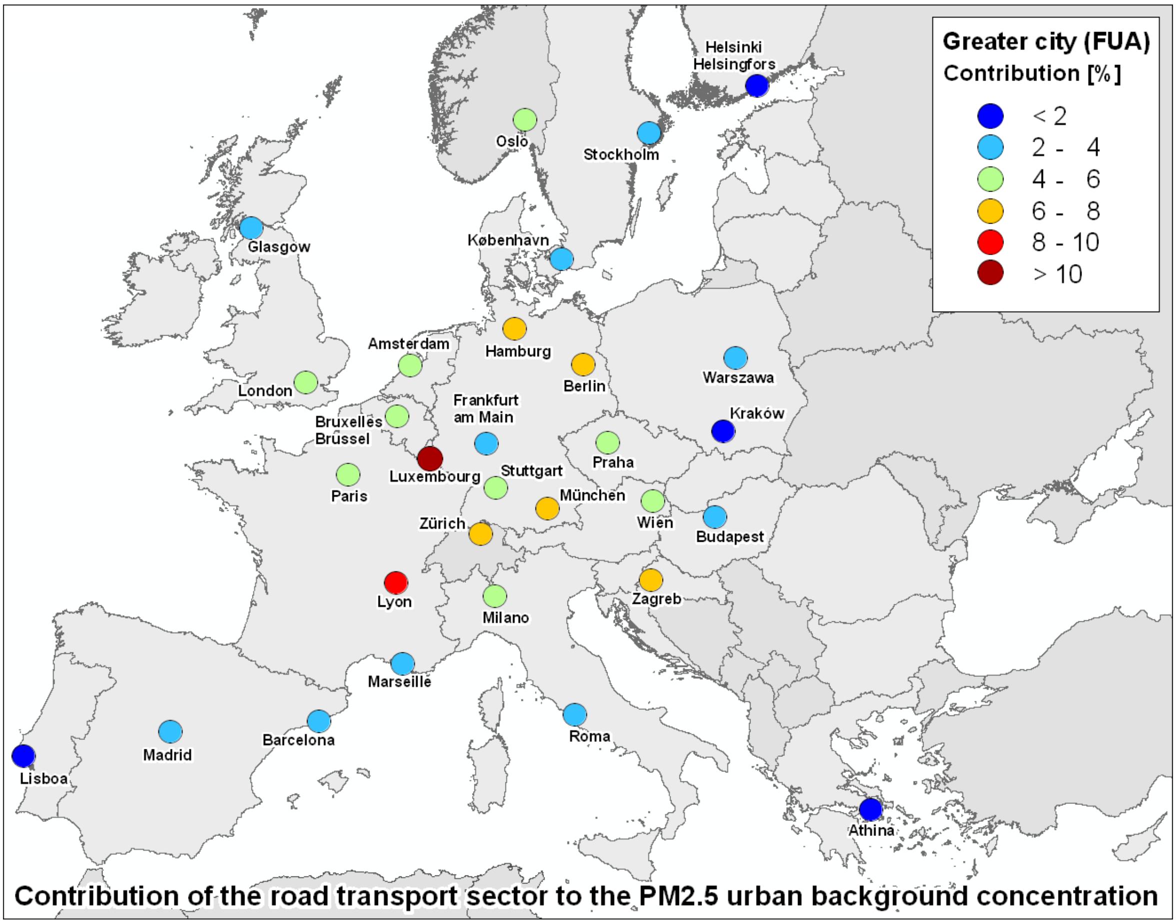

Figure 4: Contribution of the NO_X road transport emissions to the PM2.5 urban background concentration (indirect effects). Each dot represents one of the 30 cities considered in this study (using the Functional Urban Area definition, as from OECD, 2012). Functional Urban Areas consist of the core city plus the wider commuting zone, defined as the surrounding travel-to-work areas where at least 15% of the employed residents work in the city.

4.2 A breakdown of transport NO_X emissions in the EU

In this work, the analyses at city level are based on consistent EU-wide emission datasets. OpenTransportMap and OpenStreetMap were used to retrieve a spatial view of the road network and traffic flows, respectively. A dedicated dataset (provided by EMISIA SA, https://www.emisia.com/) gives the details of fleet composition and emissions per country.

In this section, we focus on the NO_X emissions at country level and analyse these emissions in terms of national fleet characteristics and usage (km driven).

As shown in Figure 5, the national NO_X emissions per capita (circle size) differ among countries with Luxembourg, Ireland, Austria, Belgium and Slovenia showing higher values. Most of the high values are correlated with a higher number of kilometres driven per capita (country shading). However, the number of kilometres driven is not the only factor explaining high emissions, which can also be due to a high share of diesel cars in the country (pie charts) or by a larger share of older cars as indicated by the EURO norms breakdown.

With the exception of some countries (e.g. Greece), diesel cars generally represent the largest share in terms of fuel used. Furthermore, the breakdown in terms of Euro norms (Figure 6) clearly shows an East-West divide, with a larger proportion of newer cars in the West. Many of the eastern countries also drive fewer kilometres per capita annually. It is worthwhile discussing the case of Luxembourg. As km-driven and emission values are derived from national statistics on fuel sold, so-called “tank-tourism” (incentivised by lower fuel prices in the country) combined with the small population lead to artificially high values for this country.

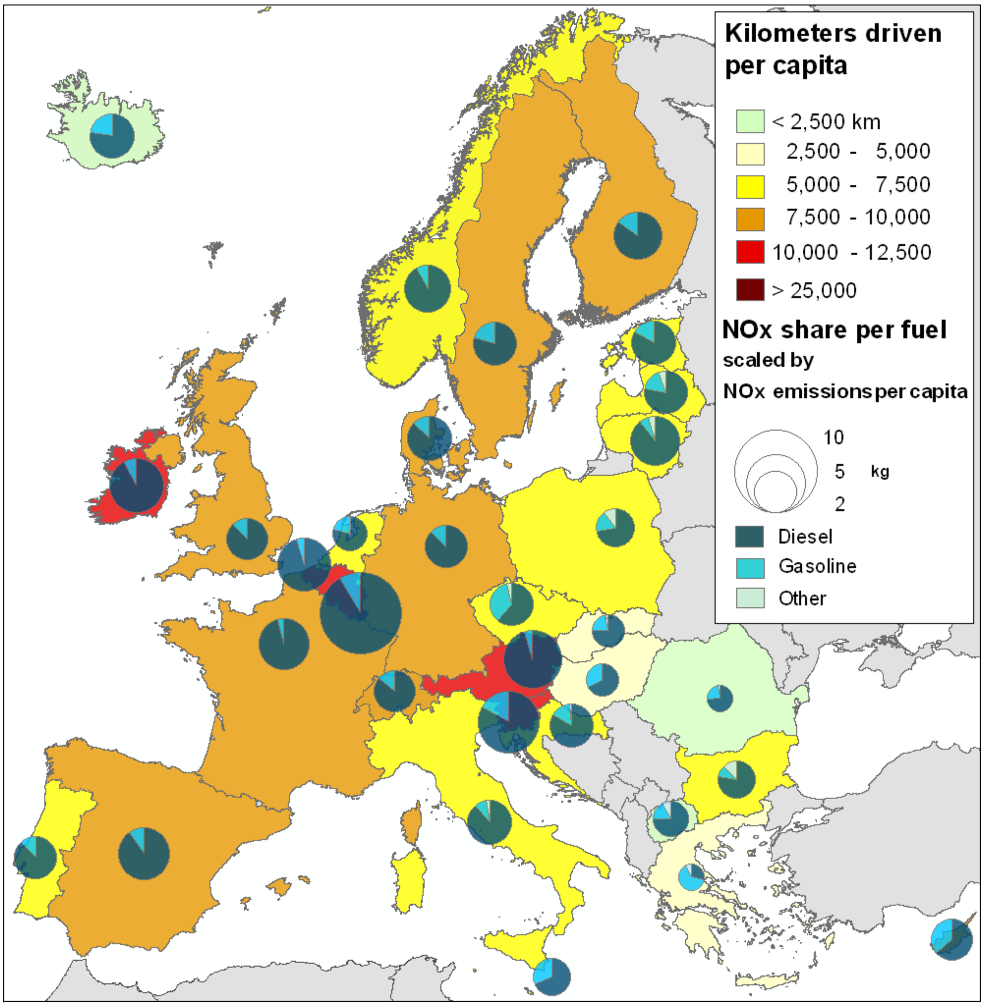

Figure 5: Country share of the NO_X emissions per type of fuel (diesel, gasoline and other), correlated with kilometers driven per capita (country shading).

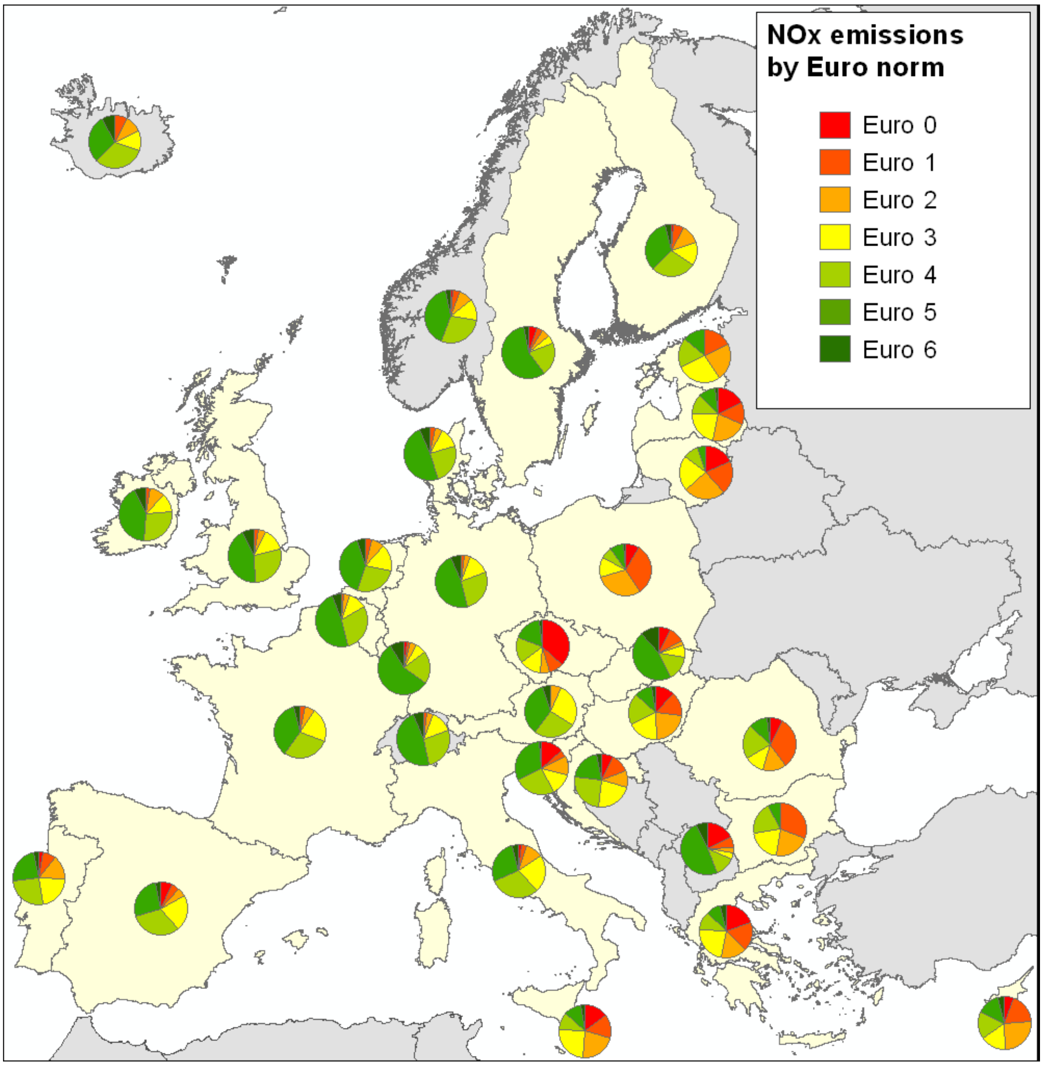

Figure 6: Country share of the NO$_X$ emissions, by Euro norm.

5 A closer look city by city

The detailed results for 30 cities in Europe can be found in the Annex.

In terms of the spatial dimension, for each city two distinct areas are considered: (1) an "**Inner Area"**, corresponding to the city area where "traffic policies" might be applied, and (2) a complementary one, corresponding to the remaining urban area for which measures are not applied.

For cities that have a Low Emission Zone (LEZ) in place, this LEZ is selected as a basis for defining the city Inner Area. In general, the following process was followed. We started with zones that have an approximate radius of 5 km around the city centre and tuned the exact boundaries so that major roads or highways are excluded. It is important to note that given this rather subjective procedure, **the city Inner Area considered in this study is not related to any formal low-emission area**.

For each city a modelling domain, where SHERPA-City simulations are performed, is defined. This domain is approximately 20x20 km wide for each city, except for London where a bigger domain is used.

The final choice of cities included in this report has been driven by considering their representativeness and relevance. While representativeness would lead to the selection of most of the EU28 capital cities (even if considering mainly the cases where limit values are not respected) to obtain a good geographical coverage and capture a large diversity of situations across Europe, we have added cities in several countries where the NO_2 concentrations are more critical (e.g. Germany). One of the main limitations of the SHERPA-City approach lies in its emission input data, in particular in the way the national data (network, fleet volume…) are disaggregated spatially over cities. Furthermore, existing traffic regulations are not accounted for in the analysis, and for each city, default dataset estimated with an EU wide approach are used.

However, the SHERPA-City methodology can suggest the "direction/amount of concentration change" due to various mobility measures. The "contributions" calculated with SHERPA-City correspond to the impact on the annual NO_2 concentration that occur when emissions from a particular fleet or spatial scale are "switched off". SHERPA-City mimics the "dynamic" responses of an air quality dispersion model for these emission reductions.

More in detail, a "city fiche" (presented in the Annex) is associated to each city.

The first part of the fiche (top, left) provides information regarding the "Inner Area" (the area for which traffic reduction measures are implemented is shown in yellow in the Figure), the location of the urban area and the geographical extension of the urban area.

The second part of the fiche (top right) provides information on measured NO_2 concentration levels and on their compliance with EU (AQD) standards. The histograms in each fiche provides an overview of the reported NO_2 concentrations in the selected cities (EEA, http://aidef.apps.eea.europa.eu) for 2016, while the colour coded dots indicate the values measured at all monitoring stations (background stations on the left and traffic stations on the right histograms) located in the urban area (green: below guidelines: red: above limit values). As the source allocation results shown in the Atlas (middle Figure) correspond to "average urban background concentrations", these station' histograms can provide qualitative information on the potential "street increment" for a given city.

The central panel of the fiche contains the summary "source allocation" diagram. This diagram shows the spatial (along the vertical axis) and sectorial (along the horizontal axis) origin of the contributions to the average NO_X concentrations inside the Inner Area. All values are expressed as relative percentages of the urban concentration, averaged over the Inner Area. Fractions of the NO_X concentrations (not NO_2) are reported because NO_X concentrations changes are proportional to the NO_X emission changes, whereas this is not the case for NO_2[4]. The results in this section show contributions to NO_X of different fuels (diesel, gasoline, ...), different vehicle types (cars, buses, …), etc. In this graph, "Inner area traffic" refers to the contributions due to the emission reductions in the Inner area tested. The "Outer area traffic" is linked to the emissions outside the Inner Area (complementary city area) but inside the modelling domain defined in the top-left box of the city fiche. Finally, "other emissions" represent contributions from all emissions not related to traffic within the modelling domain, plus contributions from all emissions originated from outside the domain.

The bottom panel shows the national statistics related to the gasoline (left) and diesel (right) emissions. In particular, the colours represent the different Euro Standard, the x-axis the vehicle kilometre driven, the y-axis the NO_X emission factors, while the area of the coloured rectangles is equal to the emissions of a given Euro Norm (computed as the product of kilometers driven and emission factors).

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[4] When the NO_X concentration decreases, the NO_2 fraction increases. This means that the NO_2 concentration reduction will always be a bit smaller than the NO_X reduction. The difference is negligible at high NO_X levels and more pronounced at low NO_X levels.

6 Conclusions

Thanks to the analysis performed in this study it is possible to derive the following conclusions:

- The NO_2 issue is city-specific and measures to reduce its impacts depend on the relative contributions of the local and background sources (here intended as everything except local transport). For example, some cities (e.g. Hamburg, Barcelona) have an important share of emissions originating from harbour activities, therefore limiting the impact of road transport measures.
- When the local share of transport is important, NO_2 in cities is mainly originating from diesel vehicle emissions. So, diesel vehicle emissions are a major concern in countries and cities where the share of diesel is largest.
- NO_2 concentration can be efficiently reduced by the application of "Traffic Policies" provided these zones do not merely move the vehicles to other routes in the city (exporting the pollution outside the "Inner Area") but instead reduce transport emissions by promoting the use of less polluting vehicles (electric vehicles) or soft modal transports (cycling, walking…).

It is worth reminding that policy measures addressing air pollution should follow a multi-pollutant approach aiming at addressing the widest possible spectrum of compounds at the same time. The hypothetical traffic limitations discussed in the present atlas are indeed expected to be beneficial also to other pollutants such as PM, CO and Ammonia, without forgetting the positive impacts in terms of noise pollution.

It is also important to note that some measures might have negative impacts. The substitution of diesel with gasoline cars could lead to increased greenhouse gas emissions (as i.e. CO_2). Along the same line, while the increasing share of electric vehicles is expected to contribute to control NO_X within cities, their overall impact on the climate system will strongly depends on their life cycle design and on the energy mix to generate electricity.

In conclusion, local authorities are advised to integrate the results provided in this Atlas with other locally produced analysis, to design a set of measures that tackles the complexity of the air quality issues while at the same time managing the interactions with other policies, starting with climate change mitigation.

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List of abbreviations and definitions

AAQD	Ambient Air Quality Directive
AQG	Air Quality Guideline
CO2	Carbon Dioxide
DOC	Diesel Oxidation Catalyst
EEA	European Environmental Agency
EGR	Exhaust Gas Recirculation
EU28	European Union (28 Member States)
JRC	Joint Research Centre
LEZ	Low Emission Zone
LNT	Lean NO_X Trap
NH3	Ammonia
NO_X	Nitrogen oxides
PEMS	Portable Emissions Measurement Systems
PM	Particulate matter
$PM_{2.5}$	Particulate matter with diameter inferior to 2.5 µm
RDE	Real Driving Emissions
SCR	Selective Catalytic Reduction
SHERPA	Screening for High Emission Reduction Potential on Air quality
VOC	Volatile Organic Compounds
WHO	World Health Organization
YLL	Years of Life Lost

List of Figures

Annexes

Annex 1. The SHERPA-City methodology

SHERPA-city is a simplified approach that allows municipalities to test the impact of traffic policies on air quality. The tool runs "fast", as the impact of a set of measures on air quality is produced within minutes. Furthermore, usually data collection in this field is difficult and time consuming, especially if measures require a high level of spatial and temporal detail (detailed traffic flow information, street aspect ratios…). SHERPA-City operates with EU default data set that cover the entire EU28, and so one can easily start to test traffic regulation measures on air quality, for a given city.

Approach

To compute concentrations from an emission field, the SHERPA-City uses a "kernel approach" derived from a Gaussian model.

A Gaussian model uses an analytic function to calculate the concentration at a given distance from the source. The concentration at one given location is obtained as the sum of contributions from all emission sources. The required inputs are wind speed, wind direction, emission strength and the release height. The Gaussian model is well suited for regions with a uniform wind field; such as with a flat geography. Calculations must be done for each hour of the year and computations times are about a day.

Based on runs performed with the Gaussian Model (using different meteorological fields depending on the considered area in Europe) "kernels" are then build for SHERPA-city. In the context of SHERPA-City, kernels simulate the concentration distributions in the modelling domain generated by a single point/line/surface source, as approximated from the full dispersion Gaussian model. These kernel distribution are then applied for each source available over the domain, finally creating the full concentration field due the considered emission scenario.

Input data

The following data are used as input for SHERPA-city:

- *Road network*: Road network and road types ("motorway", "secondary road", "residential" and "living street") are obtained from Open Street Maps (OSM).
- *Vehicle fleet*: vehicle type, fuel, vehicle size and Euro norm are provided by EMISIA (https://www.emisia.com/), done collecting national statistics.
- *Annual Average Daily Traffic (AADT)*: AADT are derived by the Open Transport Map (http://opentransportmap.info/) model, rescaling the national values to match official estimates.
- *Emission factors* for transport are derived from EMISIA and SYBIL. SYBIL is a software tool used world-wide to calculate air pollutant and greenhouse gas emissions from road transport (https://www.emisia.com/utilities/sibyl/).

Other aspects

Although dispersion modelling and input data form the core of the modelling approach, other important aspects need to be considered:

- *Background pollution*: The transport of polluted air from country/regions to the city generates a background concentration level that needs to be accounted for in the city-scale modelling. For the results presented here, SHERPA-city background is based on EMEP simulations (meteorological year used: 2015) at roughly 10 km resolution. The "external contribution", i.e. all NO_X sources except local NO_X from traffic, is evaluated by differencing 2 EMEP simulations: the basecase and a simulation without local traffic emissions. This is shown in grey on the city-fiche. The remaining local NO_X from traffic is then spatially divided into "inside and outside the Inner Area".
- *Chemistry*: In the reference method (full Gaussian) the chemical equilibrium between NO_2, NO and O_3 ($NO + O_3 \leftrightarrow NO_2 + O_2$) is calculated every hour. In the simplified SHERPA-city kernel approach, dispersion is applied to NO_X and an empirical measurement-based correlation is used to retrieve the NO_2 concentration from the NO_X concentration (Düring et al., 2011). The parameters of the empirical correlation are adjusted to match the NO_2 fraction of the basecase EMEP run. The reason behind this choice is the fact that NO_X behaves as an inert gas and its dispersion is well predicted with a Gaussian dispersion model (concentration is proportional to the NO_X emissions). In contrast, the share of NO and NO_2 is a non-linear phenomenon that depends on the absolute NO_X concentration and the ozone level.
- *Street canyons*: Busy streets with high buildings are the most problematic areas in cities in terms of exposure to air pollution. Pollution from traffic is retained between buildings and leads to high concentrations. Factors like building heights, traffic intensity, meteorology and fleet composition become keys to account for these effects. Currently, SHERPA-City models "roof-top" concentrations, while "street canyons" are still not taken into account.

Annex 2: Uncertainties and limitations

- *Indirect effects of a Traffic Policy (in this Atlas, applied over the Inner Area)*: If a policy is implemented, emissions inside the Inner Area are reduced but emissions in the surrounding of the Inner Area most probably change as well, and dirty traffic is diverted somewhere. Close to the Inner Area the fleet might be similar to the fleet inside but further away the fleet might get dirtier. This issue is not taken into account in this work.

- *The underlying Gaussian model*: the Gaussian model works with limitations in cases of complex orography. This aspect should be considered when assessing the situation in cities characterised by such features.

- *Data reported as relative fractions*: past modelling inter-comparison exercises (e.g. CityDelta, EuroDelta, Cuvelier et al., 2007, Thunis et al., 2007) showed that relative fractions, i.e. concentration change divided by concentration, are generally more robust than absolute values of concentration. This is because concentration changes and concentrations are generally correlated (an overestimation of the concentration is likely to lead to an overestimation of the concentration change as well). All results are therefore expressed in terms of relative fractions.

- *Emissions and traffic estimation*: the results presented here strongly depend on the quality of the underlying emission inventory. In the case of this work, emissions are computed based on the AADT (Annual Average Daily Traffic) as provided by Open Transport Map (http://opentransportmap.info/). As the national values from Open Transport Map were lower than the national estimations, a rescaling of the AADT has been implemented to match the national estimates. This AADT uncertainty should be taken into account when analysing the results.

Annex 3: After-treatment options to control emissions

The first NO_X emission limits, introduced by Directive 77/102/EEC (European Commission, 1977), became progressively more stringent since then. It is nowadays impossible to comply with the limits without a modern after-treatment system consisting of catalytic converters and filters.

The formation of NO_X during the combustion process is unavoidable. Nitrogen (N_2) and oxygen (O_2) that do not usually react in the atmosphere, do so at the high temperatures reached during combustion. Therefore, the first strategies to reduce NO_X were to reduce the combustion temperature (via an Exhaust Gas Recirculation, EGR, or by delaying the injection). Unfortunately, an EGR leads to more particulate formation and a slightly higher fuel consumption, while delaying the injection reduces the combustion temperature but also the fuel efficiency.

In recent years, the automotive industry introduced a series of after-treatment systems to decrease their emissions, and fulfil the Euro 6 standards.

The technology depends in the first place on the fuel: diesel or gasoline. Indeed, the composition of the exhaust gases of a gasoline and a diesel engine are very different. While a gasoline car burns a stoichiometric fuel-air mixture (exactly enough oxygen to burn all the fuel), a diesel engine injects an amount of fuel in the compressed air that is proportional to the power demand (there is still a lot of oxygen in the exhaust gasses, especially at low loads).

For gasoline cars, a three-way catalyst is used to clean the exhaust gas, i.e. convert the unburned hydrocarbons and carbon monoxide into CO_2 and water, while reducing the NO_X into nitrogen and oxygen.

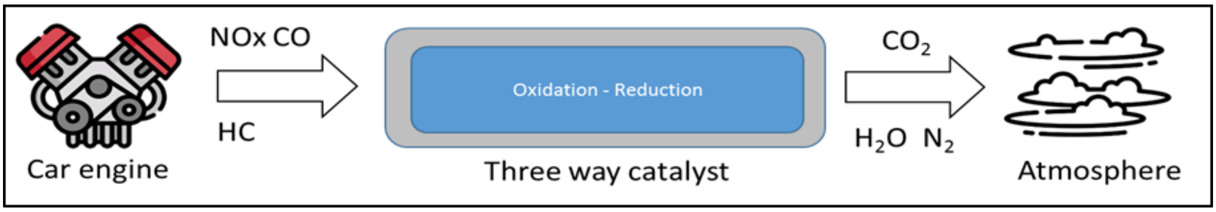


Figure 7: Three way catalyst of a gasoline engine.

For diesel cars, the diesel oxidation catalyst (DOC) oxidises the unburned hydrocarbons and carbon monoxide (easy task with the available oxygen). The main challenge is then to reduce NO_X, a difficult task in an oxygen rich environment. The two technologies employed today to reduce NO_X are the Selective Catalytic Reduction (SCR) and the Lean NO_X Trap (LNT).

The SCR includes a reservoir containing an aqueous synthetic urea solution (NH_2-CO-NH_2) which becomes ammonia after thermal hydrolysis of the urea solution injected into the system on a catalyst surface. The SCR reduces NO_X emissions by reacting the NO and NO_2 with NH_3 into N_2 and water. A SCR working in proper conditions (temperatures between 300 and 400 °C) can eliminate 70 to 80% of the NO_X, at the cost of filling up the urea tank regularly.

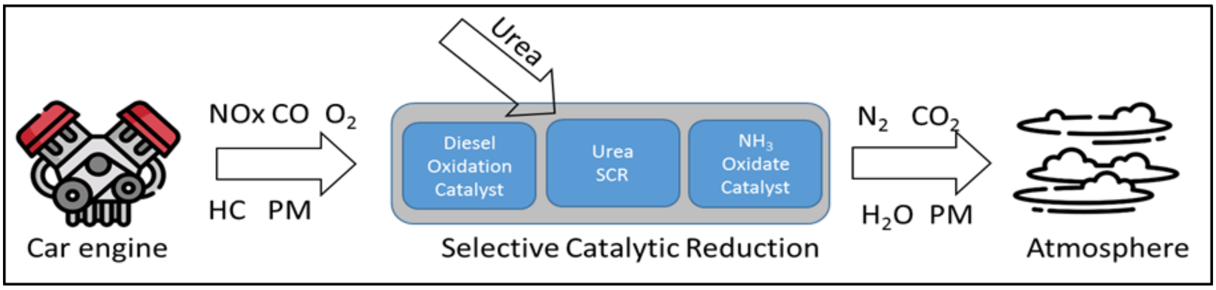


Figure 8: SCR system of a diesel engine

A LNT system operates in two phases: storage and regeneration. NO is first oxidised to NO_2 on a noble metal catalyst. Then NO_2 reacts with an adsorbent coating on the catalyst. When the adsorption capacity is reached, the system is regenerated during a period of fuel rich engine operation, producing CO. This CO reacts with NO_2 to N_2 and CO_2. A LNT requires periodic regenerations, to remove the sulphur stored in their coating, at the cost of an increased fuel consumption.

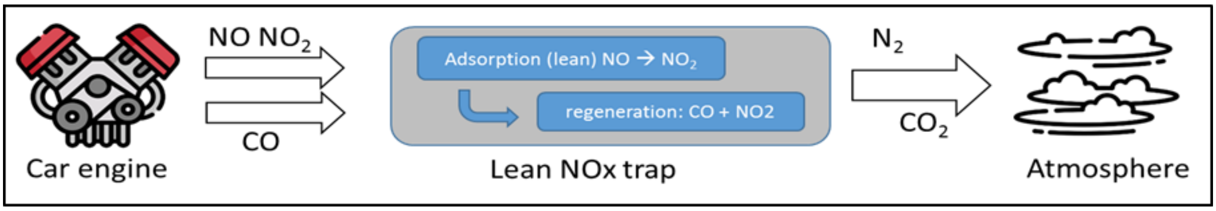


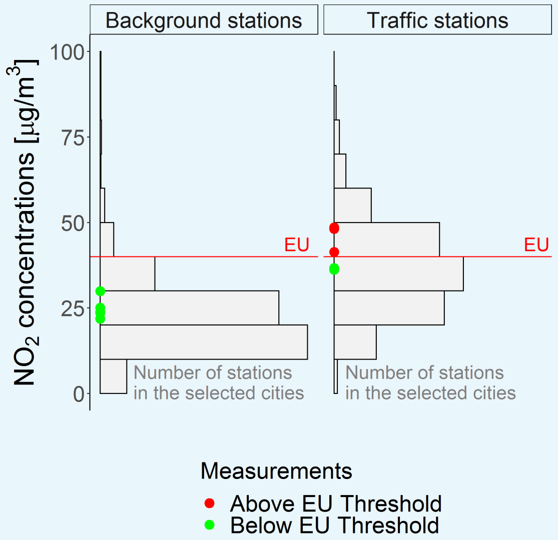
Figure 9: Lean NO_X trap for a diesel engine.

Annex 4: A closer look city-by-city (30 city-fiches)

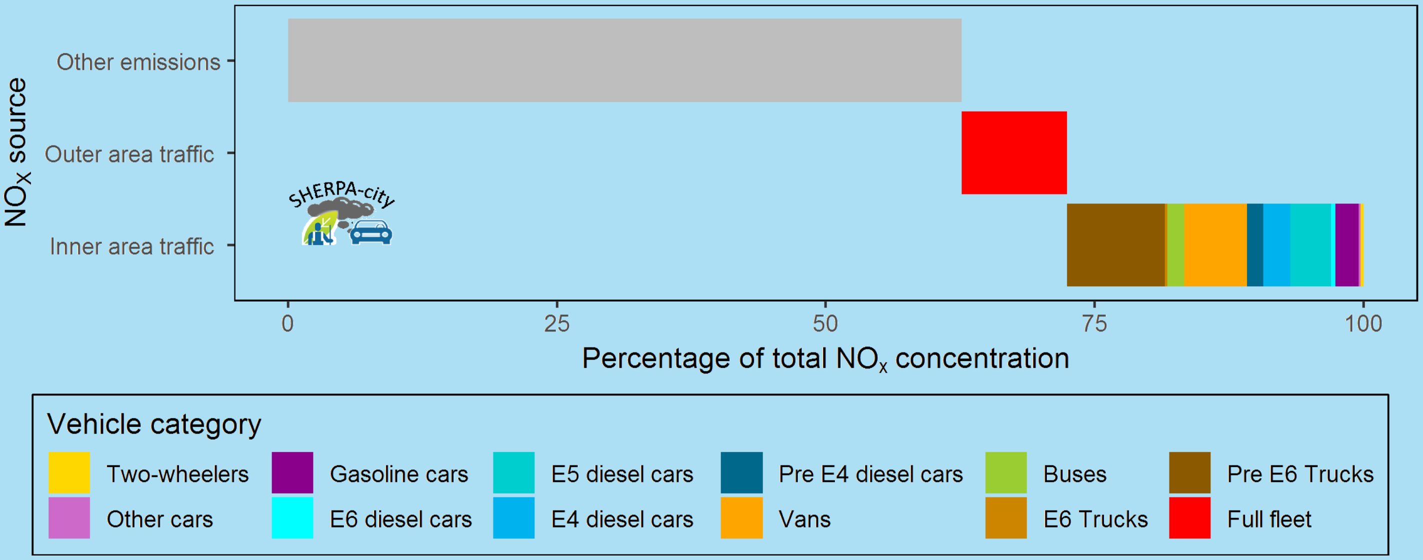
Amsterdam (Netherlands)

Inner (yellow) **and Outer** (white) **Area definition**

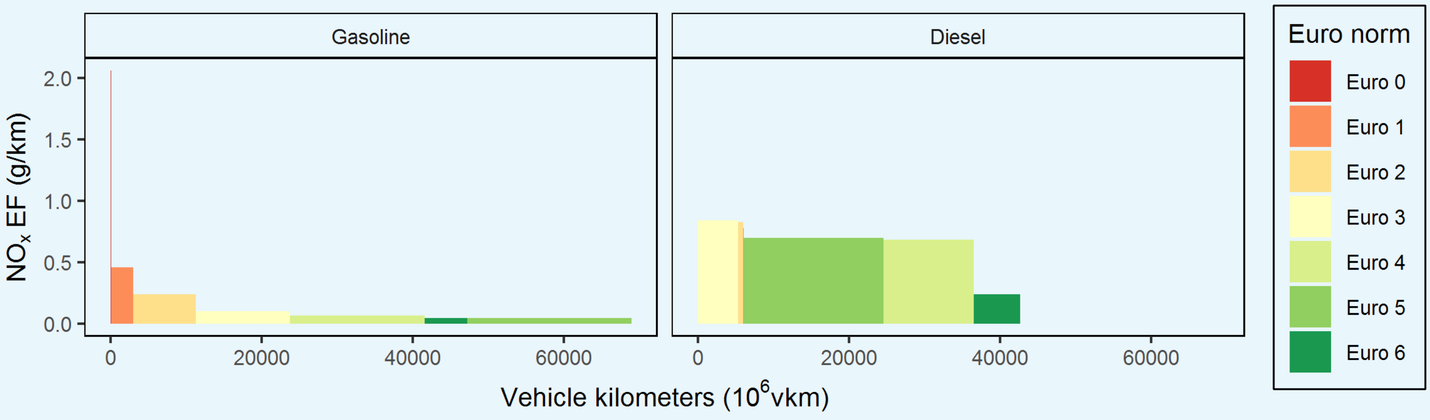
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

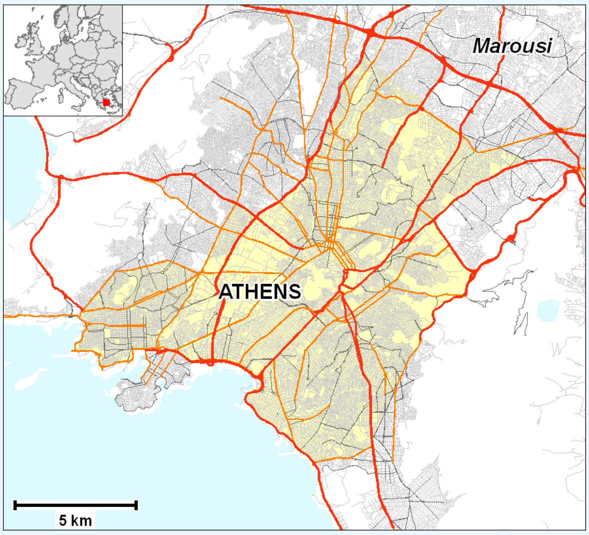


National emissions per fuel and Euro norm (passenger cars)

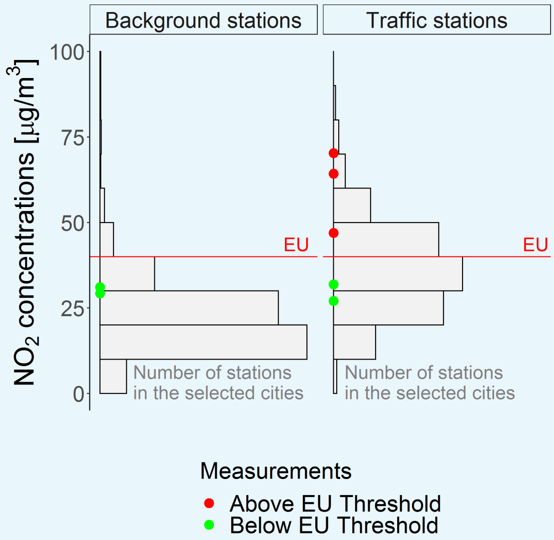


Athina (Greece)

Inner (yellow) and Outer (white) Area definition



Yearly average concentration (2016)



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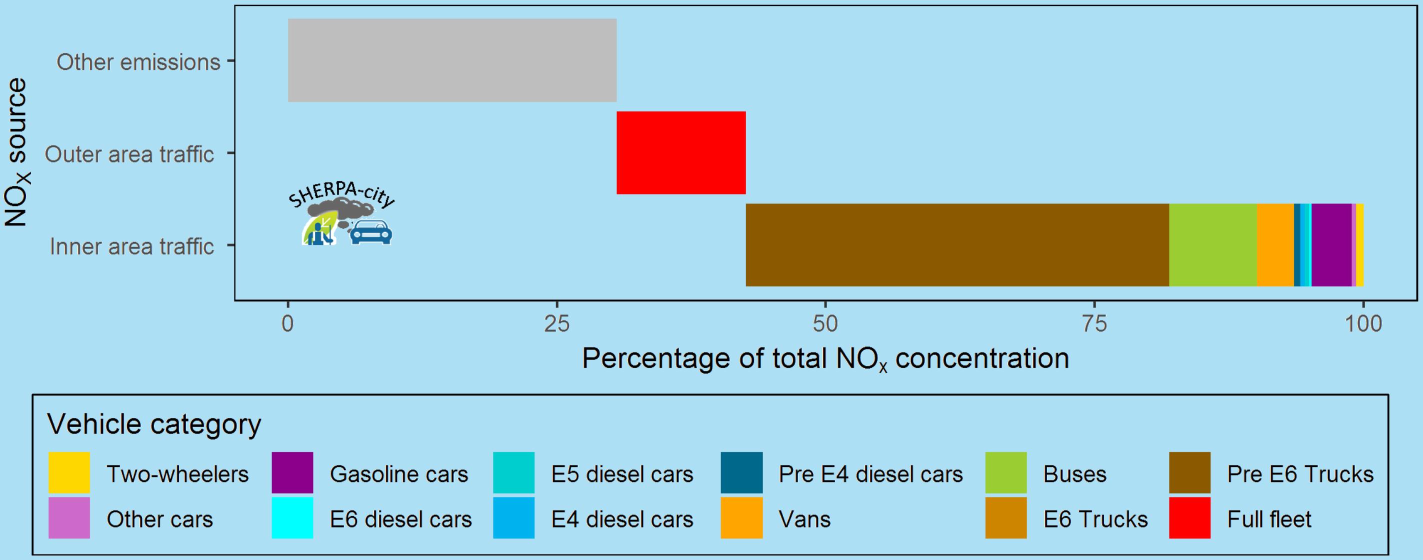
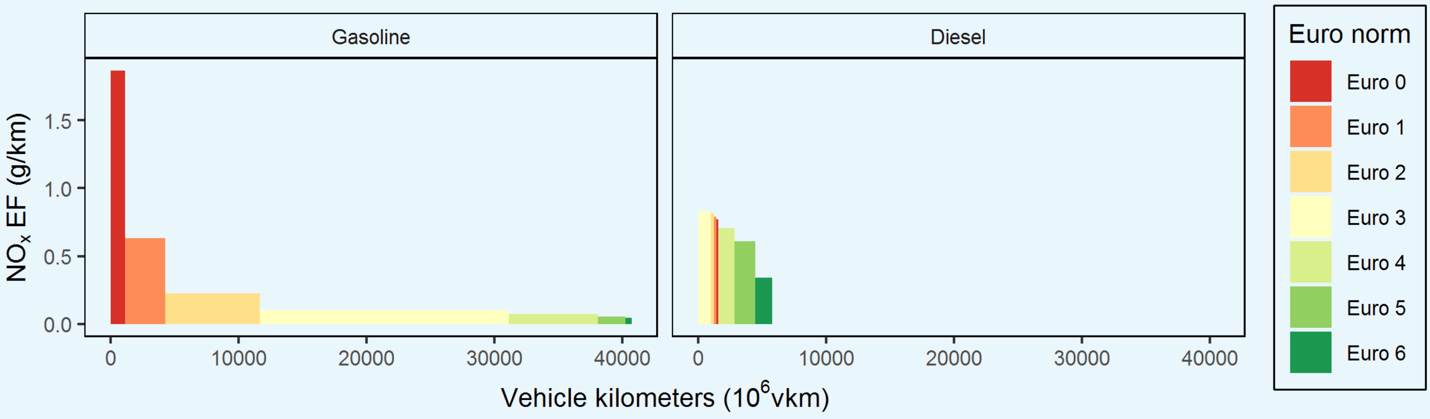


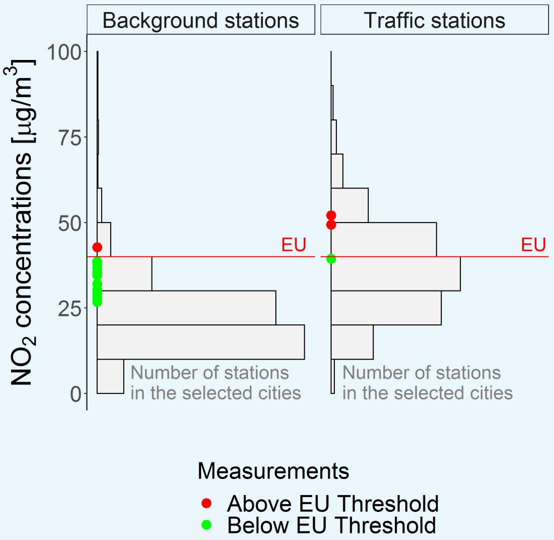
National emissions per fuel and Euro norm (passenger cars)



Barcelona (Spain)

Inner (yellow) **and Outer** (white) **Area definition**

Yearly average concentration (2016)



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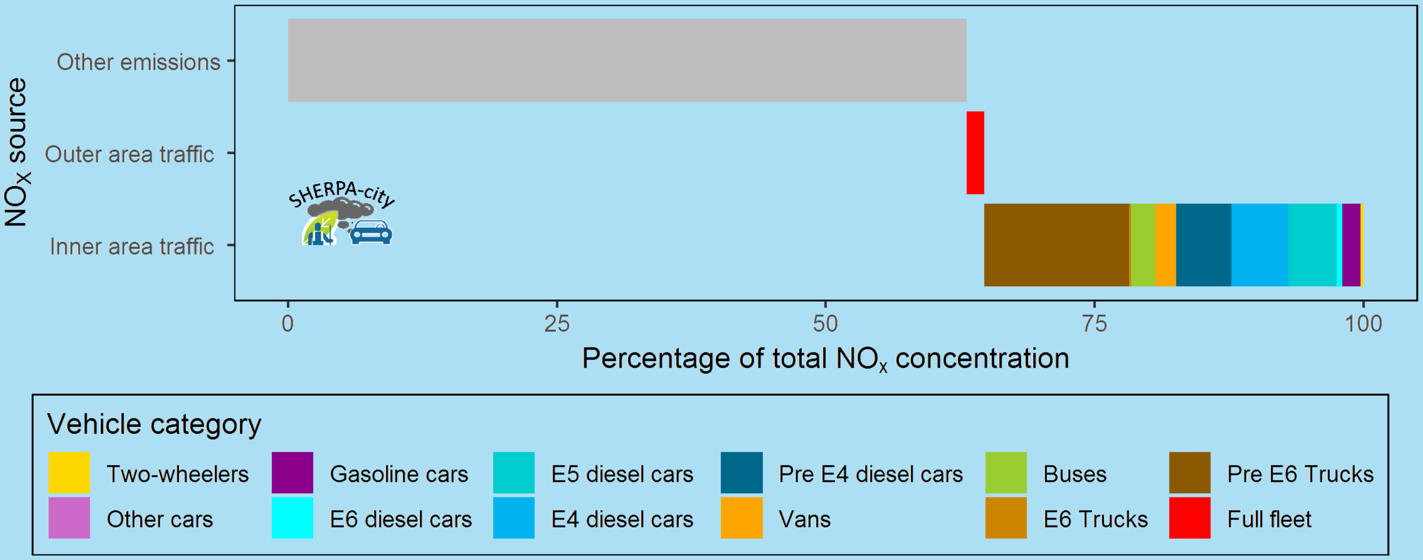
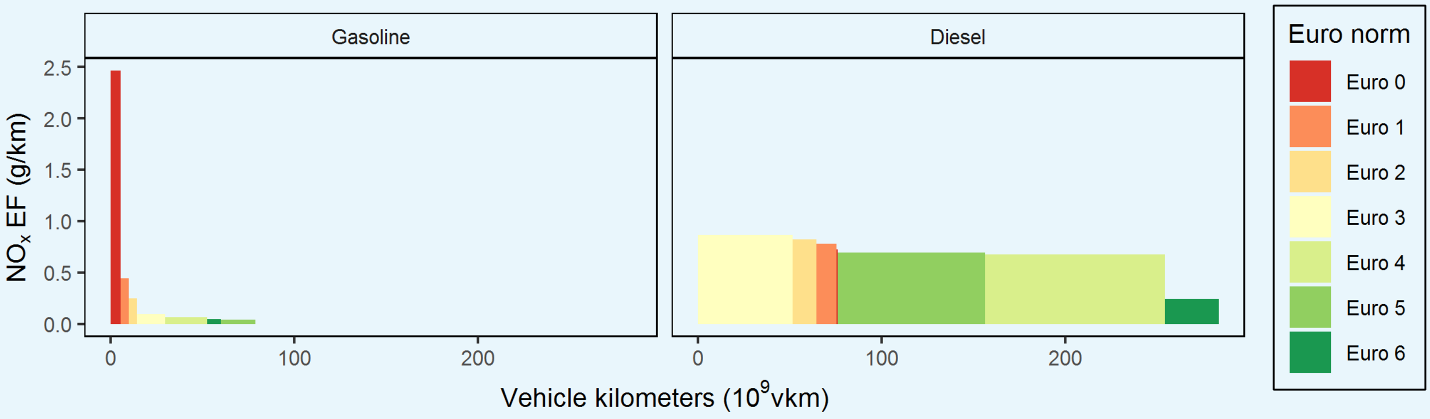
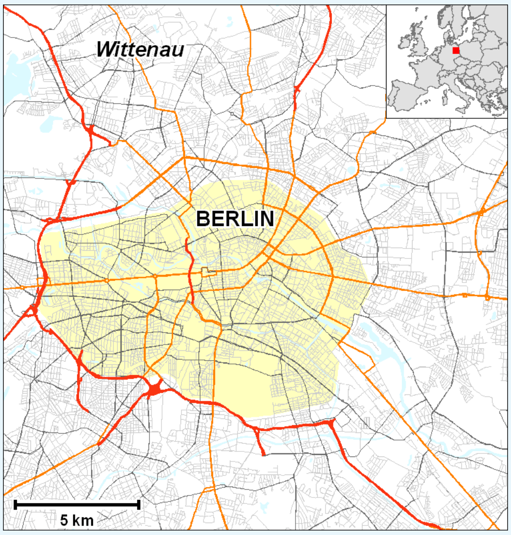


National emissions per fuel and Euro norm (passenger cars)

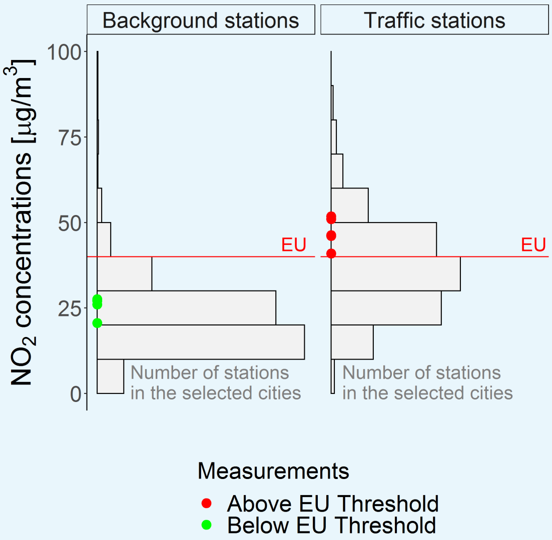


Berlin (Germany)

Inner (yellow) **and Outer** (white) **Area definition**



Yearly average concentration (2016)



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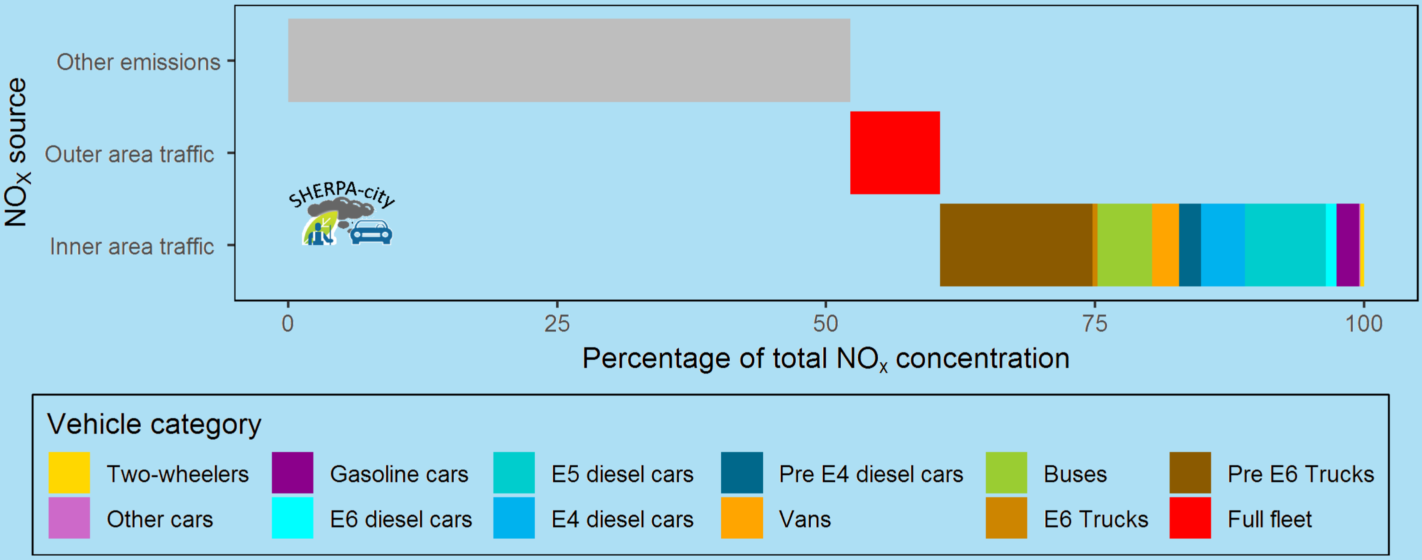
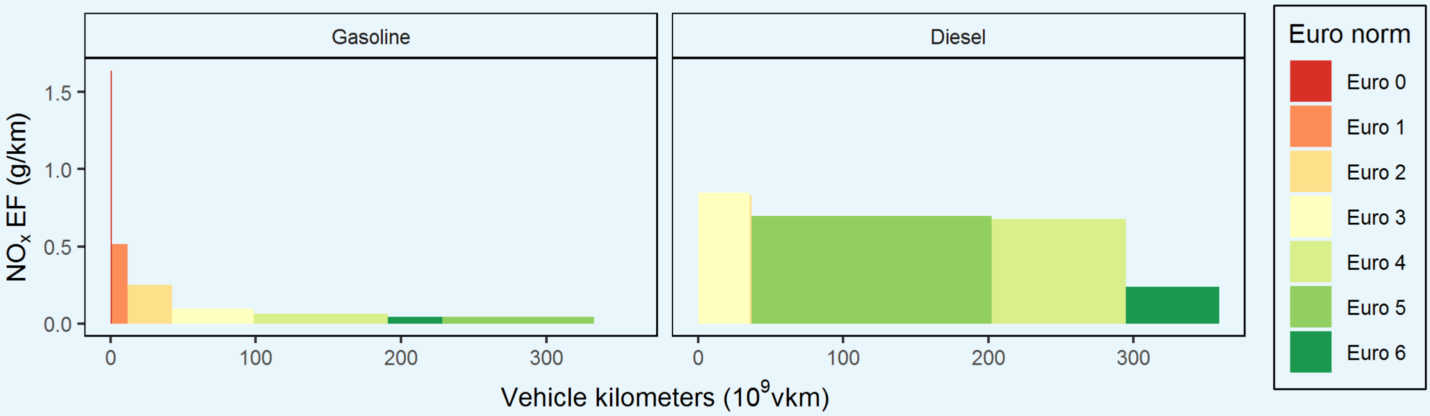
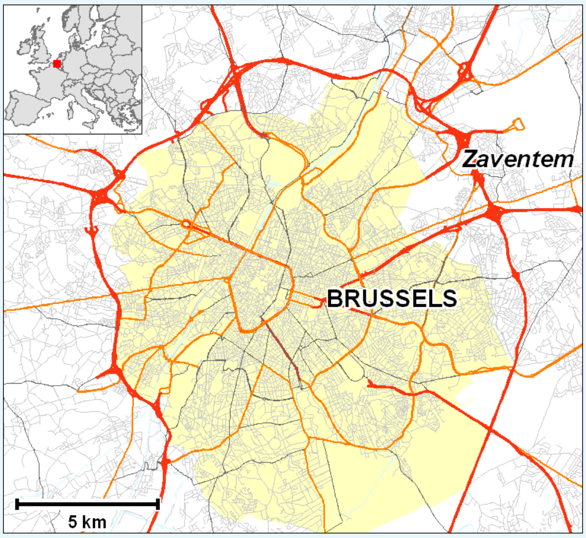


National emissions per fuel and Euro norm (passenger cars)

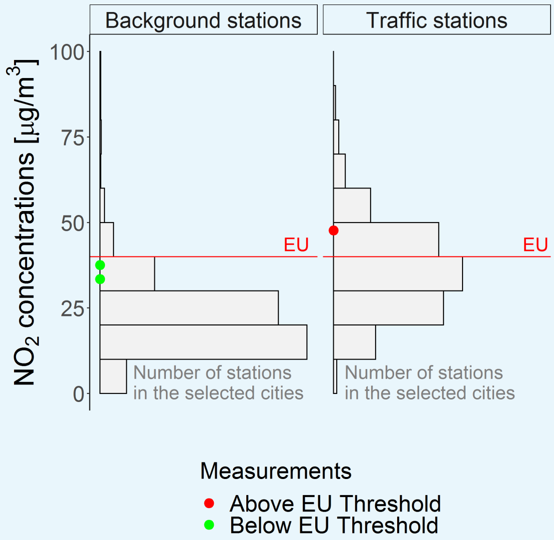


Brussels (Belgium)

Inner (yellow) **and Outer** (white) **Area definition**



Yearly average concentration (2016)



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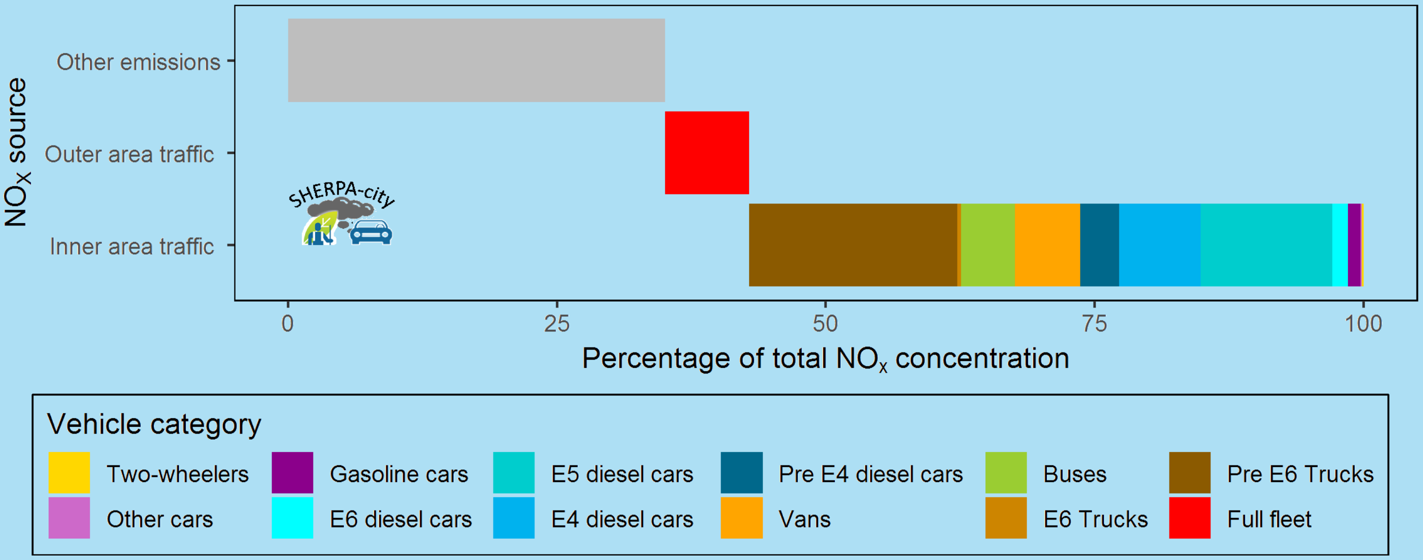
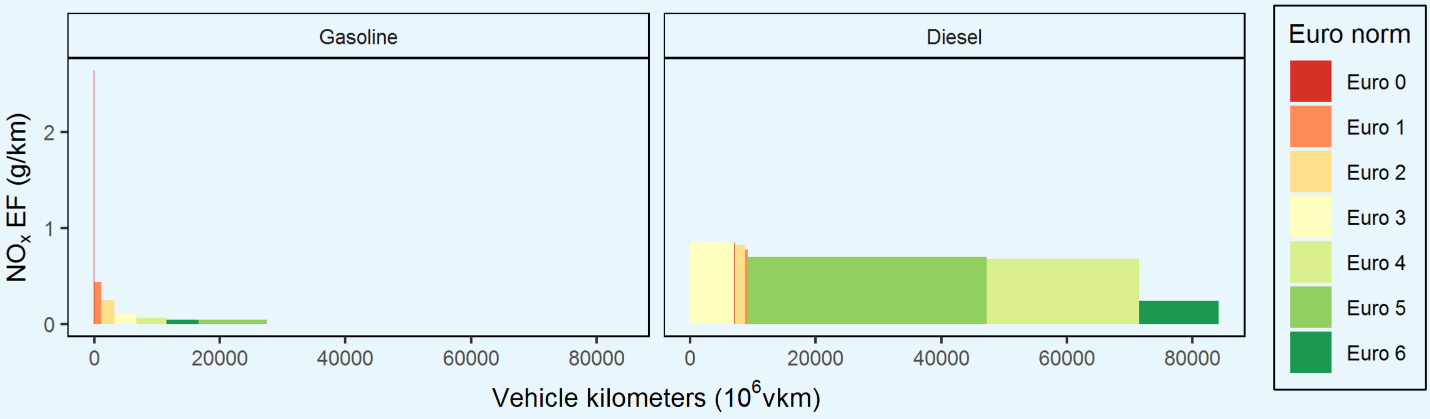
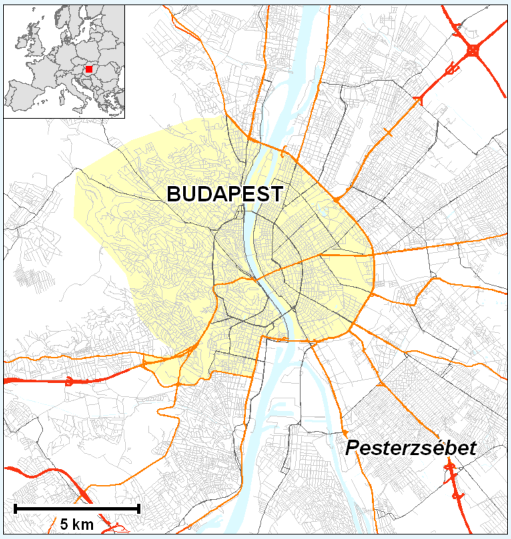


National emissions per fuel and Euro norm (passenger cars)



Budapest (Hungary)

Inner (yellow) **and Outer** (white) **Area definition**



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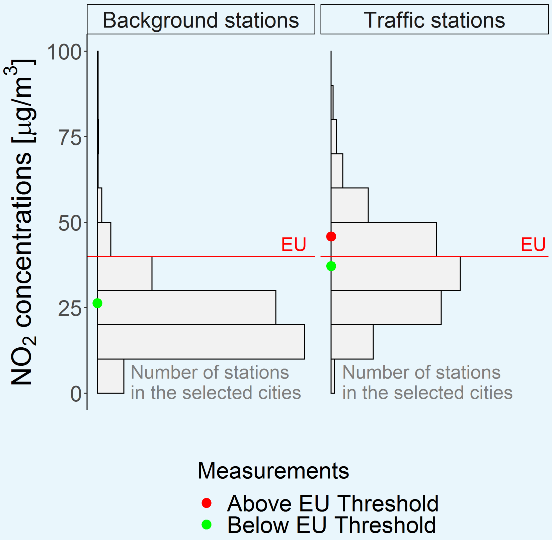

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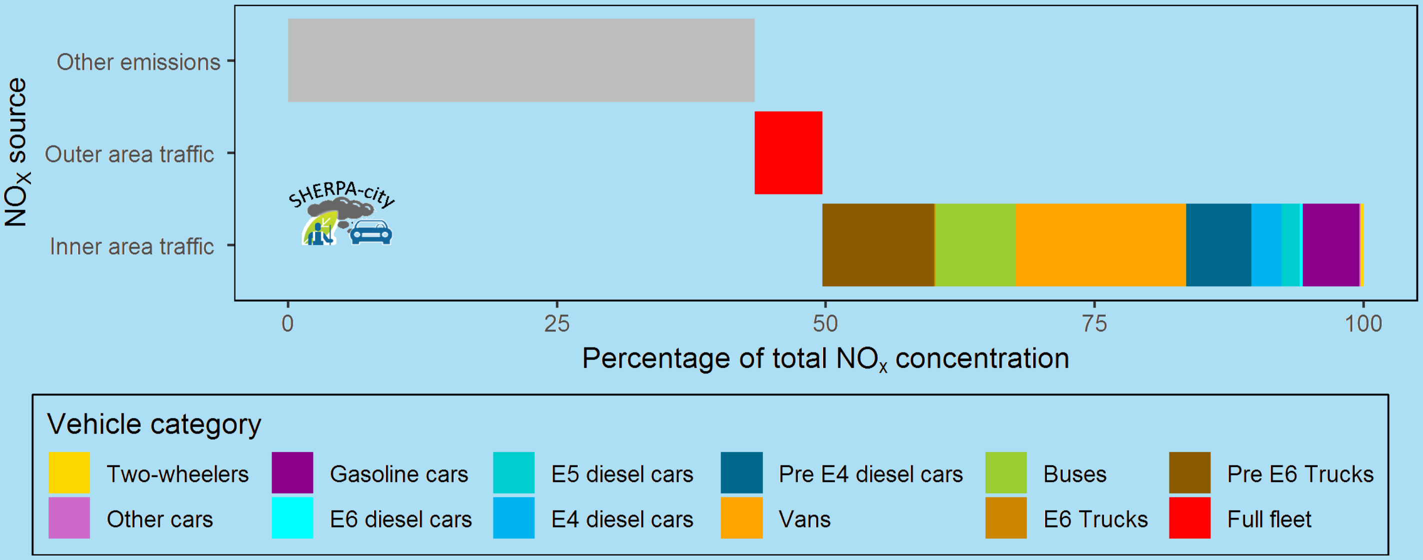
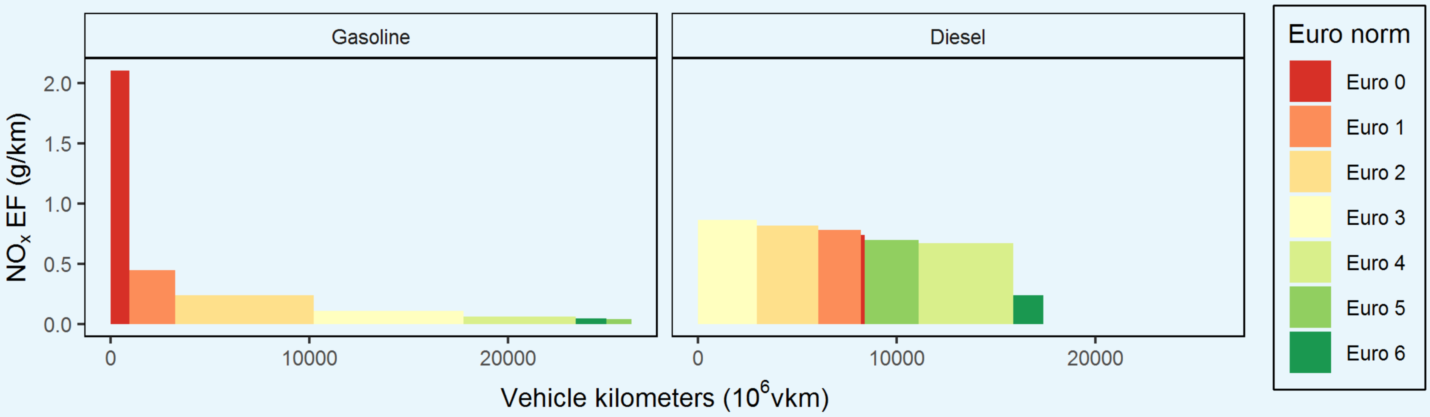
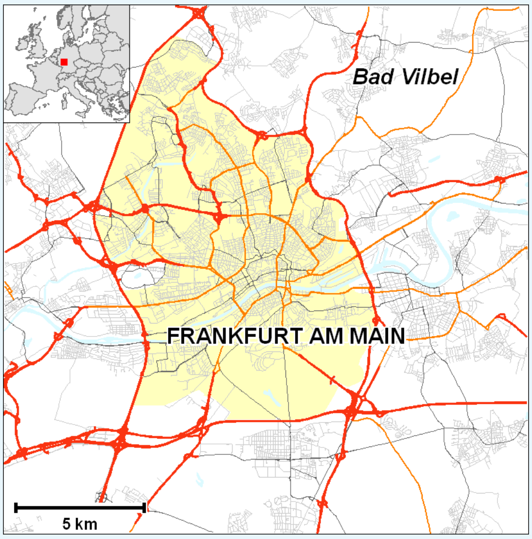


National emissions per fuel and Euro norm (passenger cars)

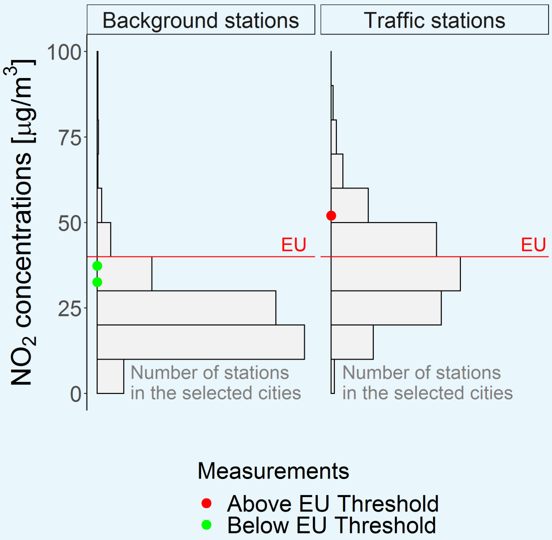


Frankfurt am Main (Germany)

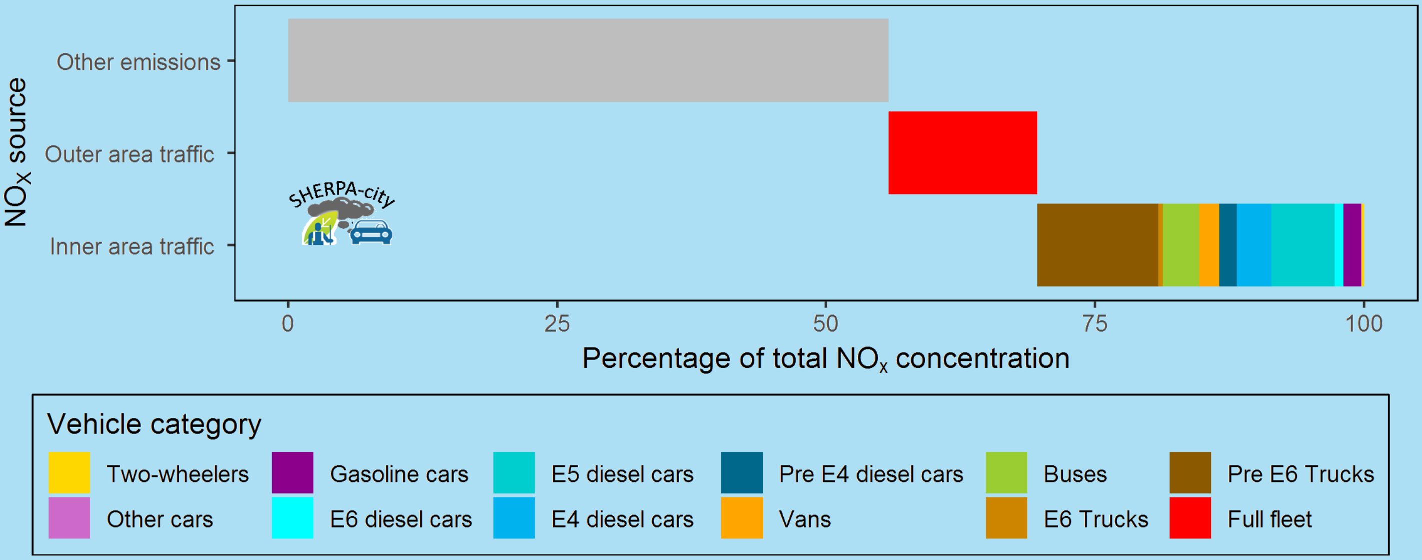
Inner (yellow) **and Outer** (white) **Area definition**



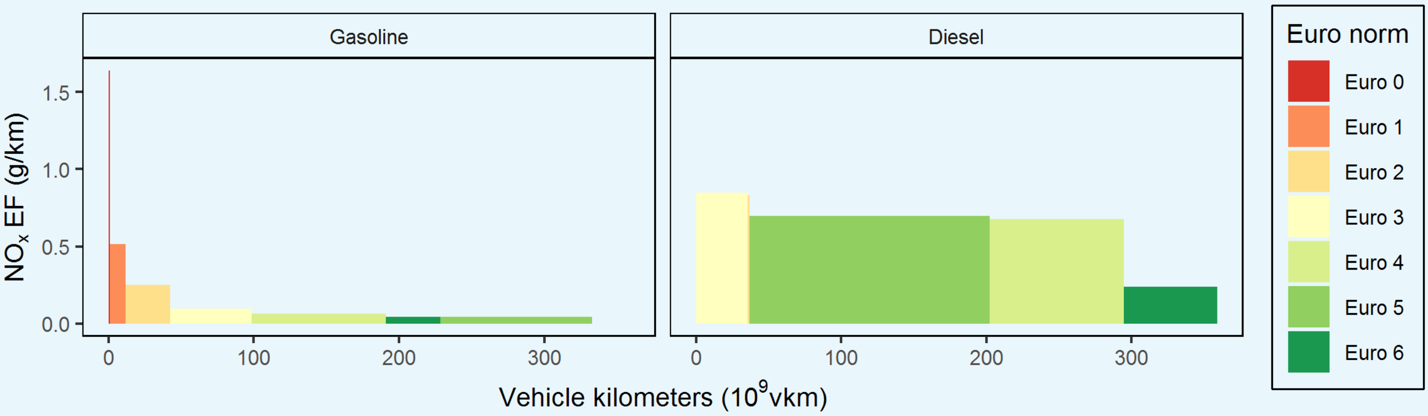
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

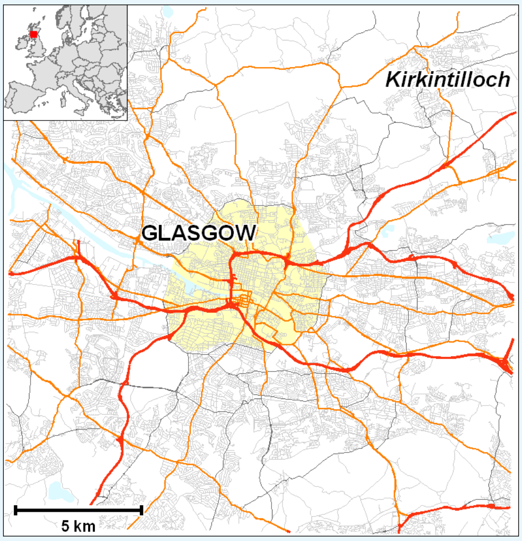


National emissions per fuel and Euro norm (passenger cars)

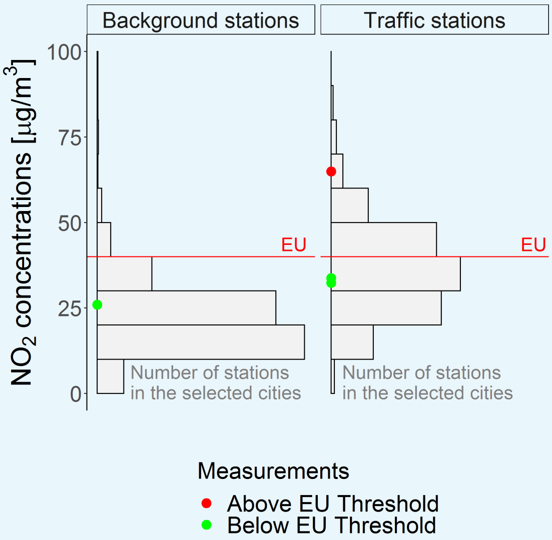


Glasgow (United Kingdom)

Inner (yellow) **and Outer** (white) **Area definition**



Yearly average concentration (2016)



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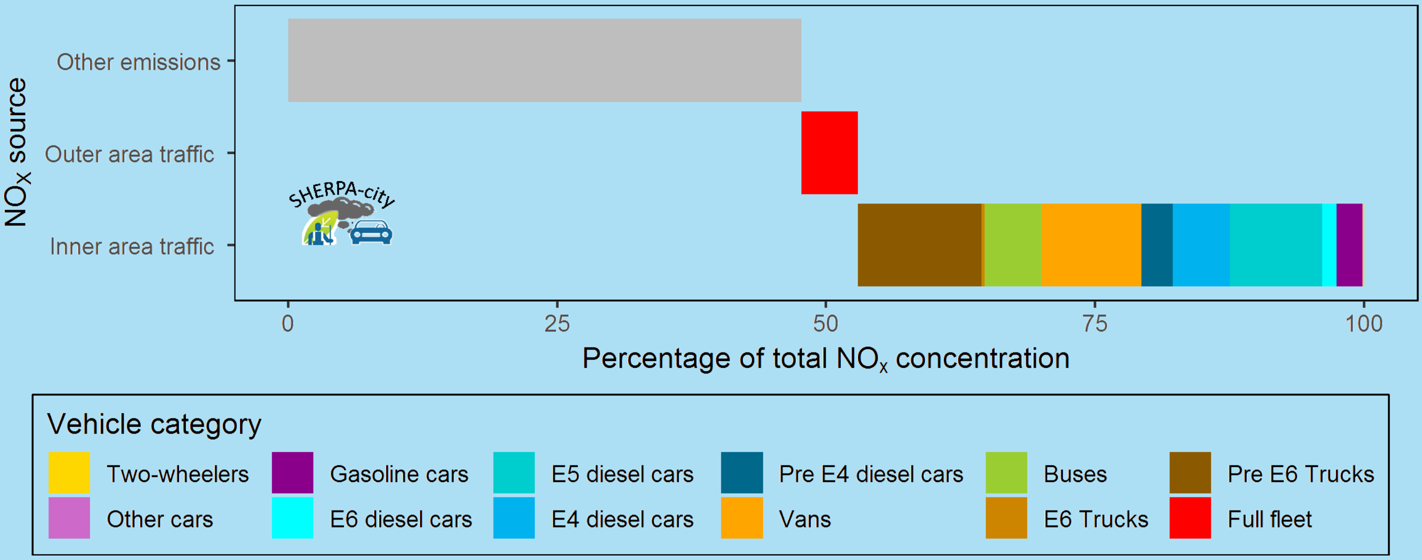
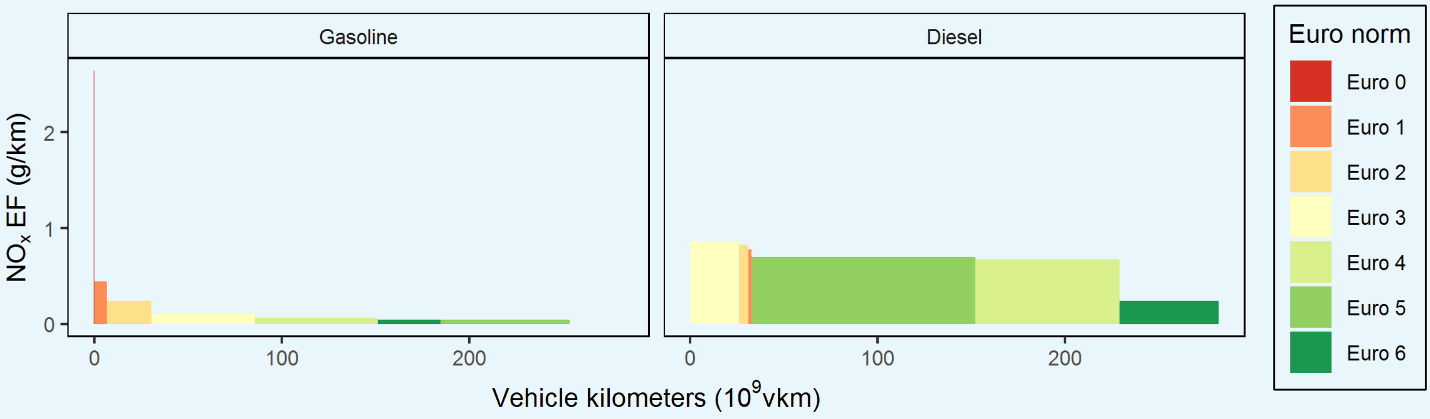
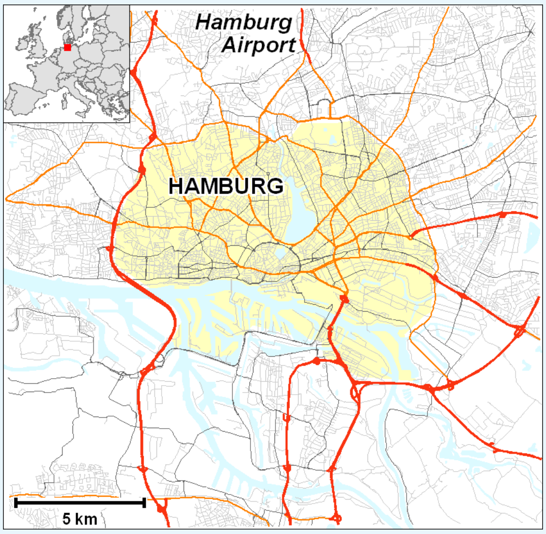


National emissions per fuel and Euro norm (passenger cars)

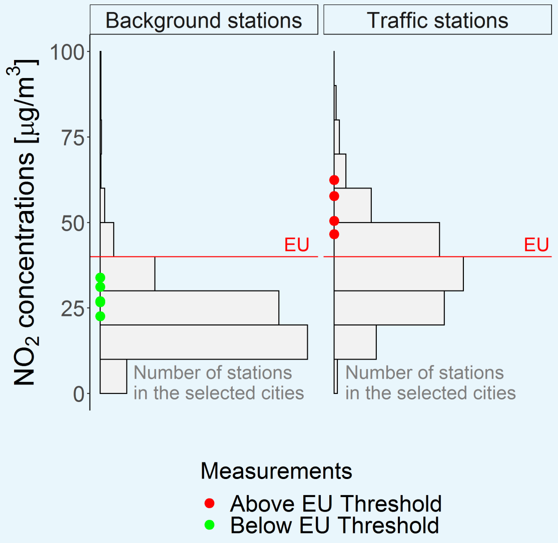


Hamburg (Germany)

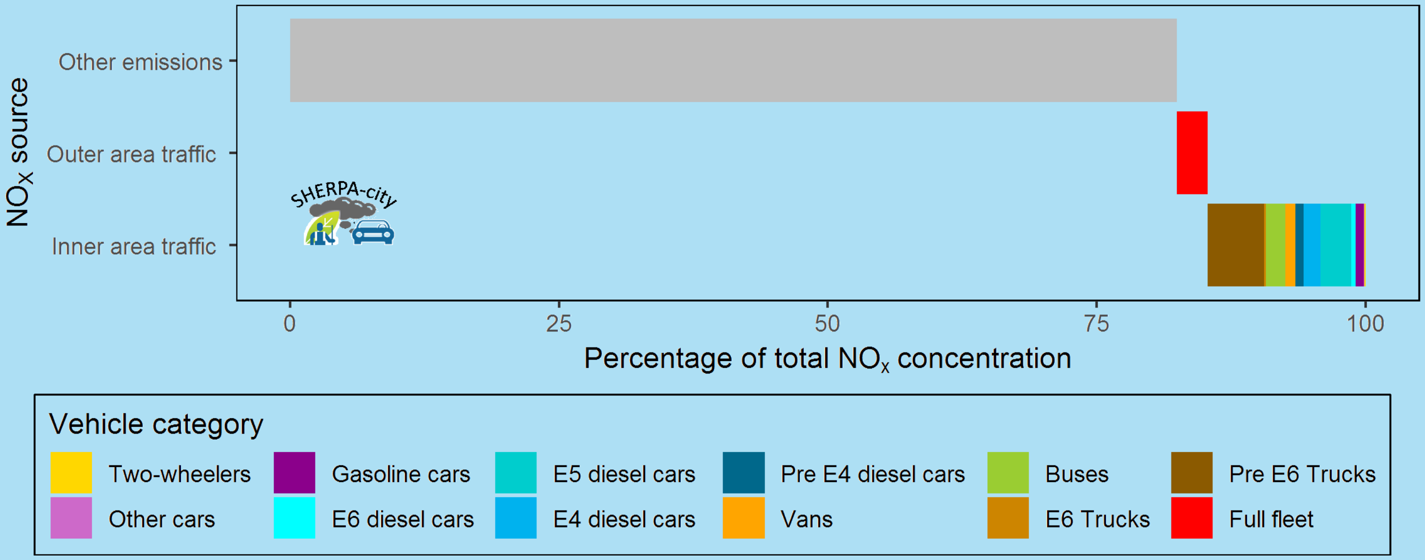
Inner (yellow) **and Outer** (white) **Area definition**



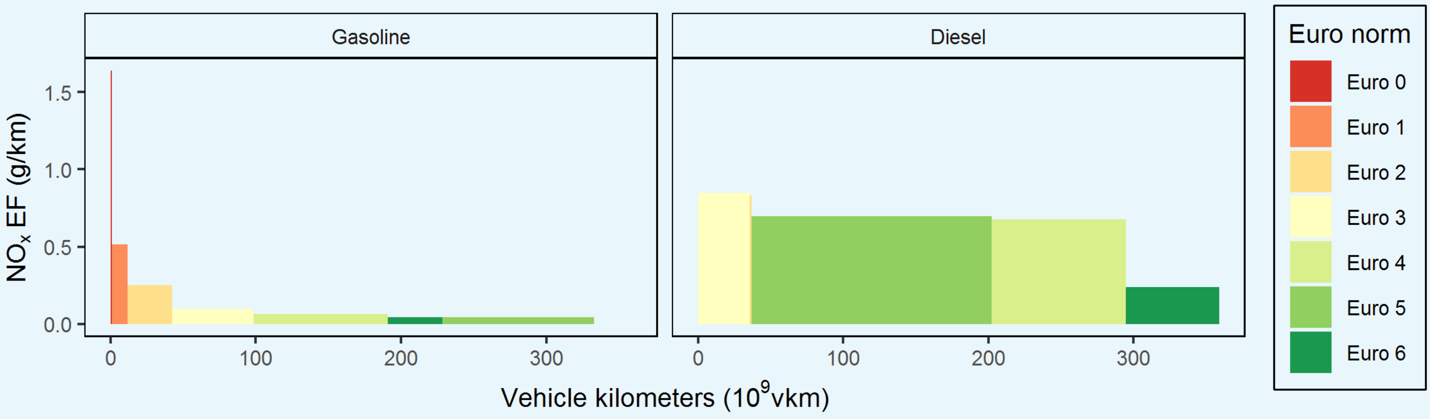
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

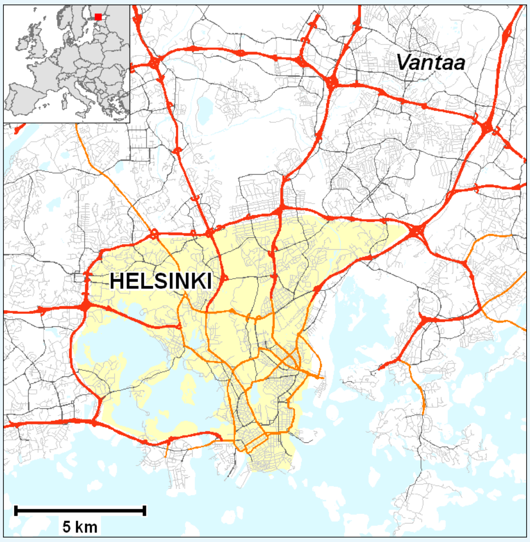


National emissions per fuel and Euro norm (passenger cars)

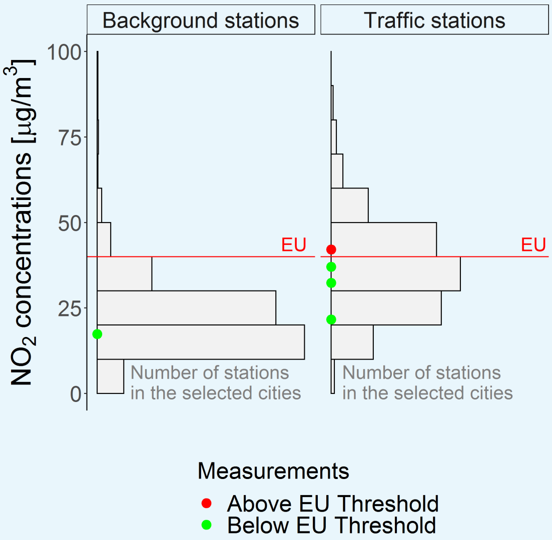


Helsinki (Finland)

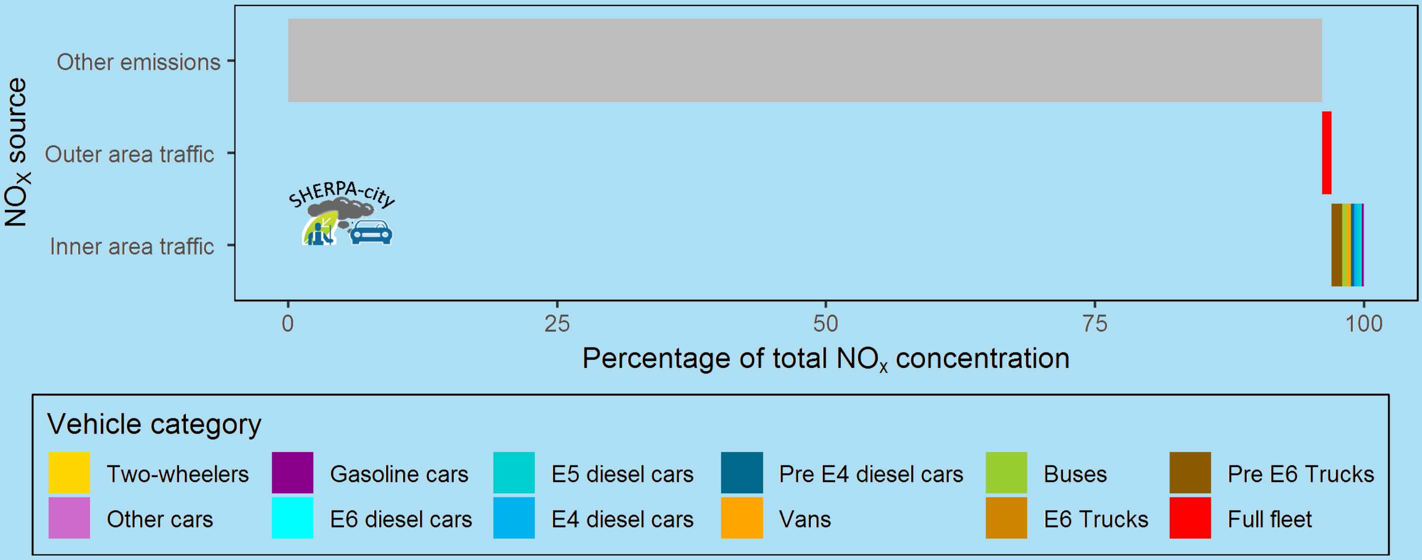
Inner (yellow) **and Outer** (white) **Area definition**



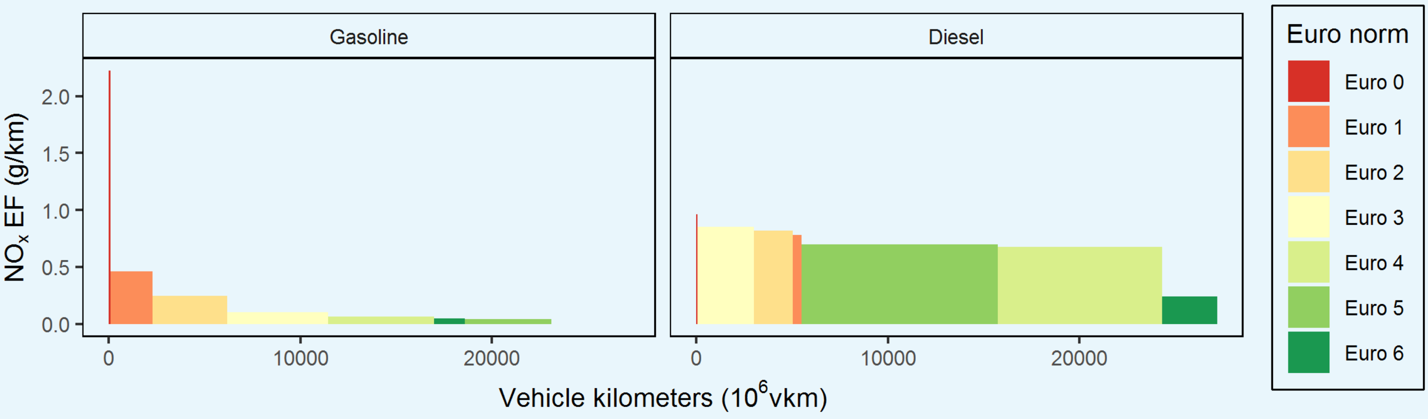
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

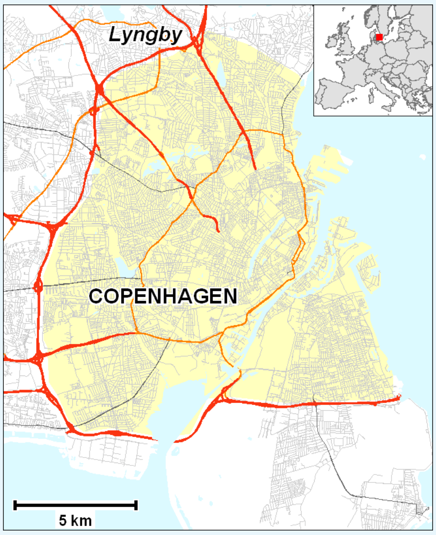


National emissions per fuel and Euro norm (passenger cars)

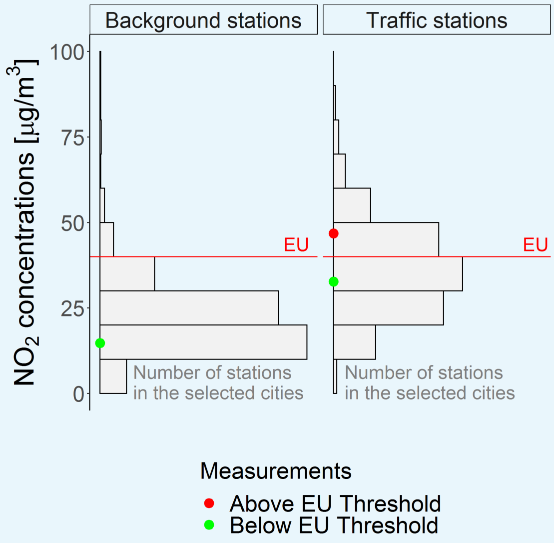


København (Denmark)

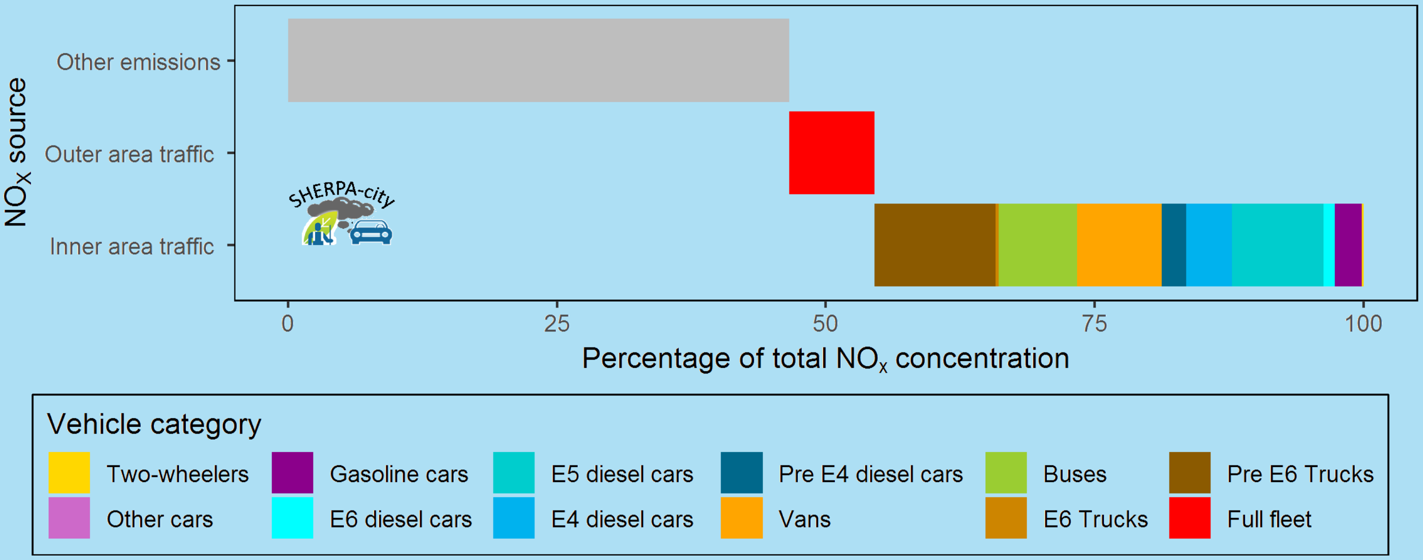
Inner (yellow) **and Outer** (white) **Area definition**



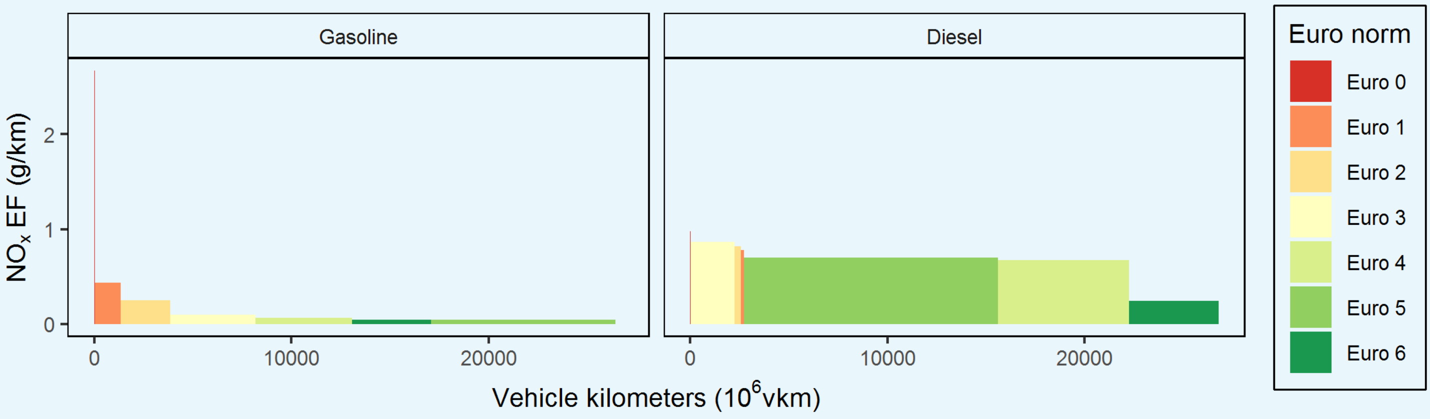
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

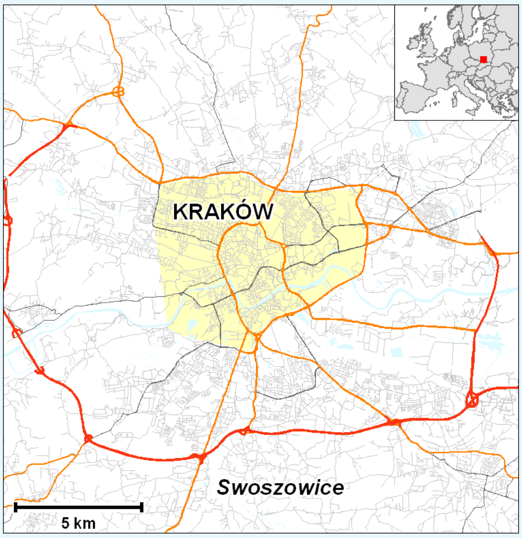


National emissions per fuel and Euro norm (passenger cars)

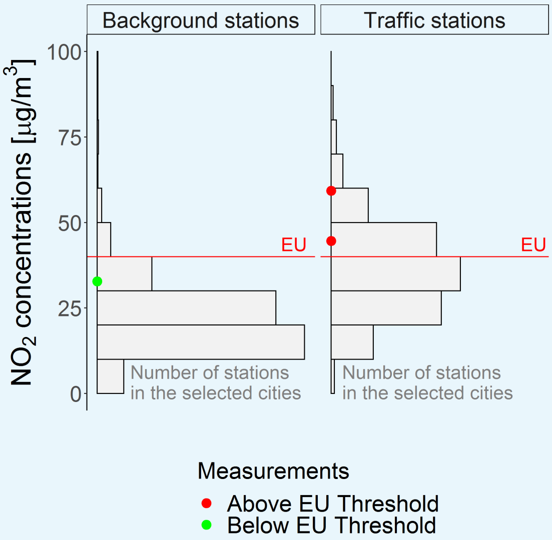


Kraków (Poland)

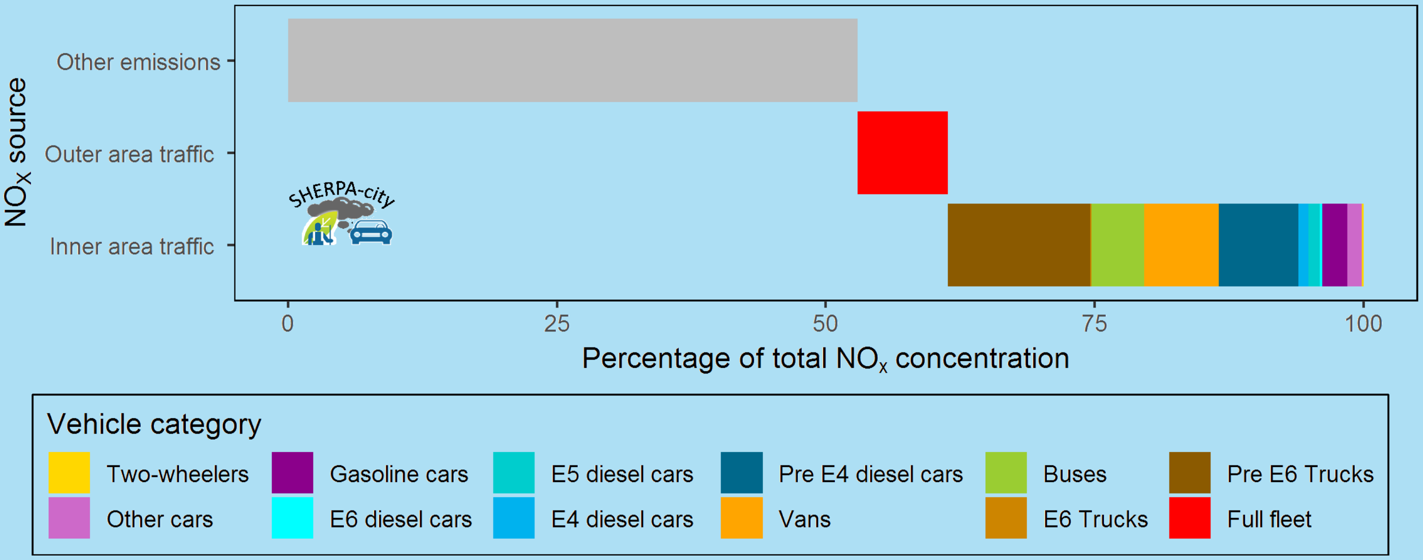
Inner (yellow) **and Outer** (white) **Area definition**



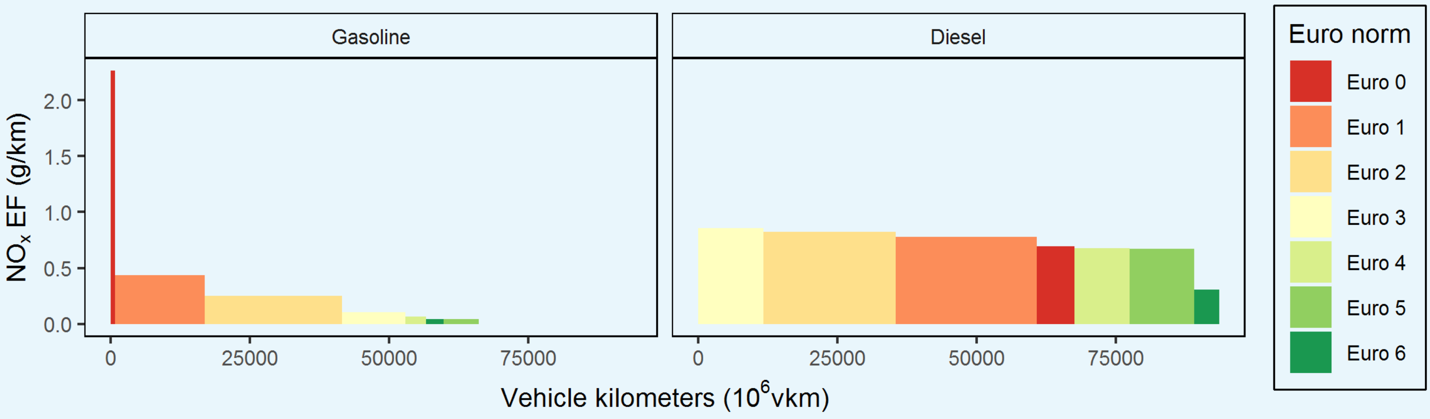
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area



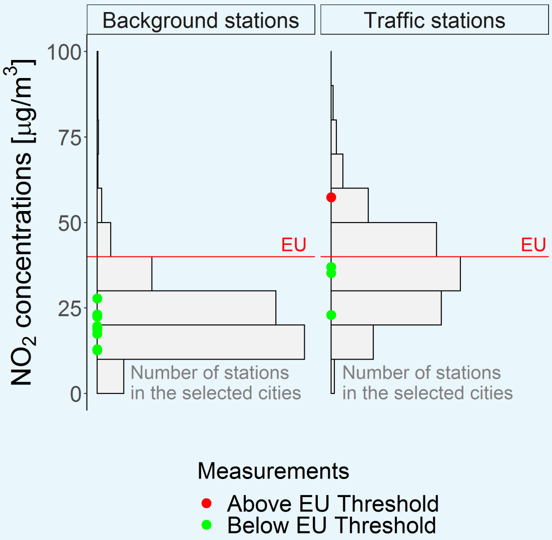
National emissions per fuel and Euro norm (passenger cars)



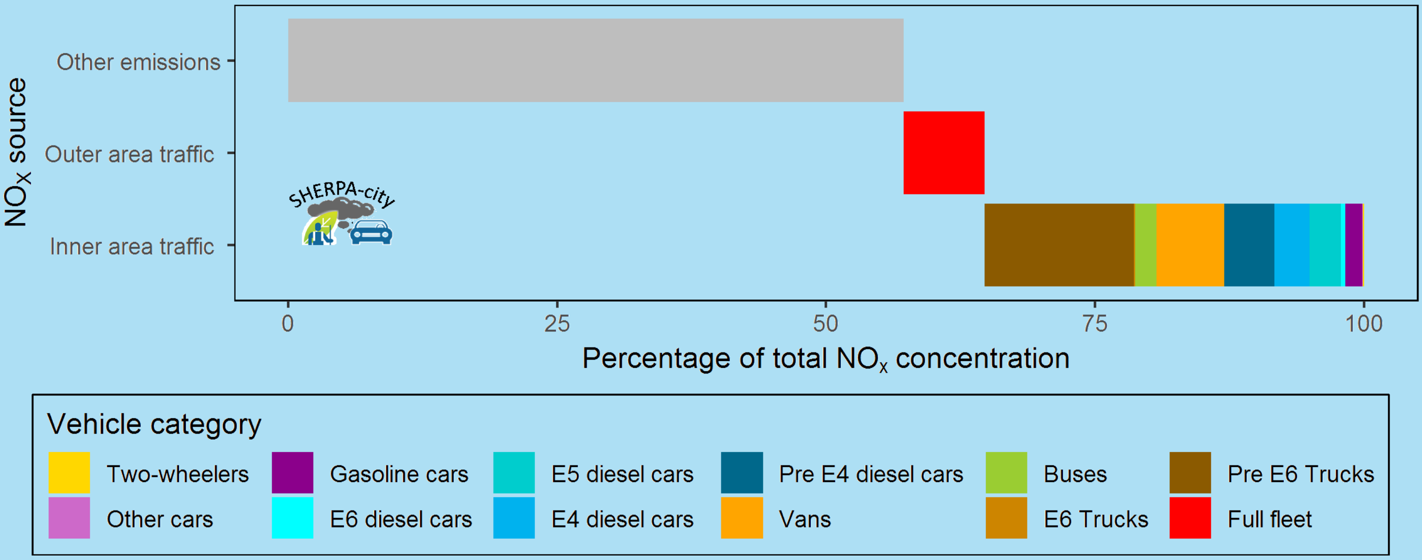
Lisboa (Portugal)

Inner (yellow) **and Outer** (white) **Area definition**

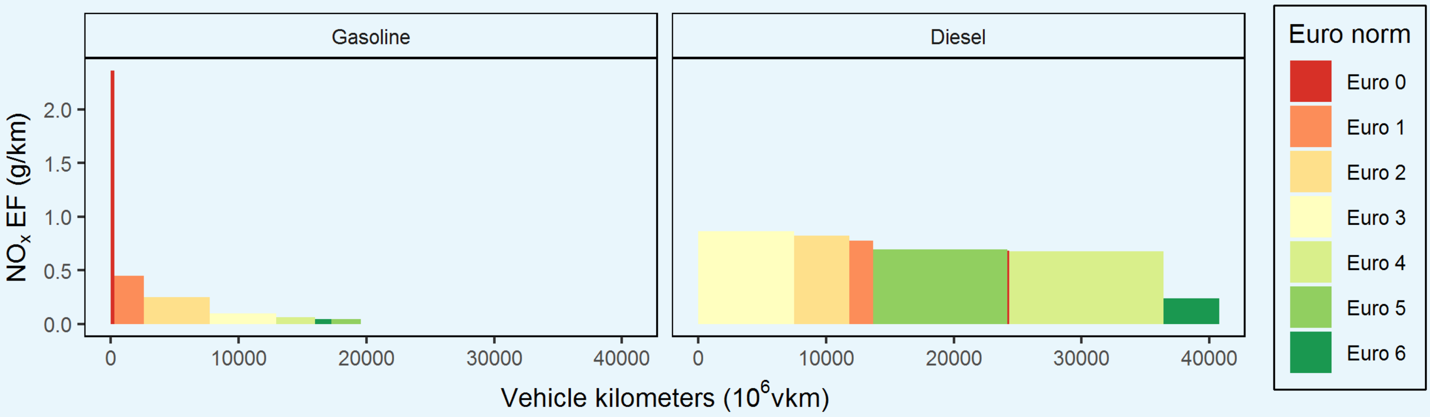
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

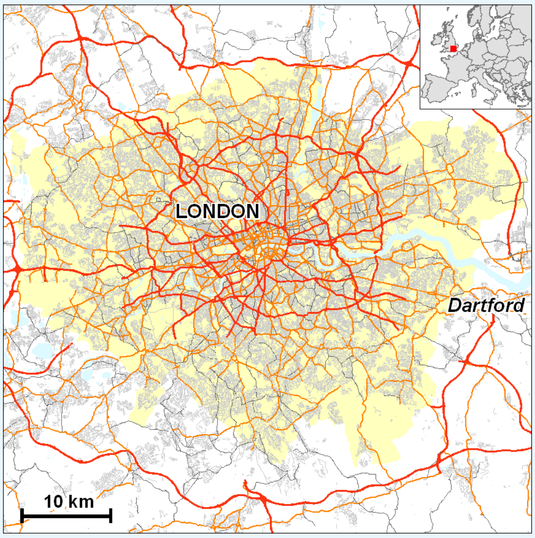


National emissions per fuel and Euro norm (passenger cars)

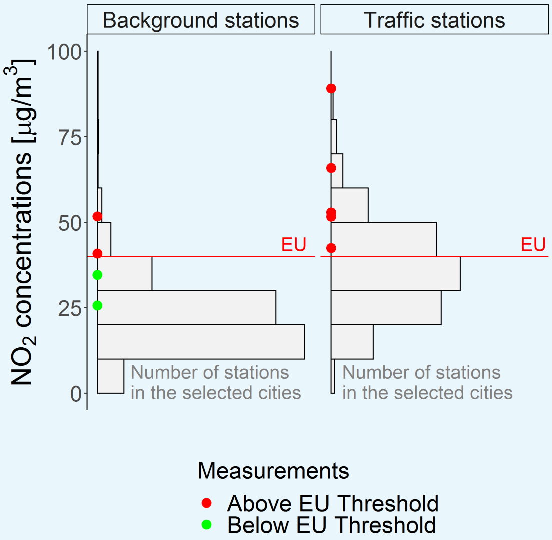


London (United Kingdom)

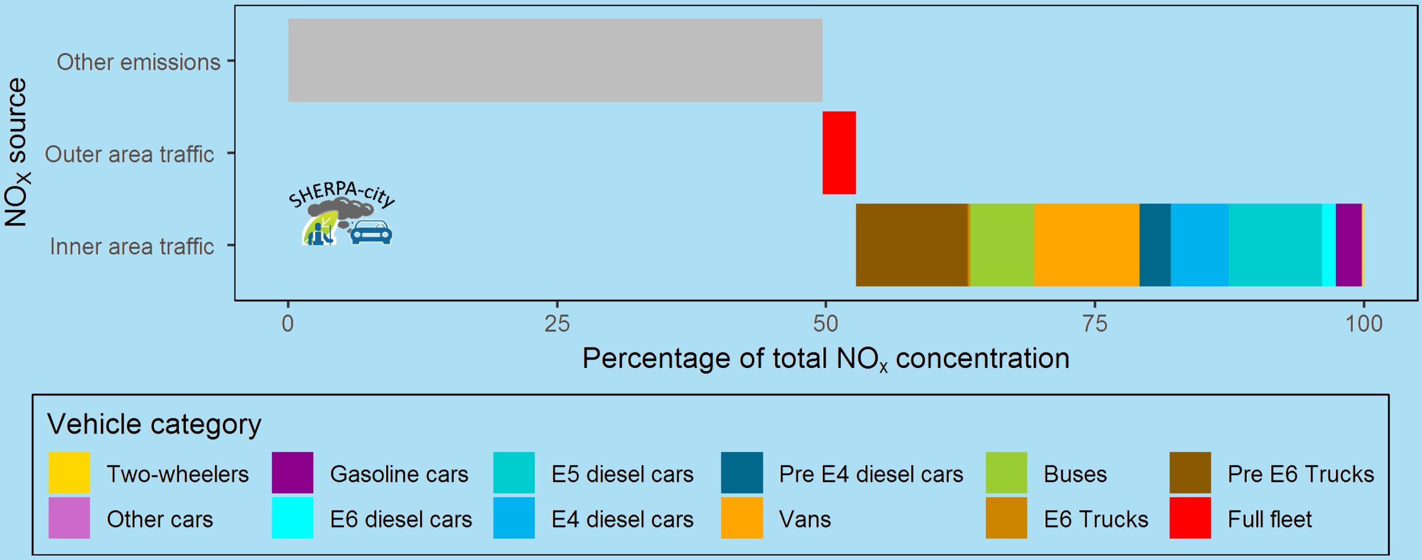
Inner (yellow) **and Outer** (white) **Area definition**



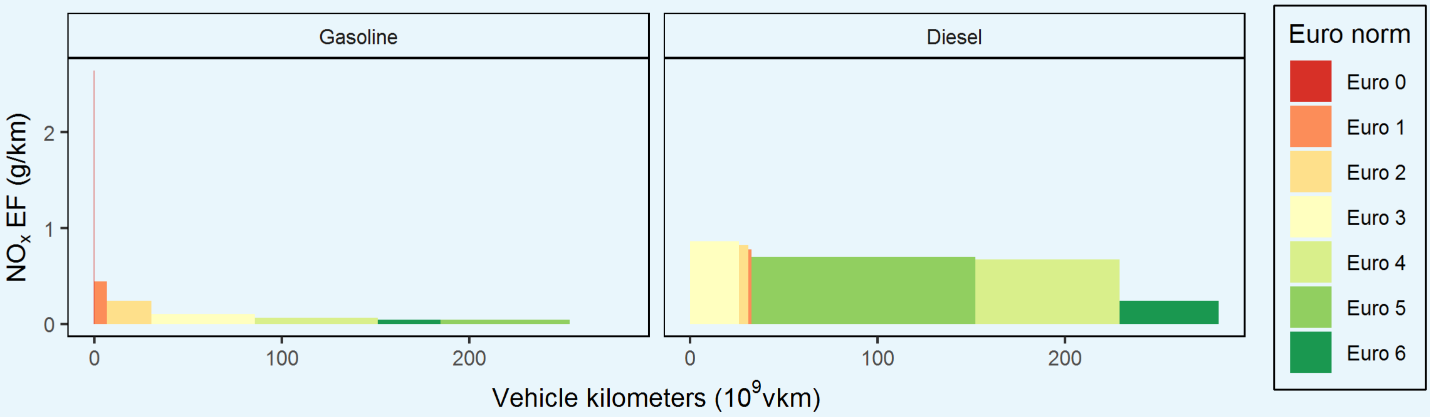
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

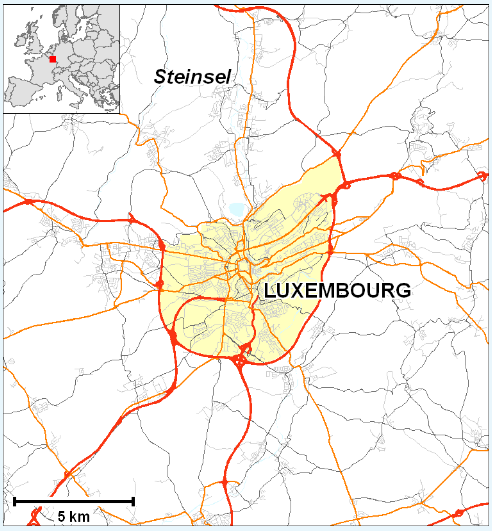


National emissions per fuel and Euro norm (passenger cars)

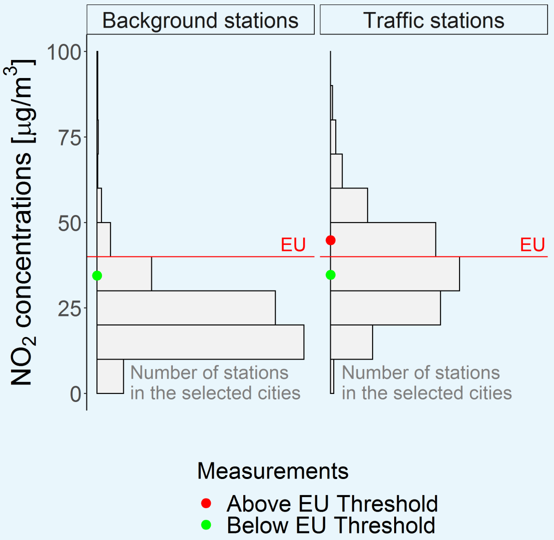


Luxembourg (Luxembourg)

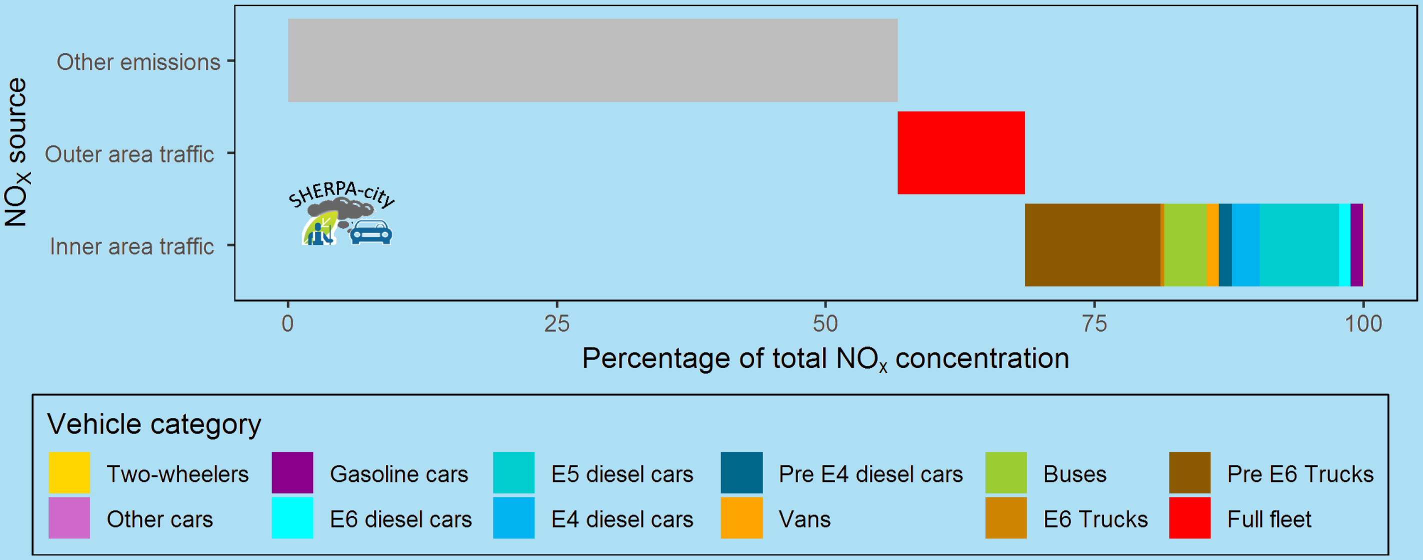
Inner (yellow) **and Outer** (white) **Area definition**



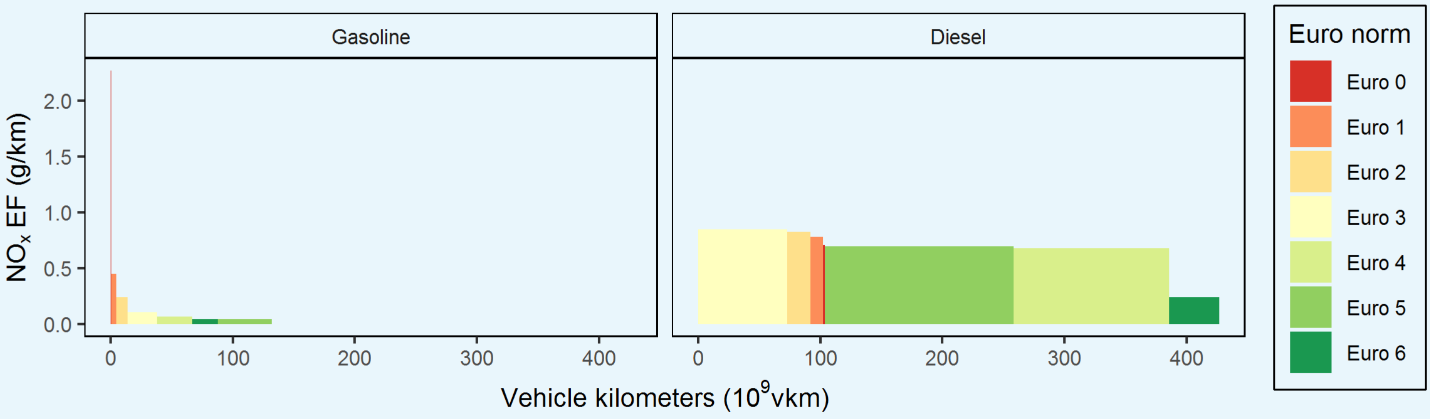
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

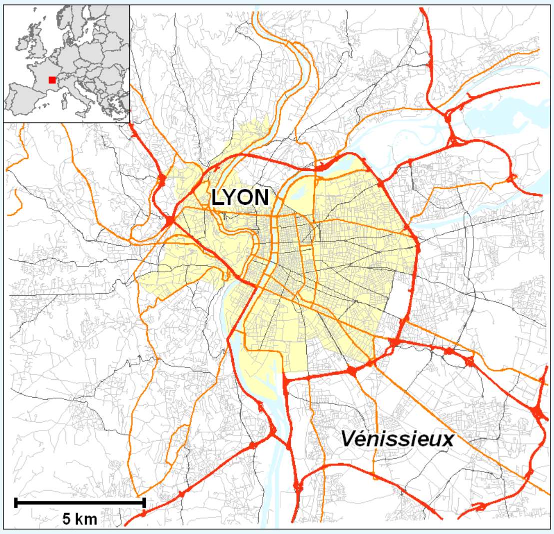


National emissions per fuel and Euro norm (passenger cars)

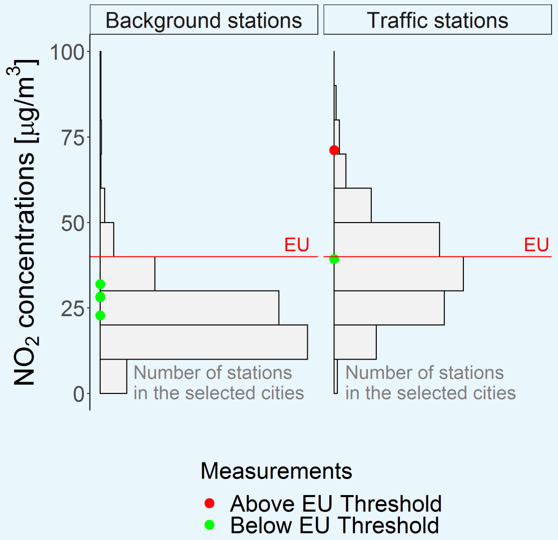


Lyon (France)

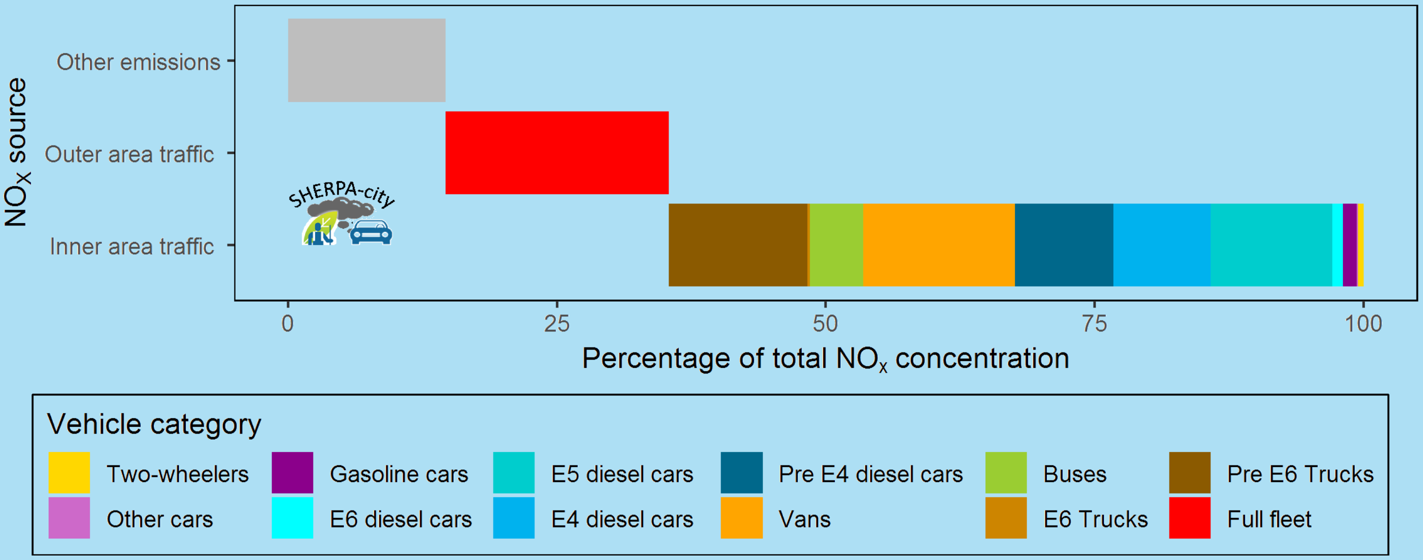
Inner (yellow) **and Outer** (white) **Area definition**



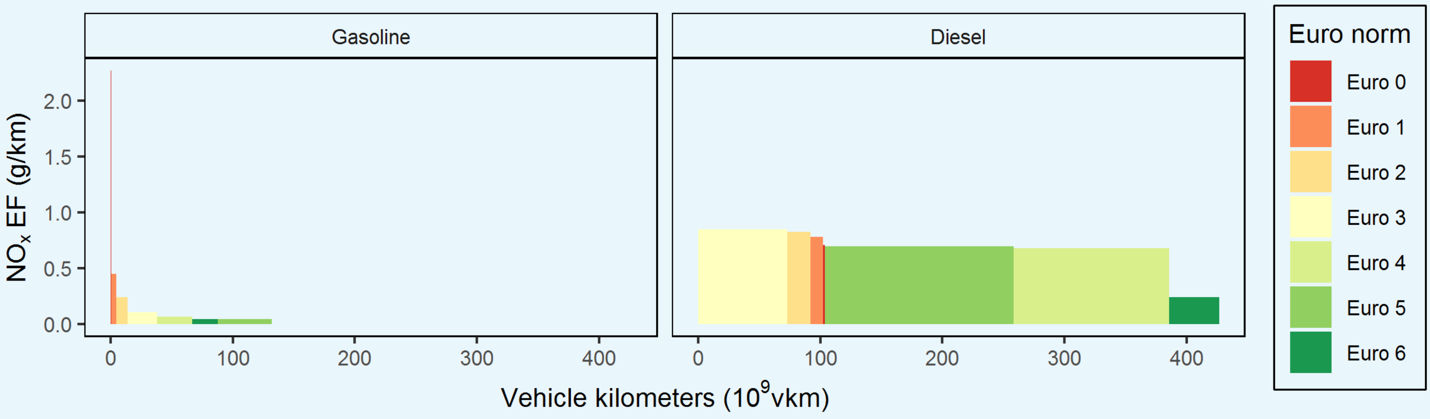
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

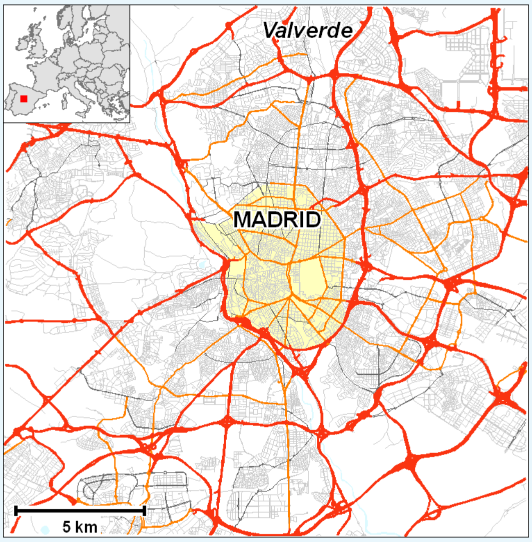


National emissions per fuel and Euro norm (passenger cars)

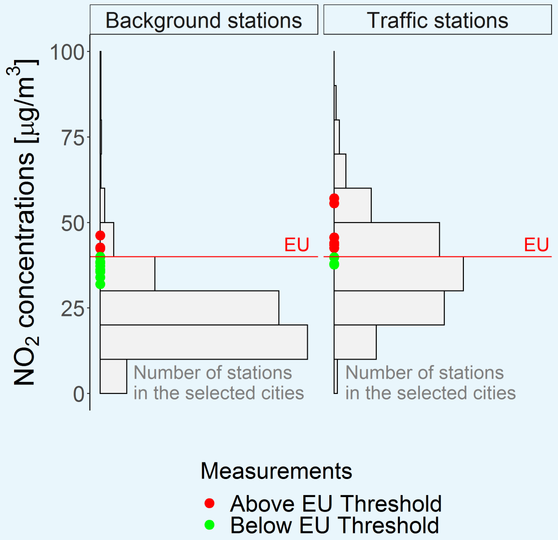


Madrid (Spain)

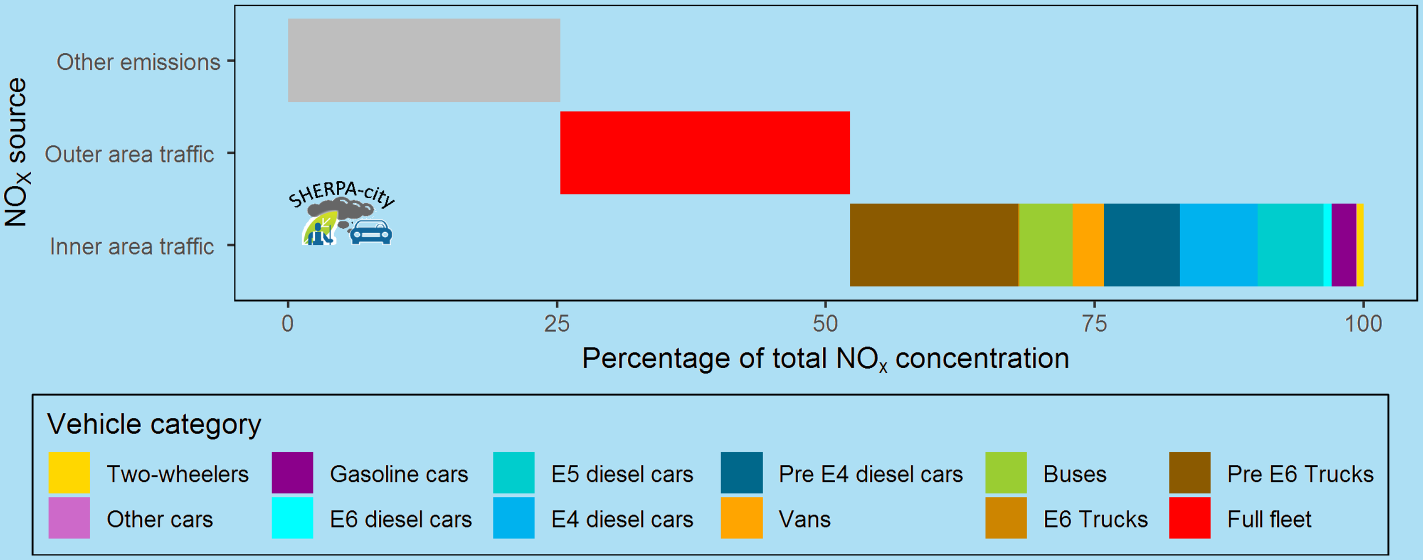
Inner (yellow) **and Outer** (white) **Area definition**



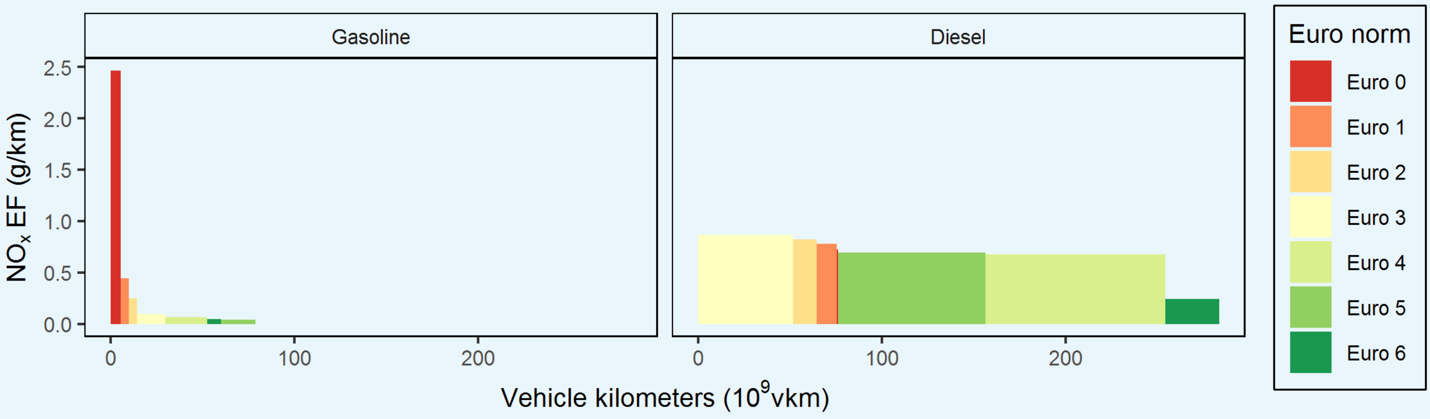
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

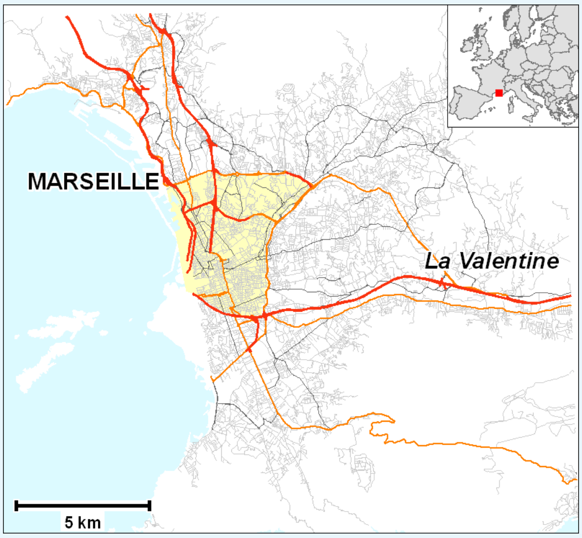


National emissions per fuel and Euro norm (passenger cars)

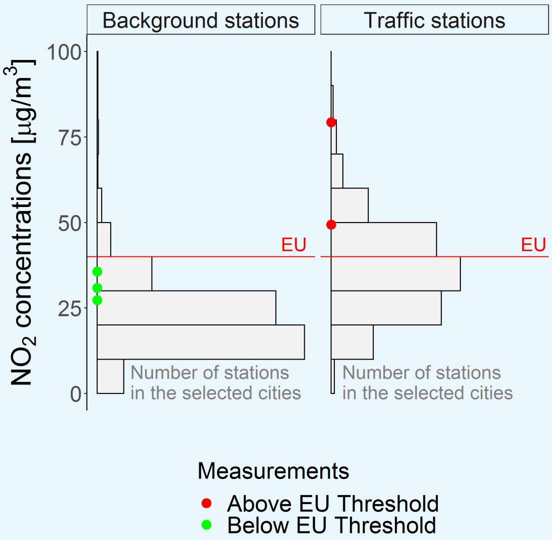


Marseille (France)

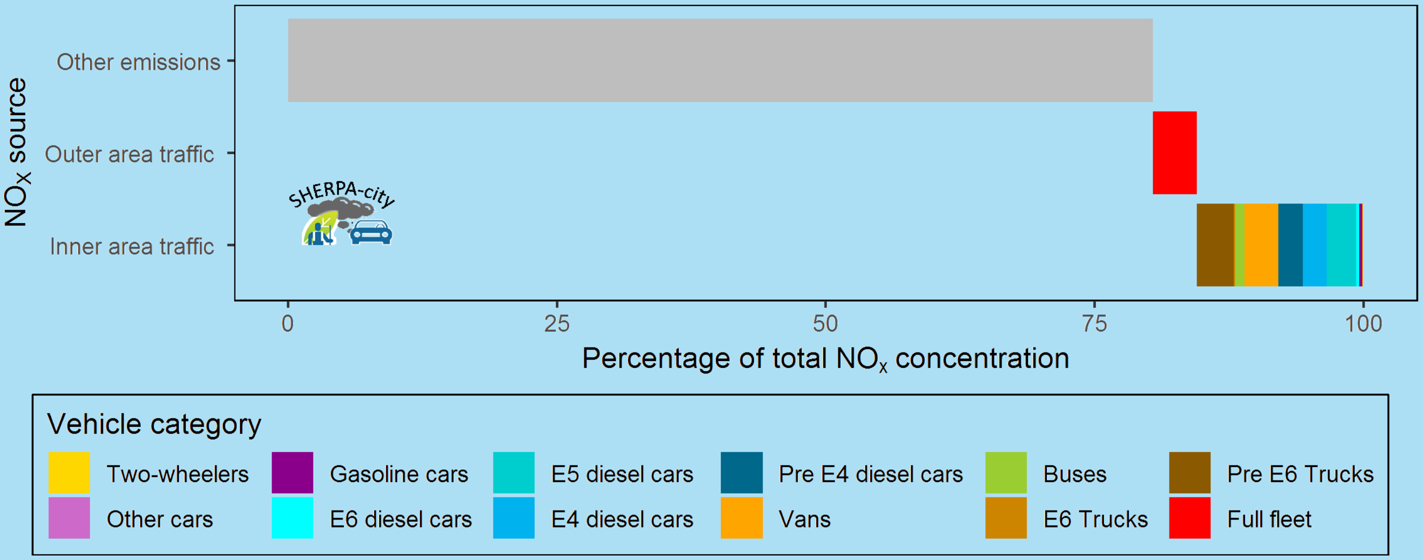
Inner (yellow) **and Outer** (white) **Area definition**



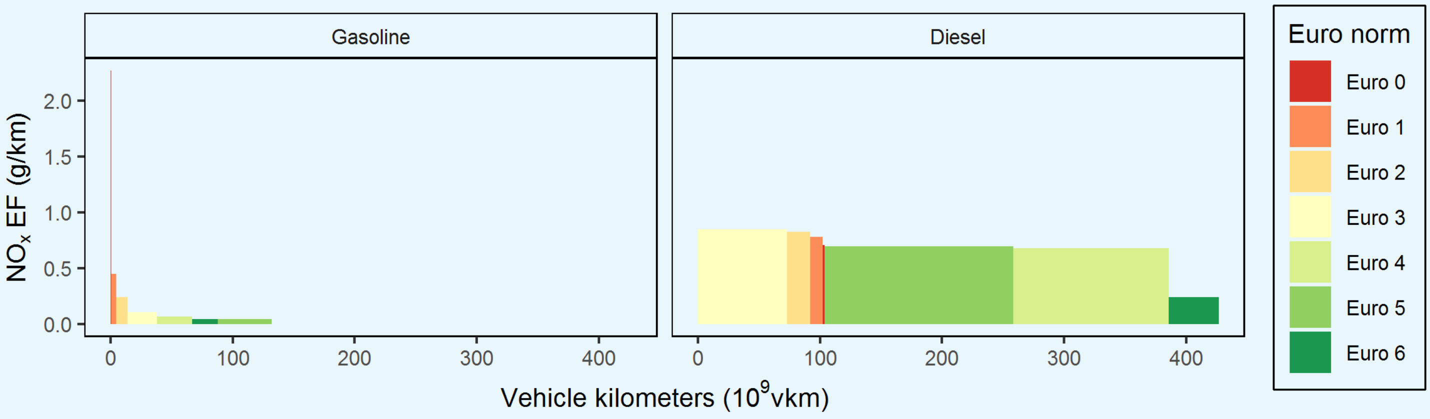
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area



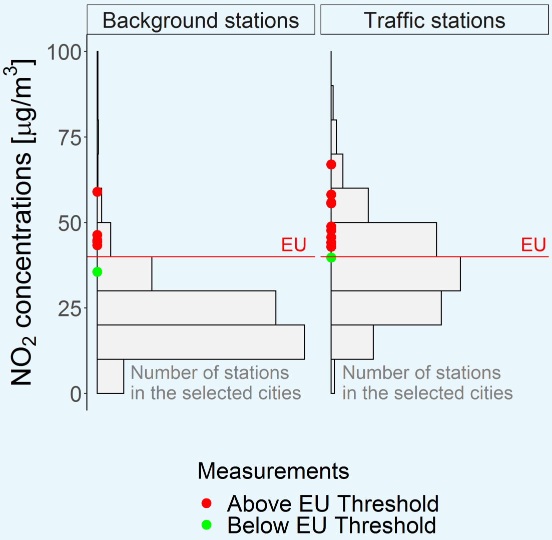
National emissions per fuel and Euro norm (passenger cars)



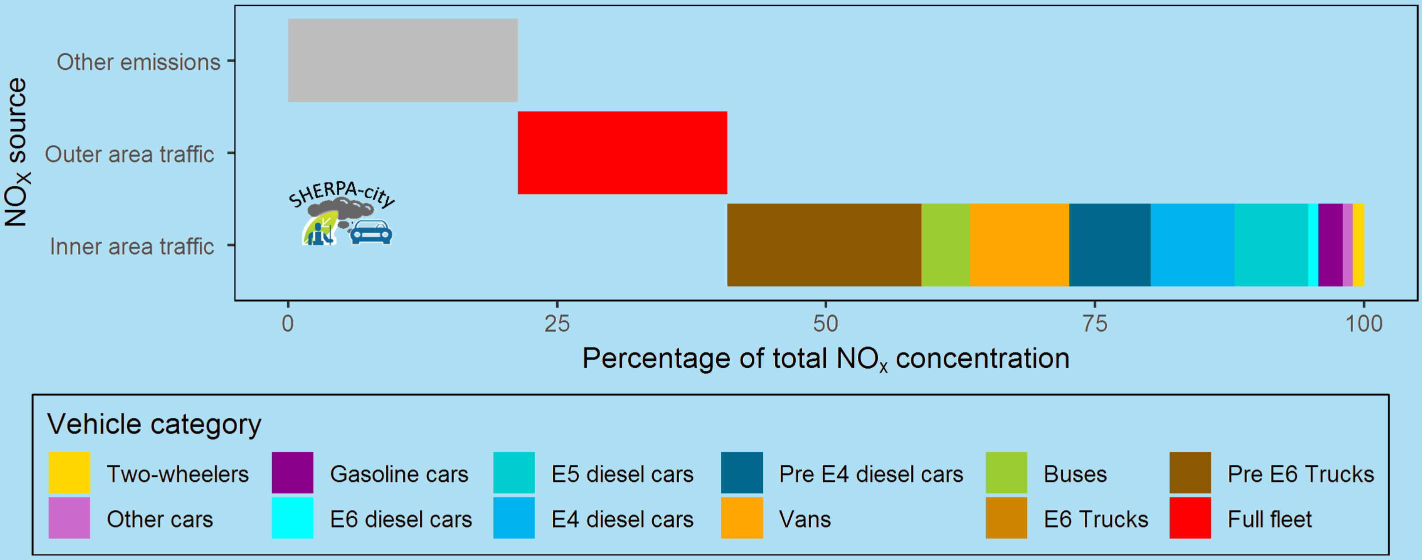
Milano (Italy)

Inner (yellow) **and Outer** (white) **Area definition**

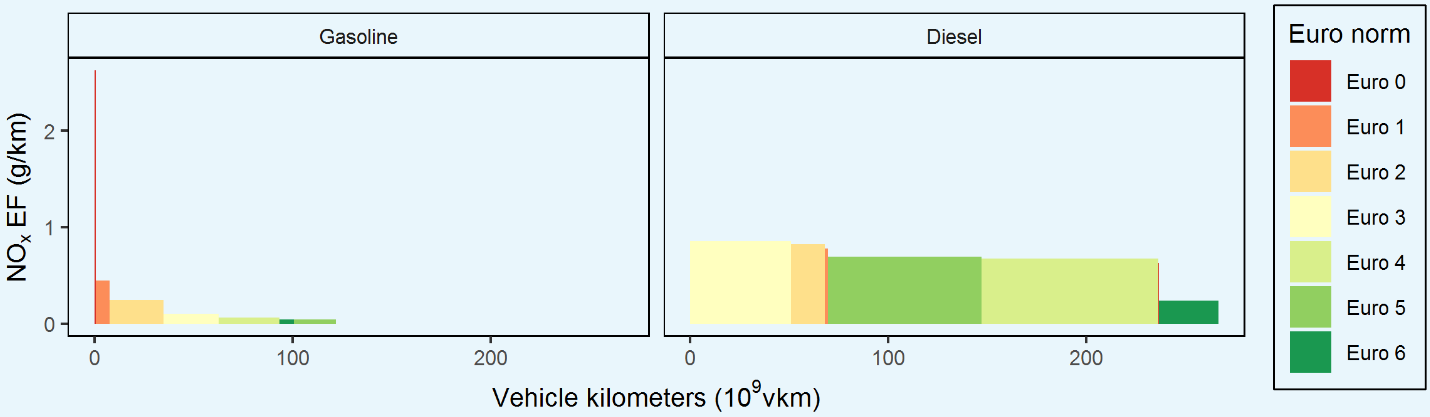
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

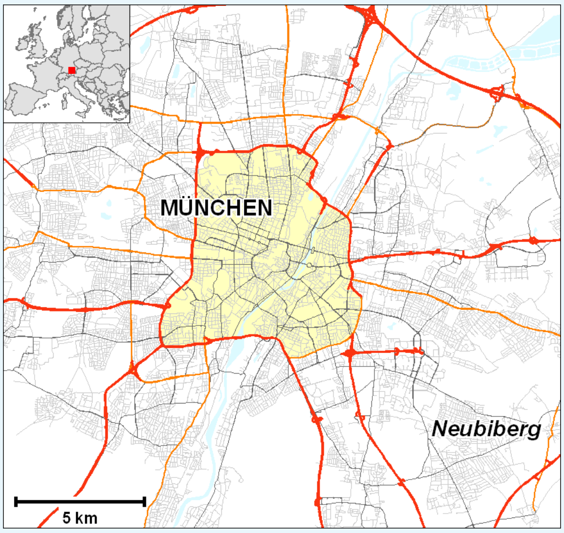


National emissions per fuel and Euro norm (passenger cars)

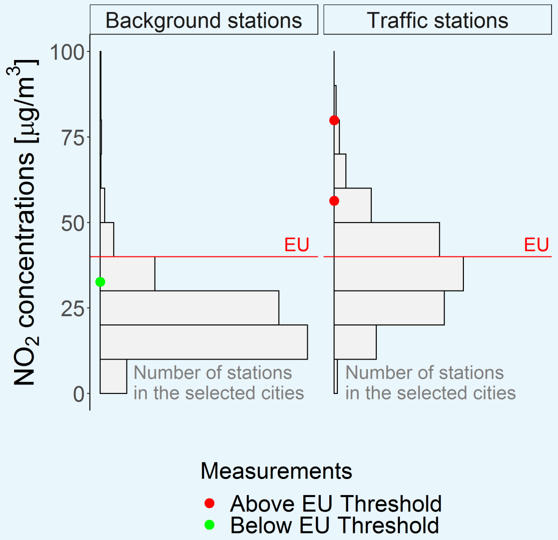


München (Germany)

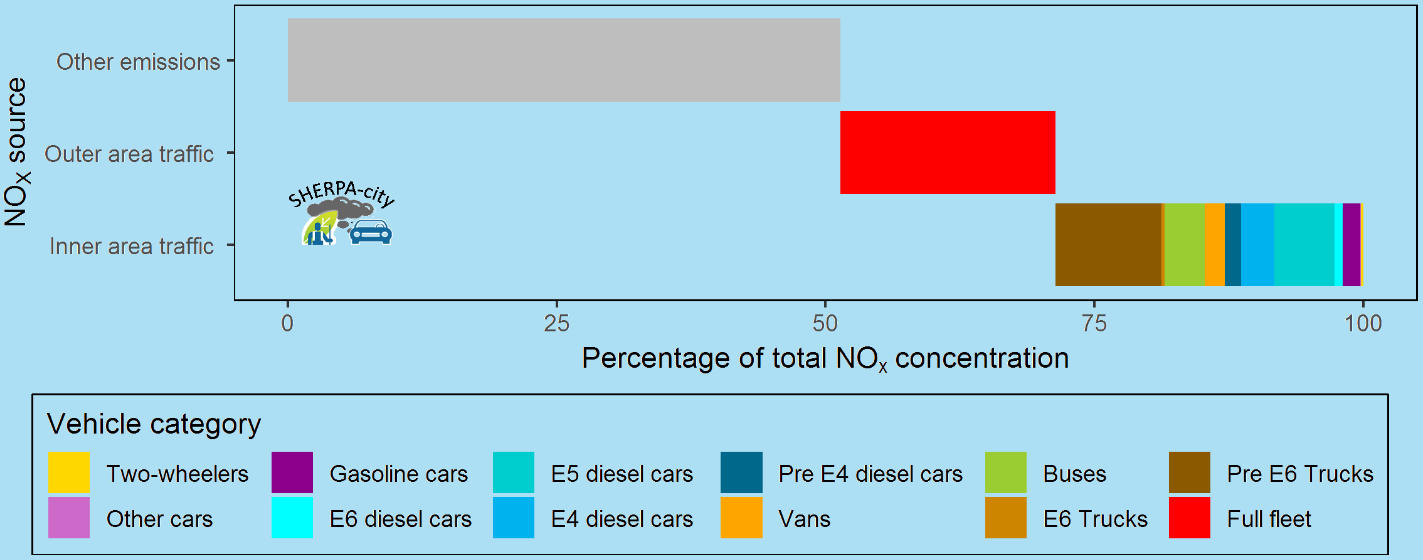
Inner (yellow) and Outer (white) Area definition



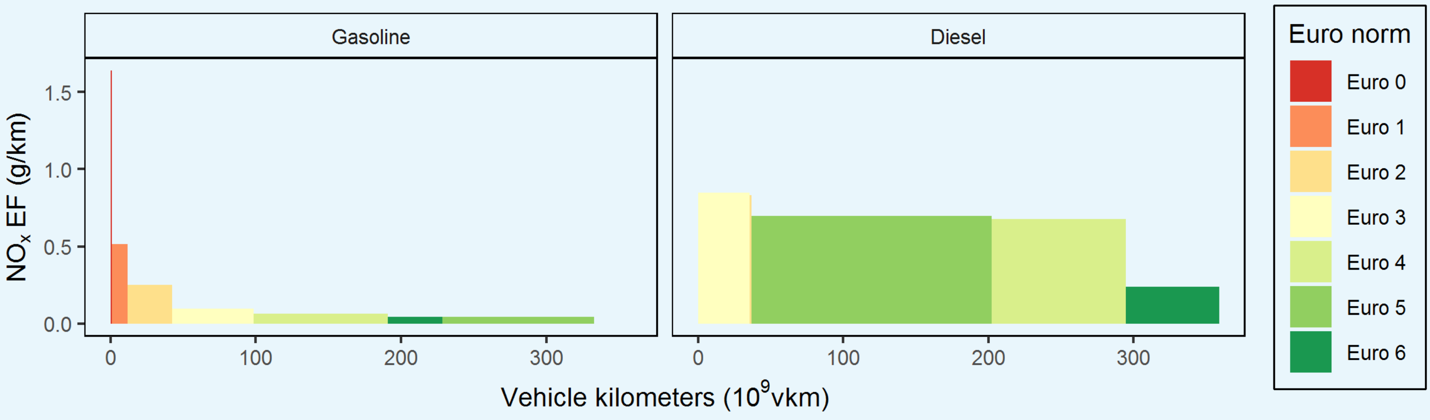
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

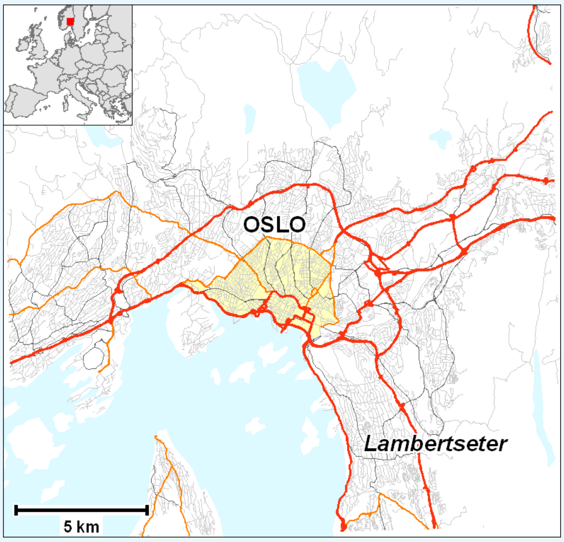


National emissions per fuel and Euro norm (passenger cars)

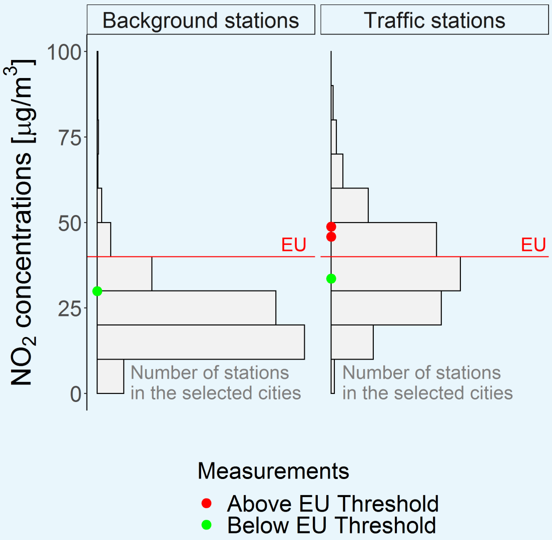


Oslo (Norway)

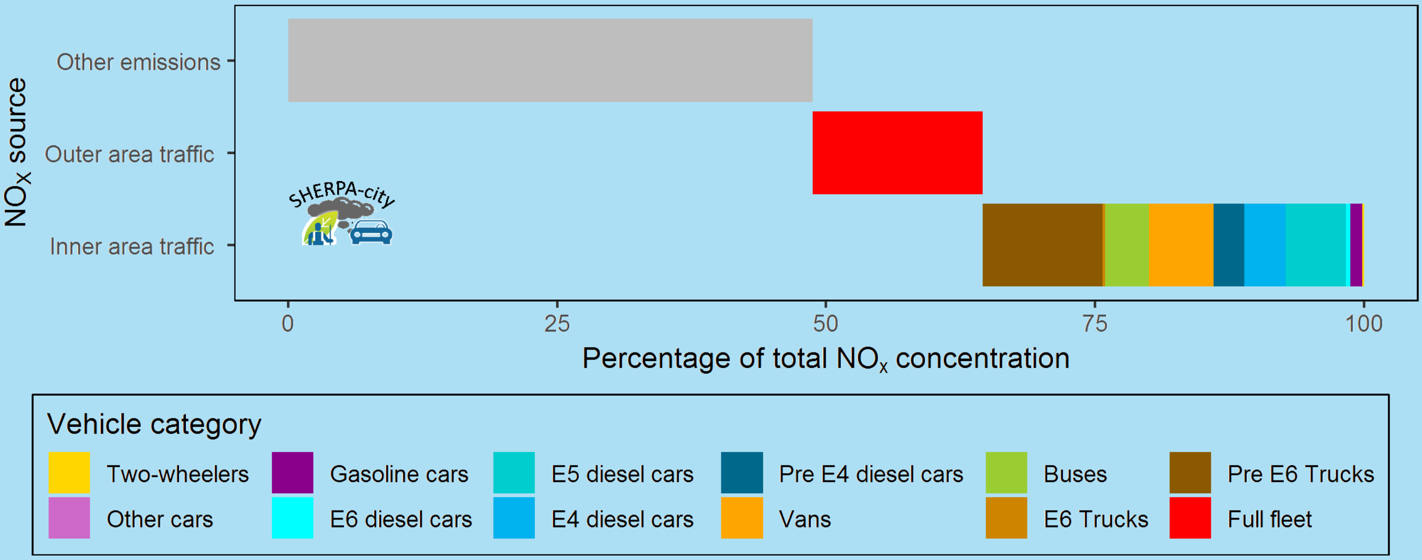
Inner (yellow) **and Outer** (white) **Area definition**



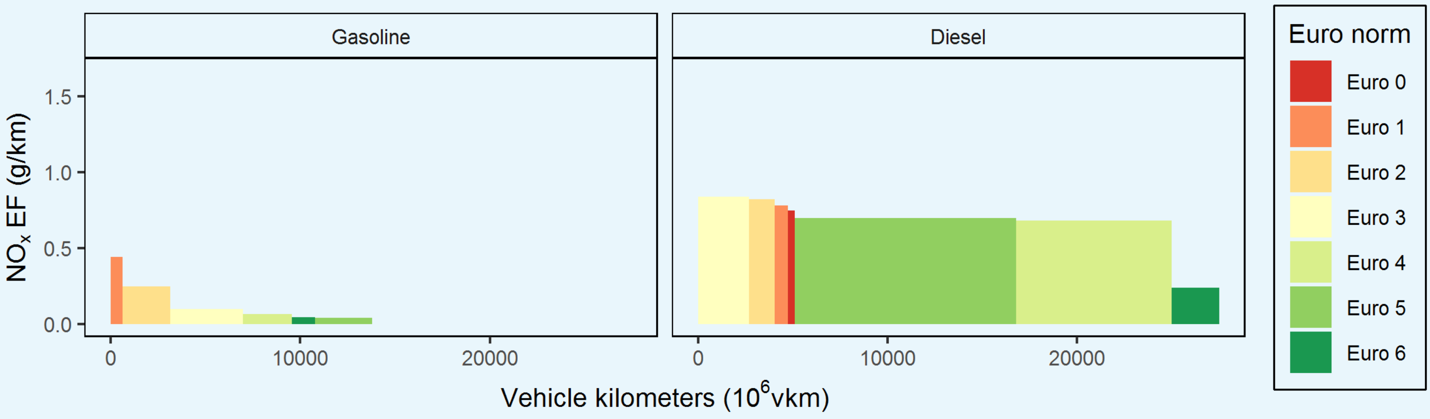
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

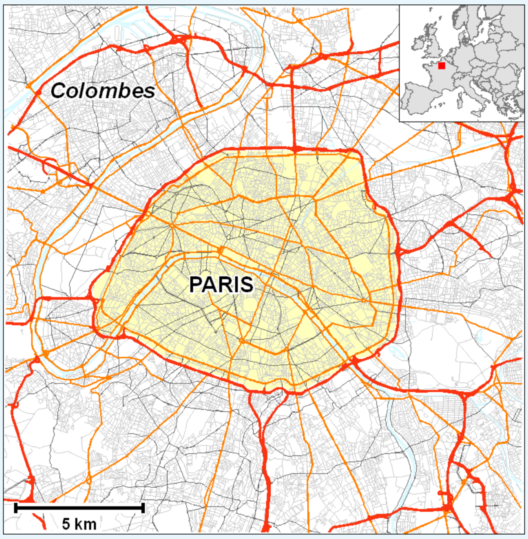


National emissions per fuel and Euro norm (passenger cars)

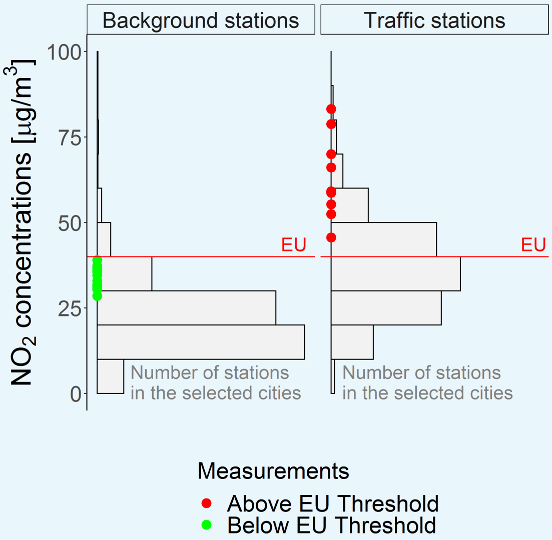


Paris (France)

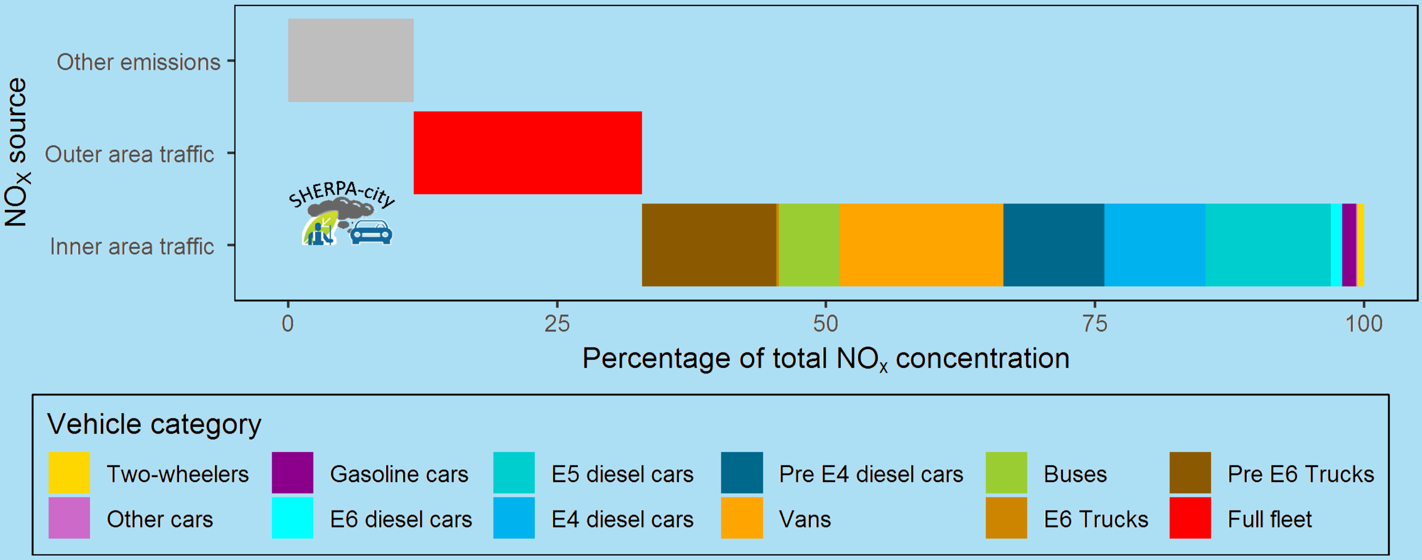
Inner (yellow) **and Outer** (white) **Area definition**



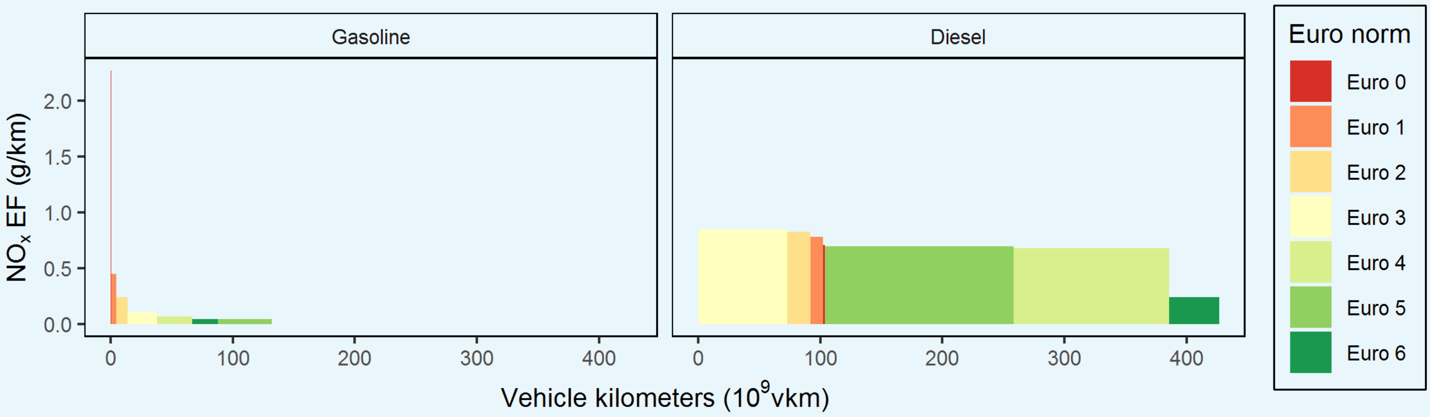
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

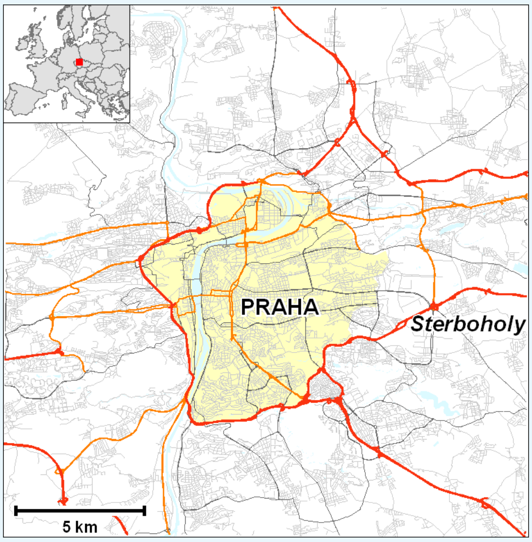


National emissions per fuel and Euro norm (passenger cars)

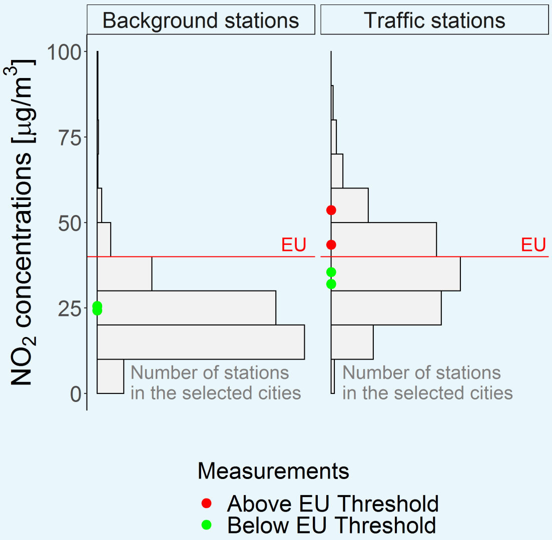


Praha (Czech Republic)

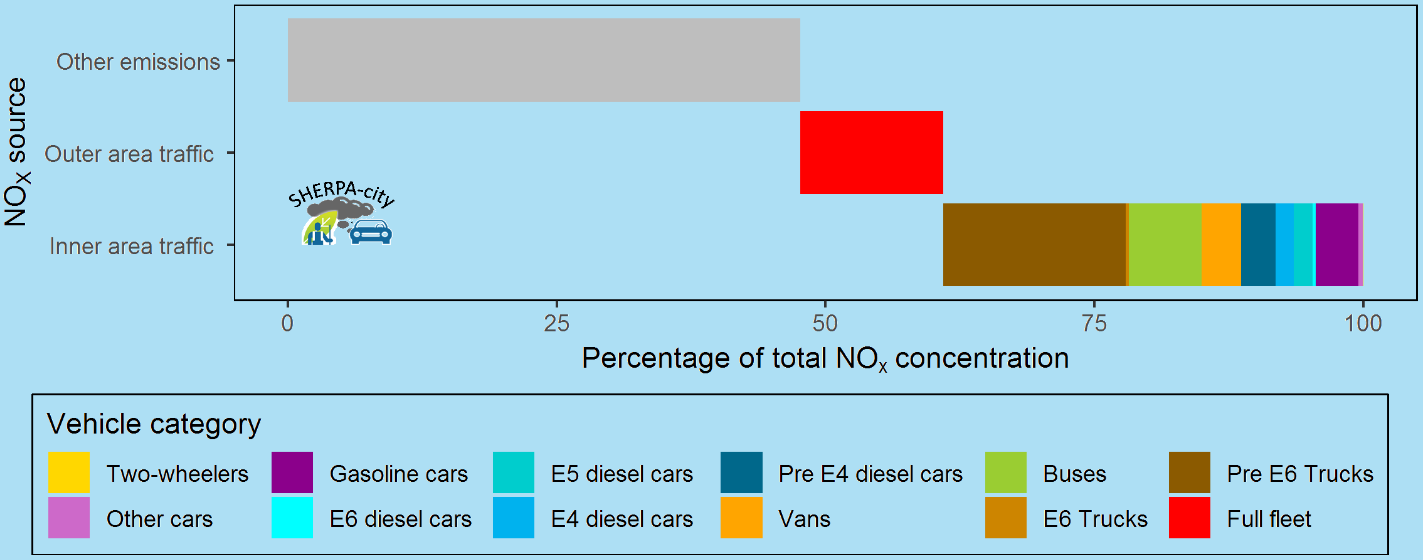
Inner (yellow) **and Outer** (white) **Area definition**



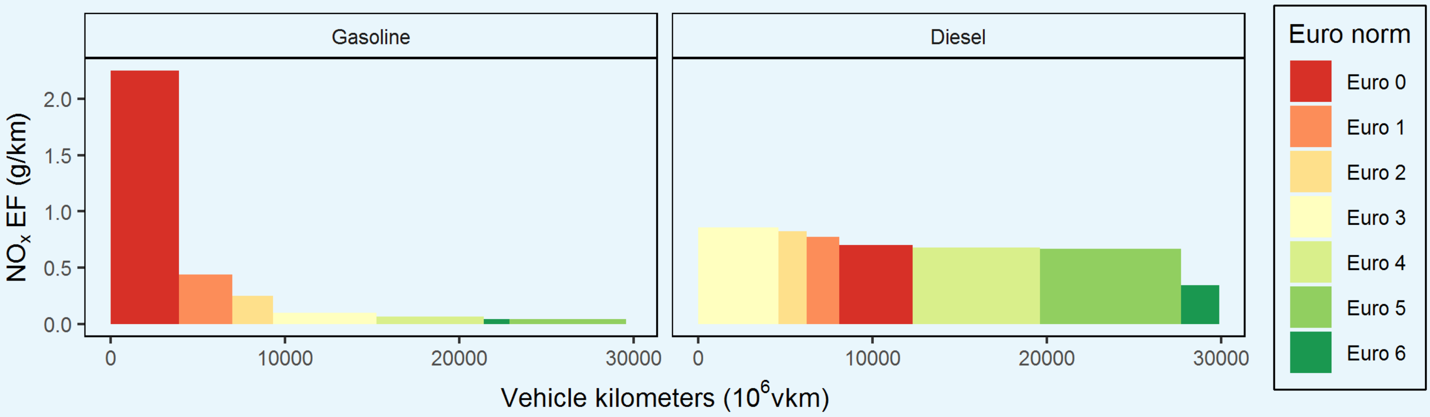
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

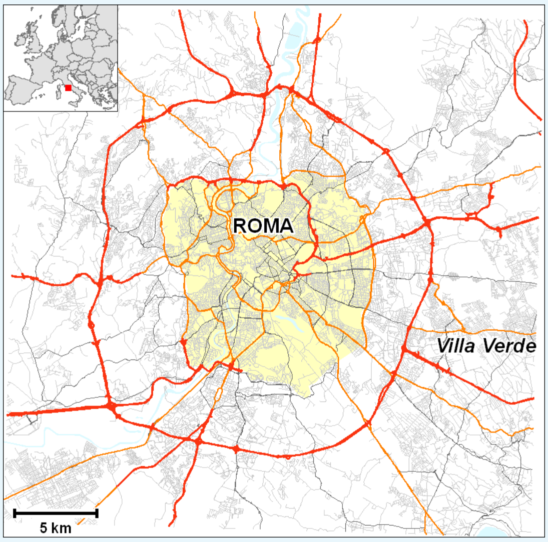


National emissions per fuel and Euro norm (passenger cars)

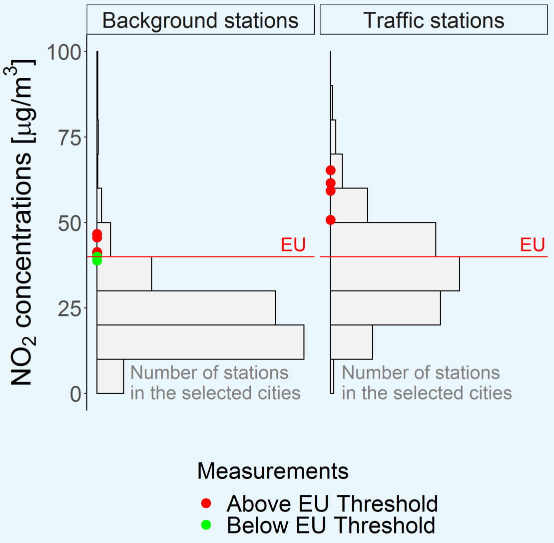


Roma (Italy)

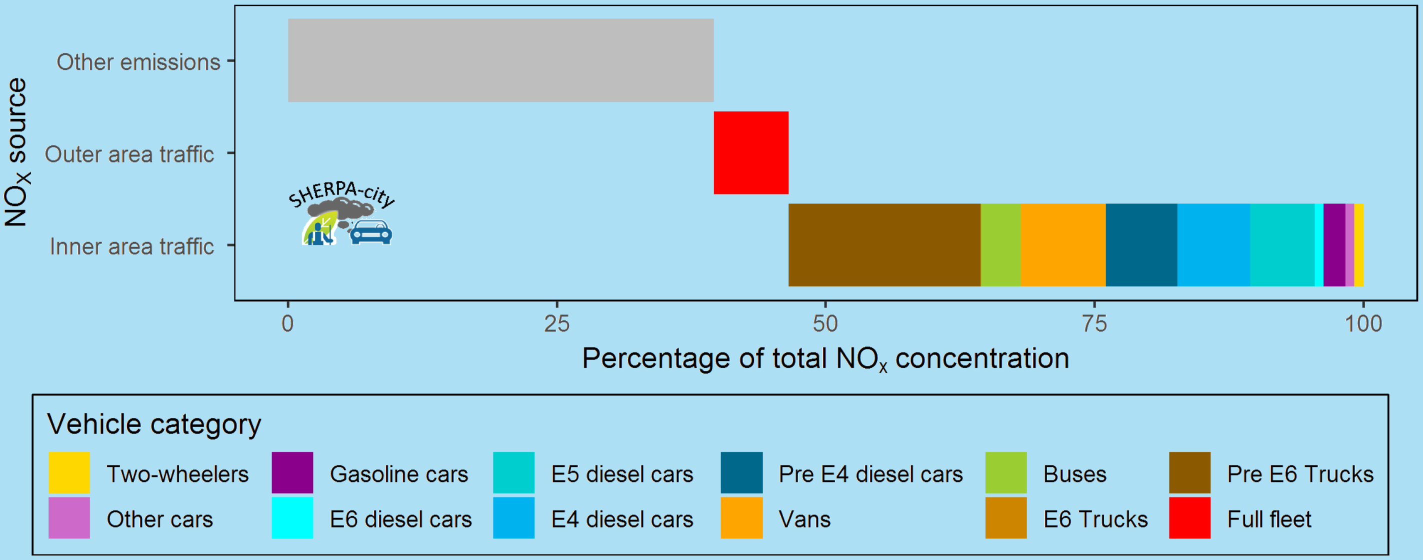
Inner (yellow) **and Outer** (white) **Area definition**



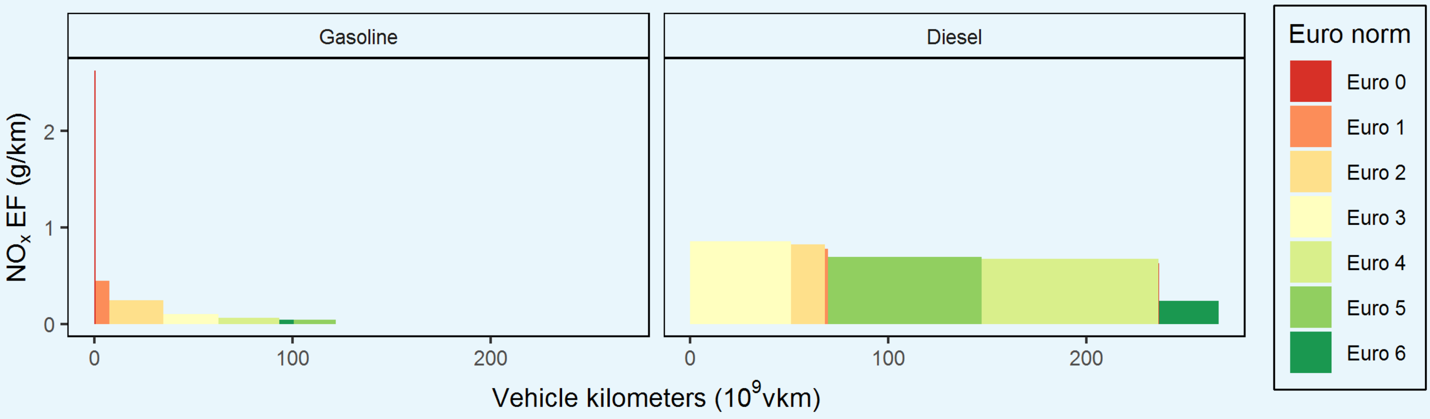
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

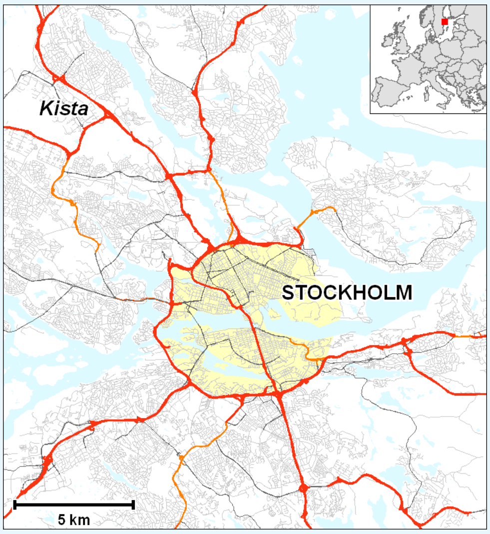


National emissions per fuel and Euro norm (passenger cars)

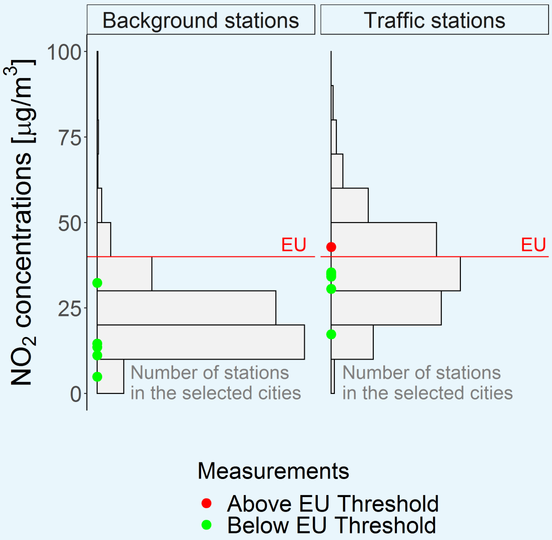


Stockholm (Sweden)

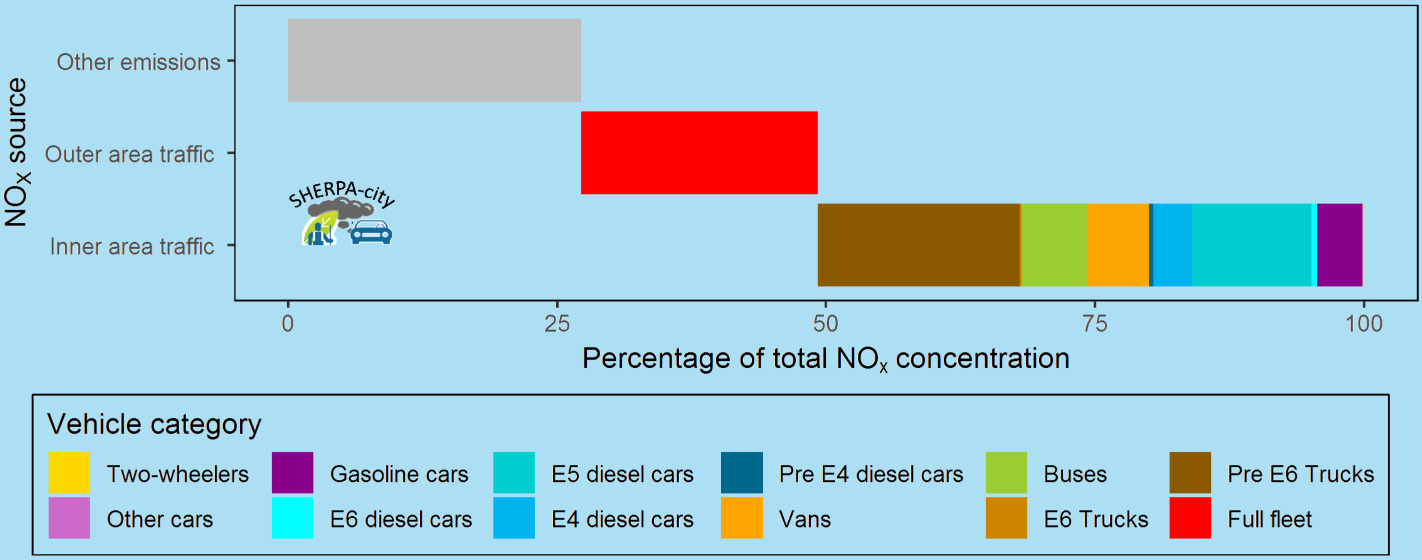
Inner (yellow) and Outer (white) Area definition



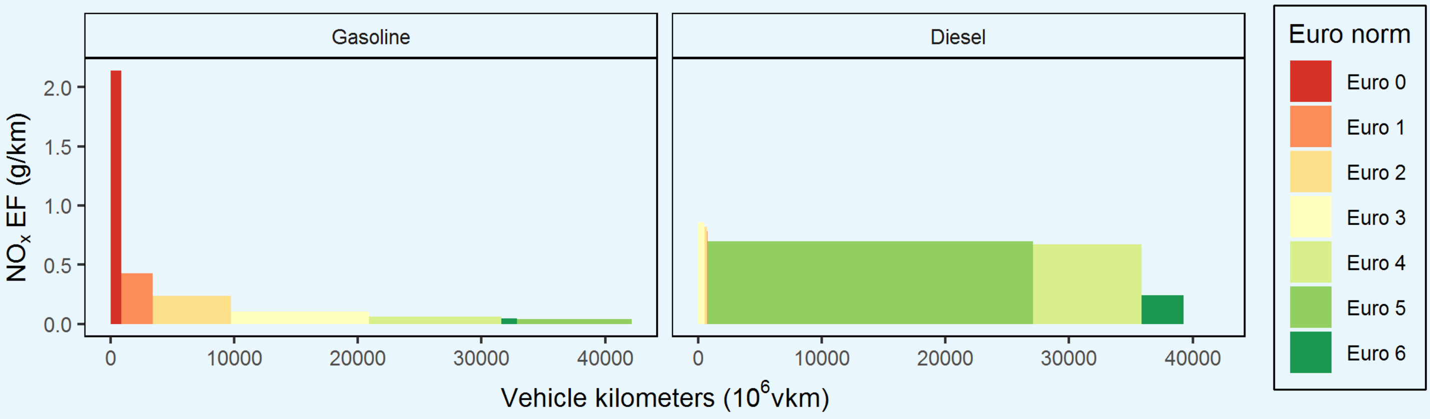
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

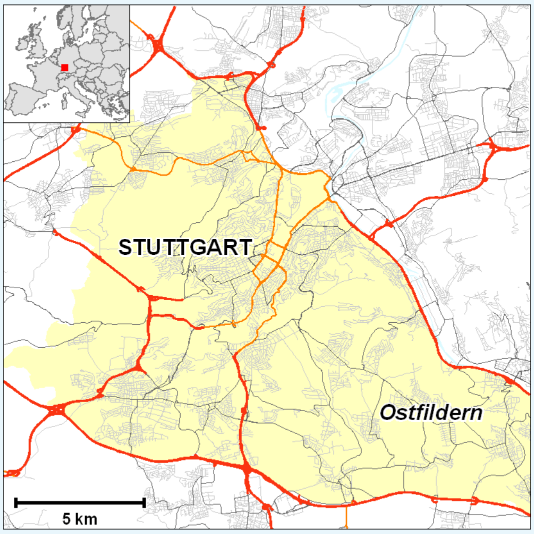


National emissions per fuel and Euro norm (passenger cars)

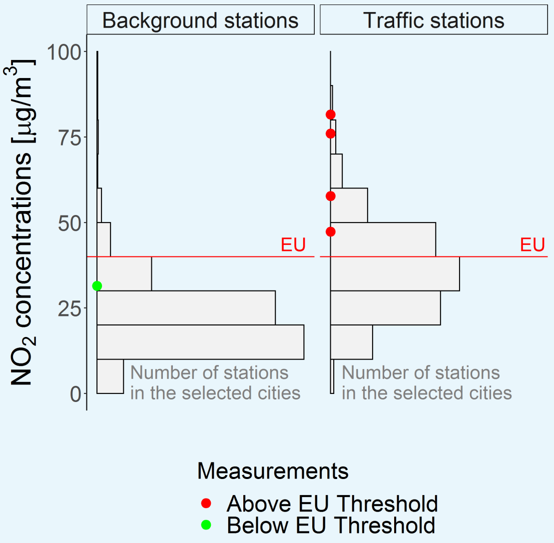


Stuttgart (Germany)

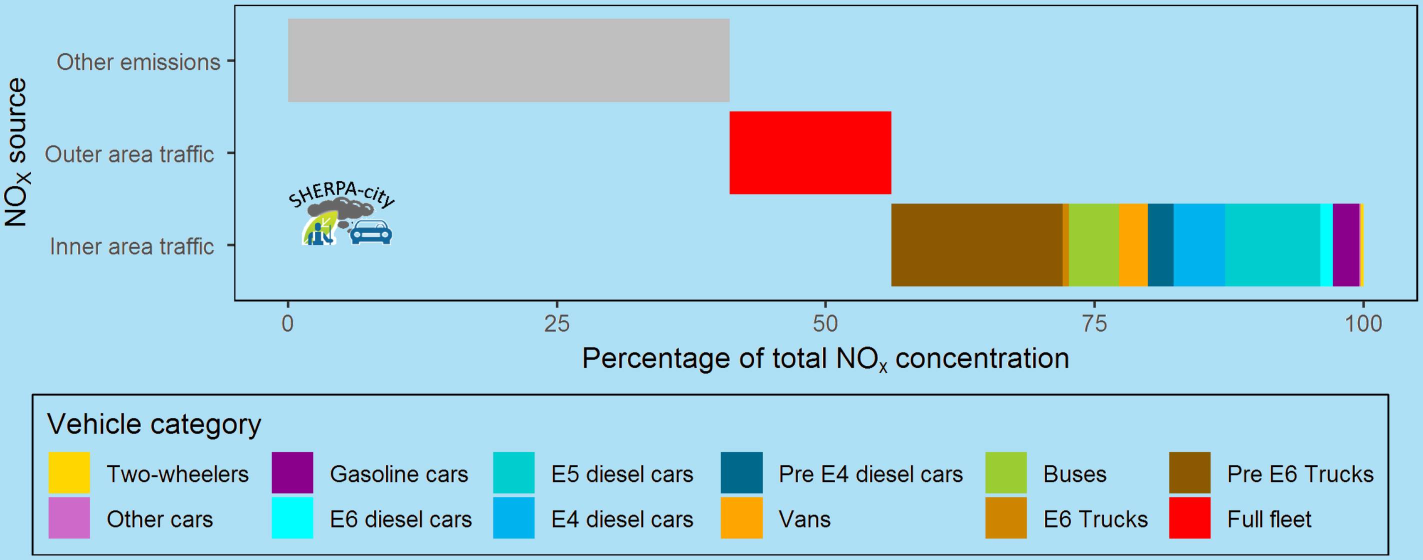
Inner (yellow) **and Outer** (white) **Area definition**



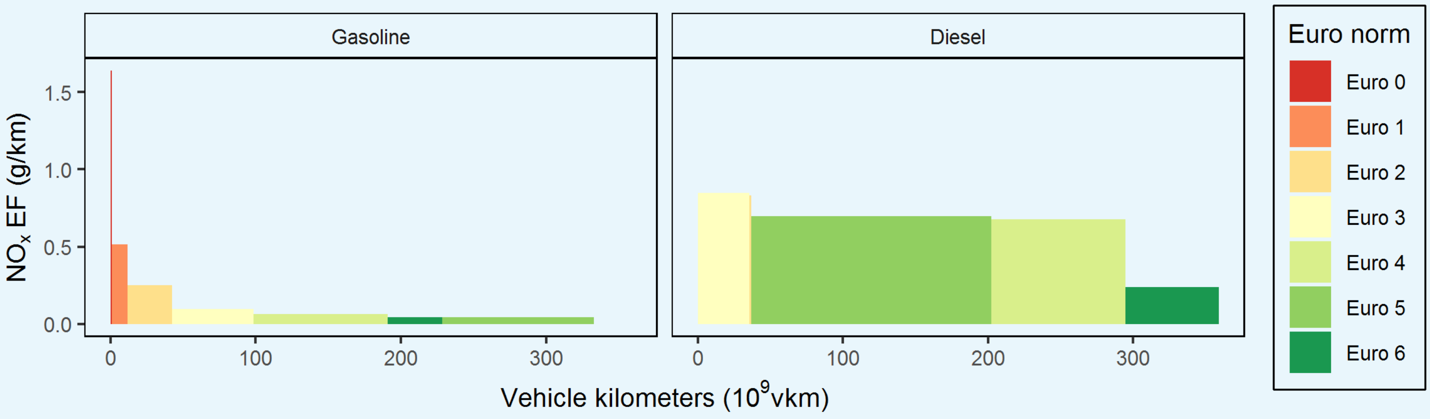
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

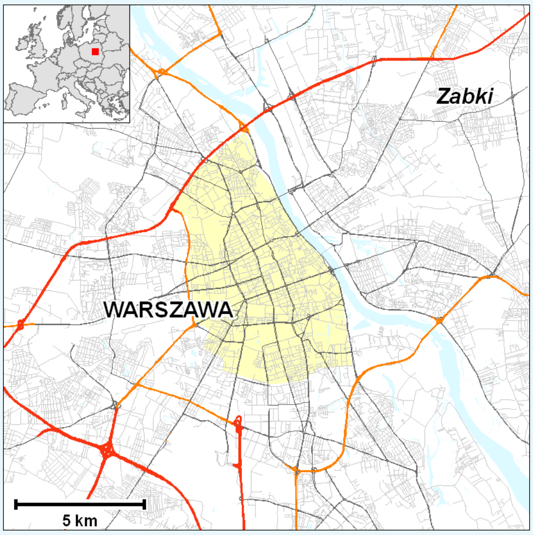


National emissions per fuel and Euro norm (passenger cars)

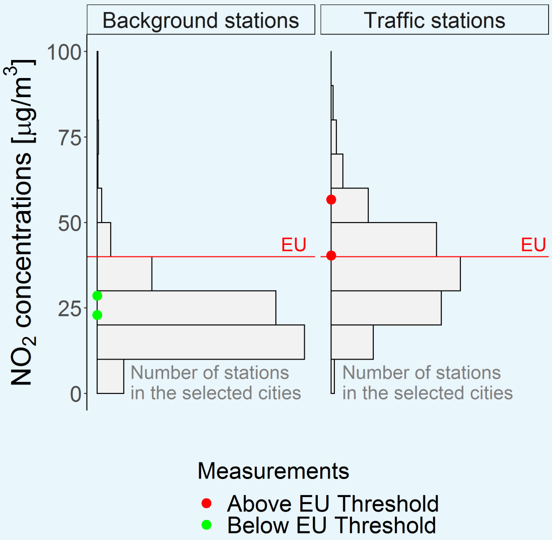


Warszawa (Poland)

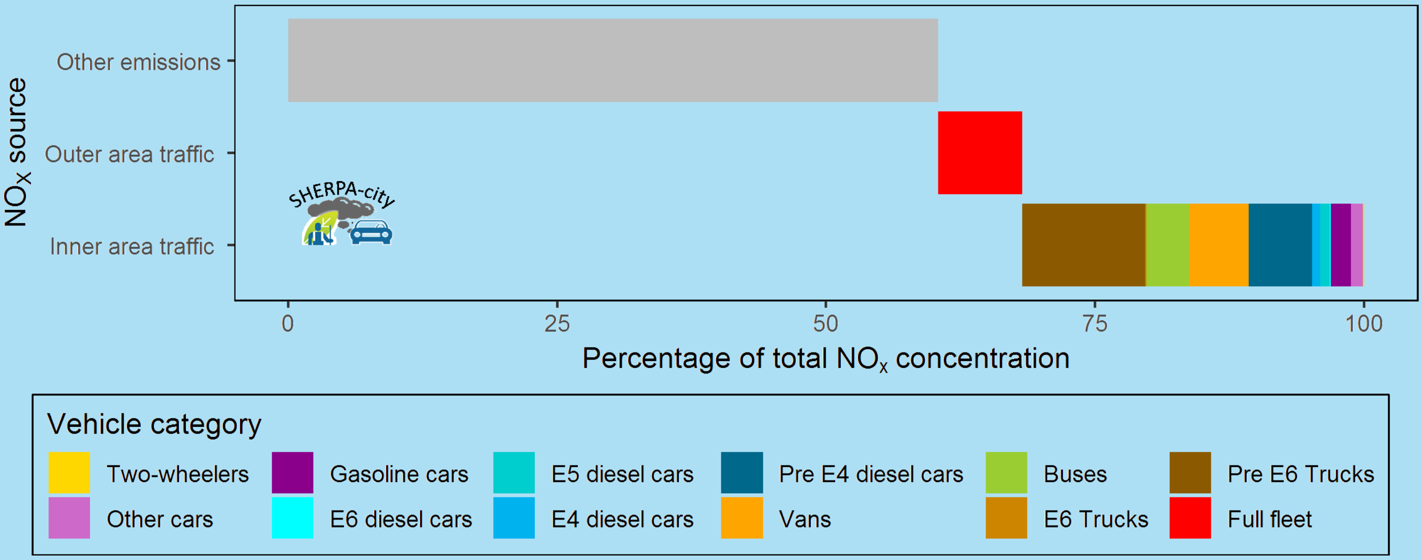
Inner (yellow) **and Outer** (white) **Area definition**



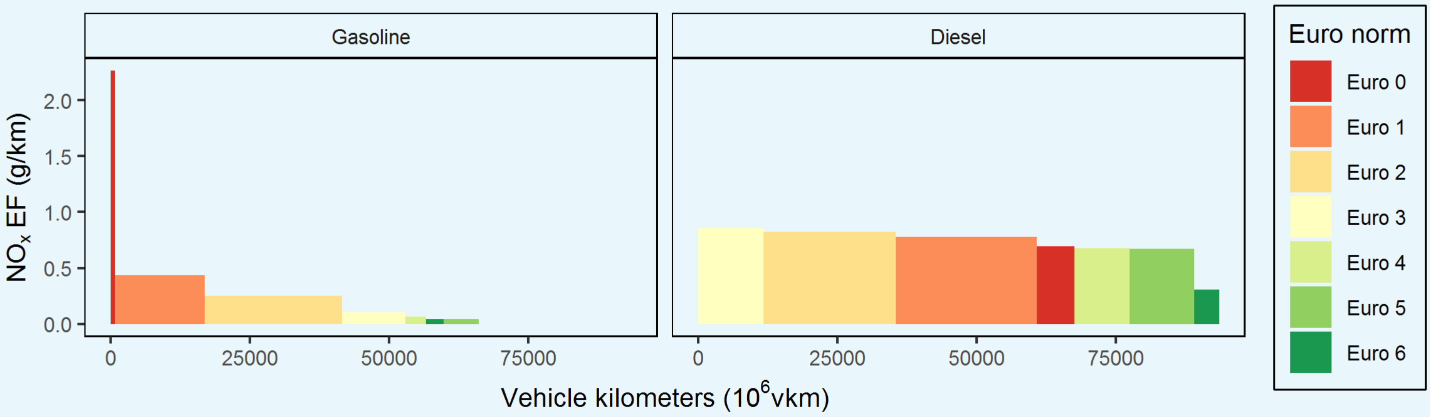
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

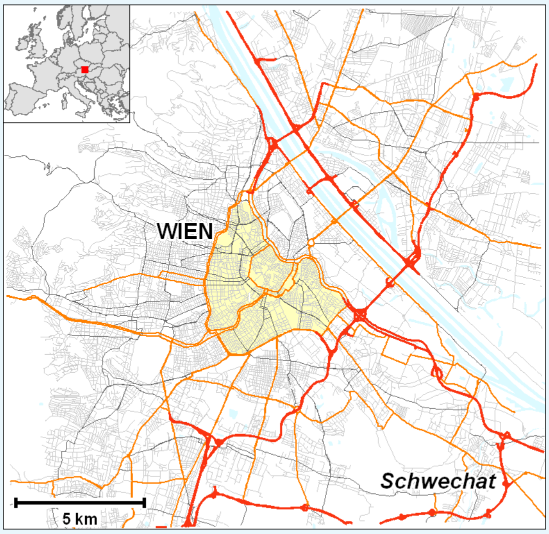


National emissions per fuel and Euro norm (passenger cars)

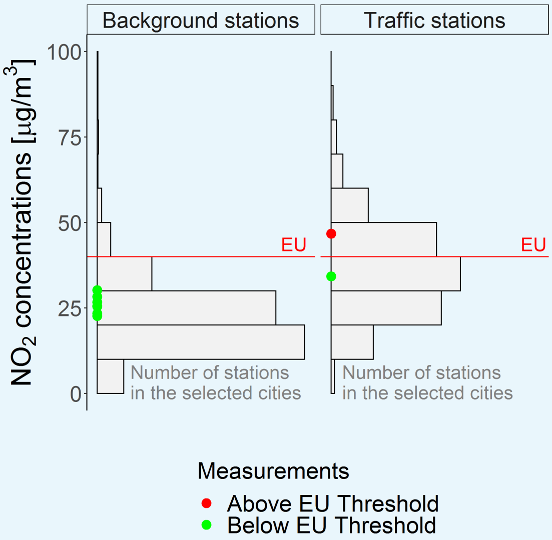


Wien (Austria)

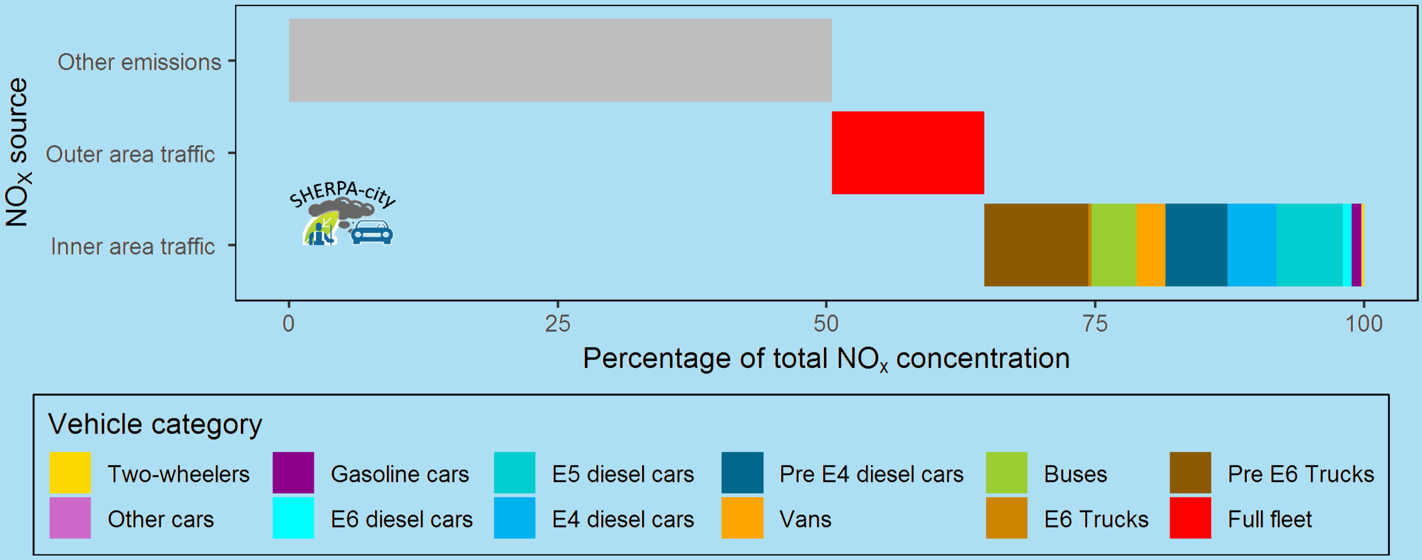
Inner (yellow) **and Outer** (white) **Area definition**



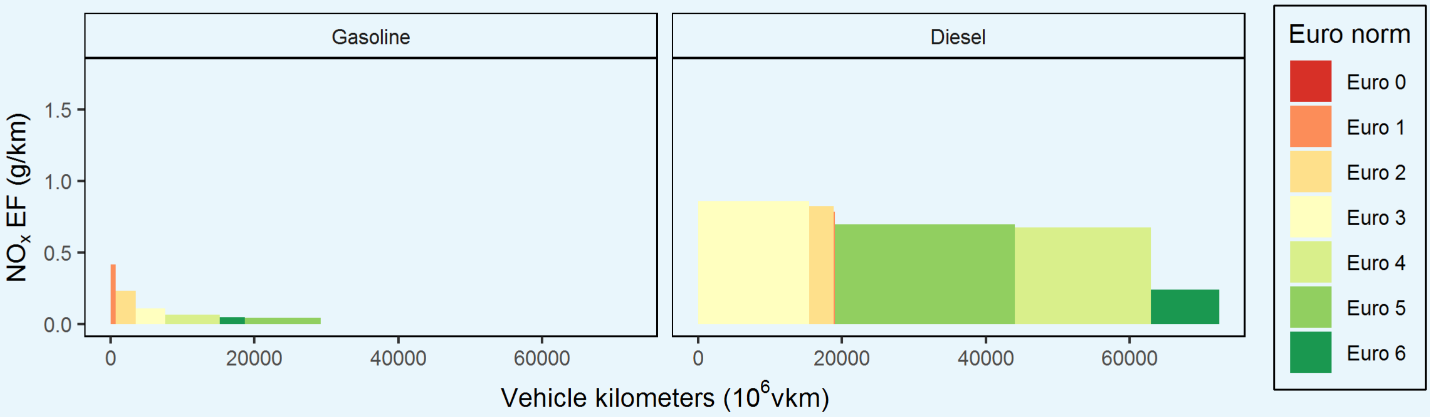
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

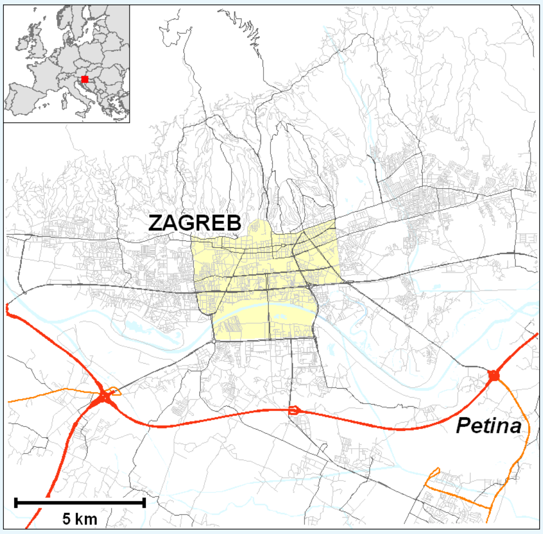


National emissions per fuel and Euro norm (passenger cars)

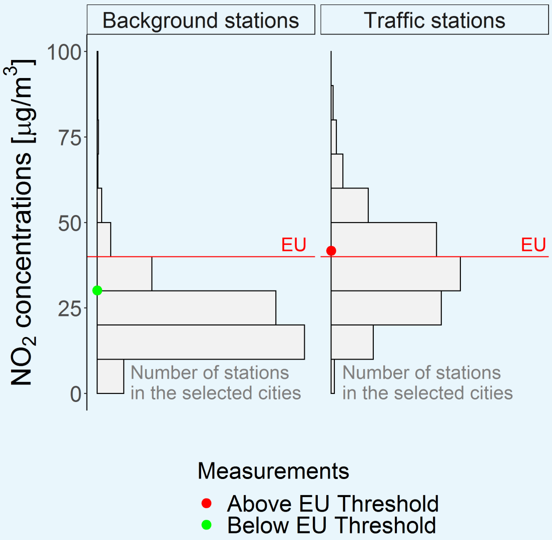


Zagreb (Croatia)

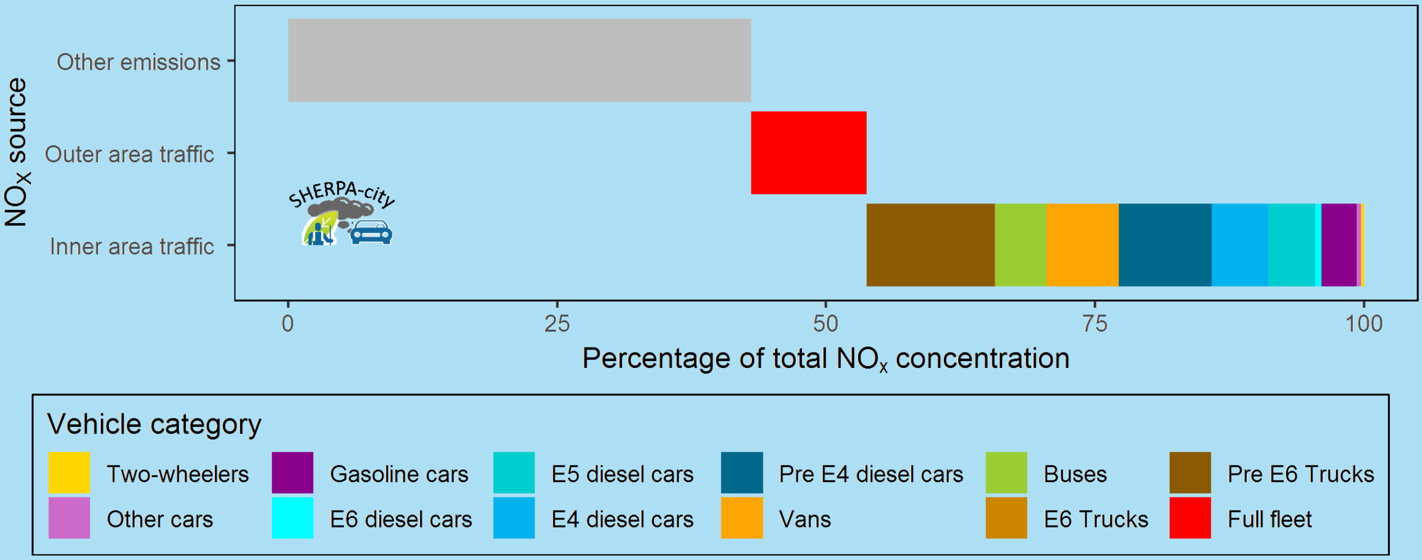
Inner (yellow) **and Outer** (white) **Area definition**



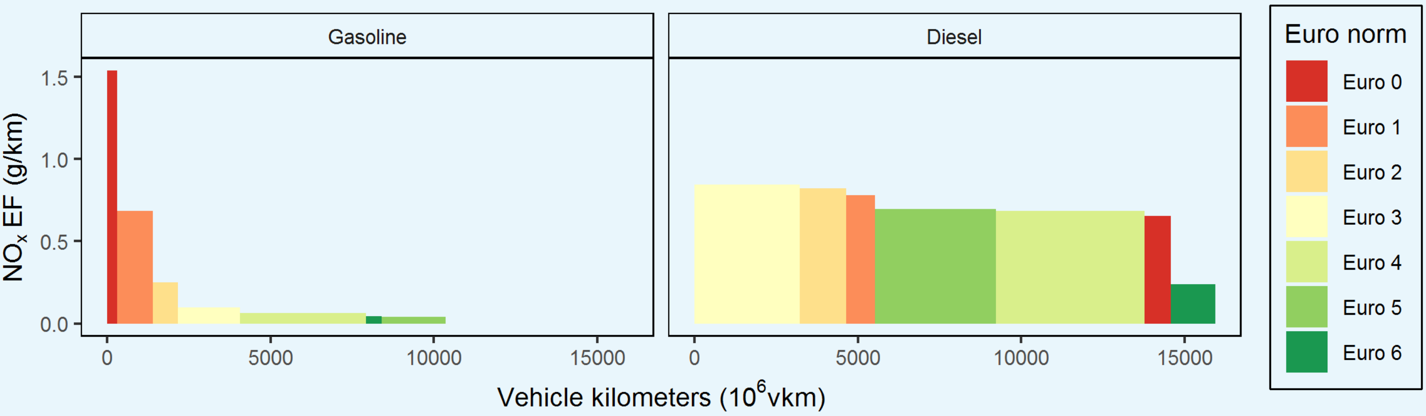
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area

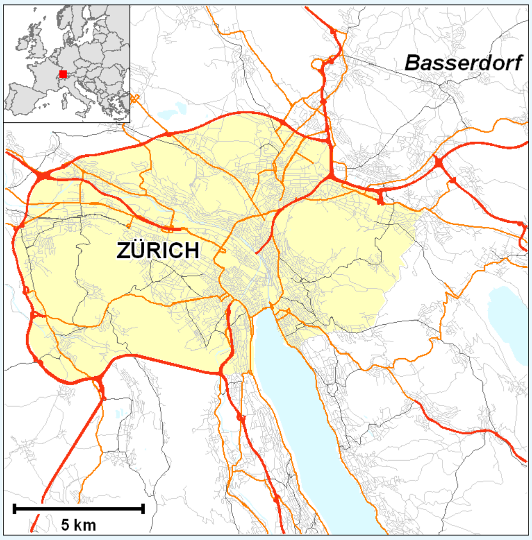


National emissions per fuel and Euro norm (passenger cars)

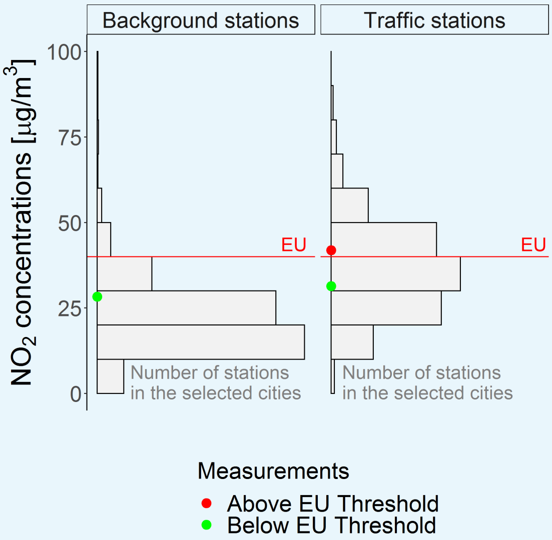


Zürich (Switzerland)

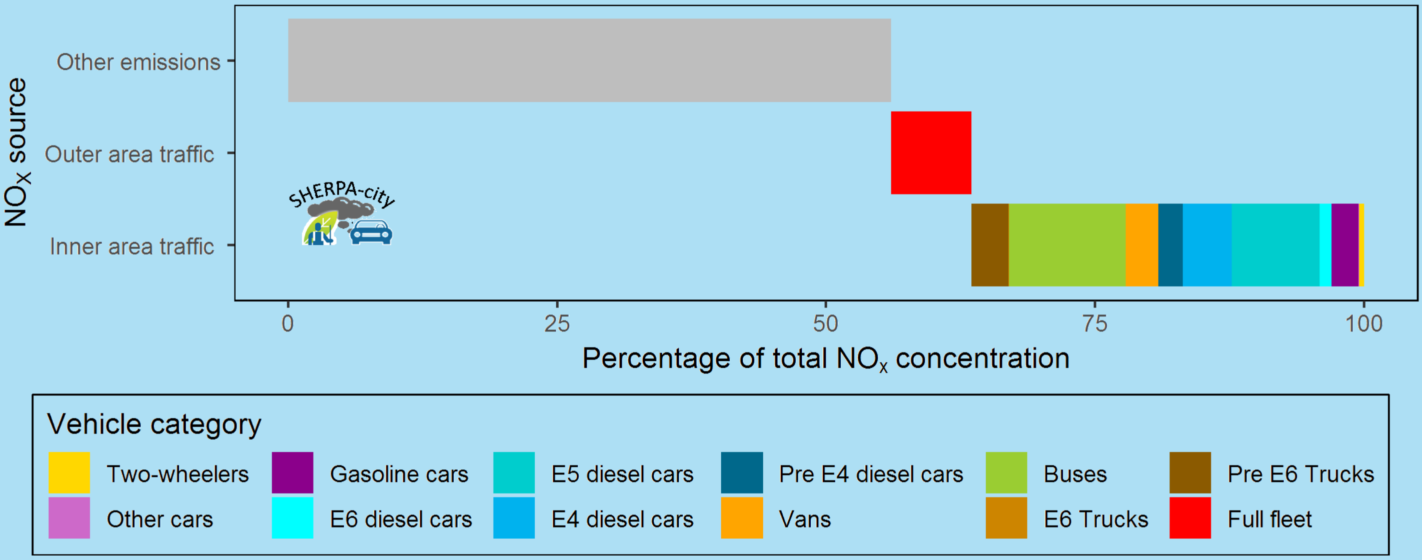
Inner (yellow) **and Outer** (white) **Area definition**



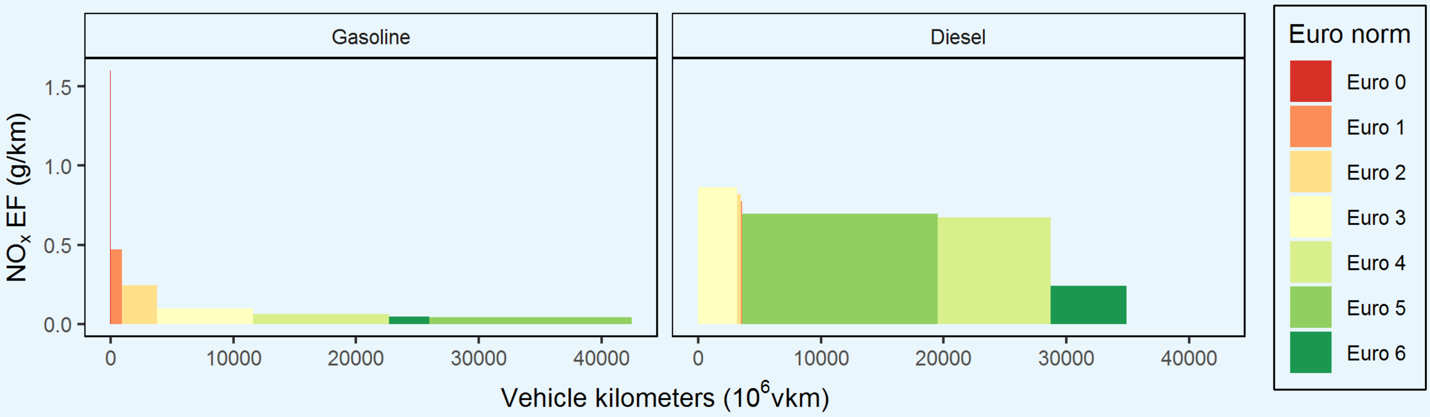
Yearly average concentration (2016)



Source allocation for the average concentration in the Inner area



National emissions per fuel and Euro norm (passenger cars)



Cities index

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