Dynaxibility4CE

D.T2.2.8. Guideline for air quality data collection / Management approaches for clean mobility

FINAL VERSION
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Index

1. Introduction

Mobility is recognized as one of major contribution to atmospheric pollution together with the different production activities (industry, agriculture) and also domestic heating (and cooling). This is certainly true at least for a subset of pollutants which have been demonstrated as a real threat for people health.

The effect on pollutant concentrations due to the various contributions is rather different according to the location where air quality conditions are considered (urban areas vs. countryside); also inside cities the situation may be different among the various areas (traffic flow, residential areas, parks).

For all of these reasons, the impact of mobility on air quality is certainly an essential issue to be considered. Administrations at all different levels (local, national, European) are taking decisions aiming at reducing the traffic flow as well as at reducing traffic impact on air quality inside our cities and their surroundings. At the same time, new technologies developing in the framework of car industry are also essential toward a further mitigation of negative effects associated to mobility.

These guidelines represent an attempt to put together major issues associated to mobility and air quality. The first part of the guidelines deals with the main links between air quality and mobility issues, which will be reviewed in order to set up the framework of the guidelines themselves. A section will be devoted to the collection of the mobility information which are relevant for air quality assessment, with a specific focus on data collected among the municipalities involved in Dynaxibility project. On the other hand, the second part of the guidelines is more specifically devoted to the monitoring of air pollutants, starting from the reference approach (standard monitoring stations), but also new cutting edge techniques which are recently developing. Each approach will be developed in a specific section. In addition, a review of the most important tools currently used to assess air quality will be presented in a specific section with some insights on the most used techniques.

2. Air quality and mobility

This chapter is devoted to a brief discussion about the contribution of mobility to air quality in Europe. The first section reports some information about the changes in EU emission standards of vehicles over the last decades. The second section includes data on the contribution of mobility to total emissions for some key traffic related pollutants. The last section aims at providing some hints about the expected evolution of traffic emissions over the coming decades.

2.1. EU emission standard for vehicles

Although the first emissions regulations date back to 1970, the first EU-wide standard – known as Euro 1 – wasn't introduced until 1992. Since then, there have been a series of Euro emissions standards, leading to the current Euro 6, introduced in September 2014 and rolled out for the majority of vehicle sales and registrations in September 2015. The regulations, which were designed to become more stringent over time, defined acceptable limits for exhaust emissions of vehicles sold in EU and EEA (European Economic Area) member states. The aim of Euro emissions standards was to reduce the levels of harmful exhaust emissions, chiefly: nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM).

The introduction of the Euro 1 standard in 1992 required the switch to unleaded petrol and the universal fitting of catalytic converters to petrol cars to reduce carbon monoxide (CO) emissions. Euro 4 (January 2005) and the later Euro 5 (September 2009) concentrated on cleaning up emissions from diesel cars, especially reducing particulate matter (PM) and oxides of nitrogen (NOx). Some Euro 4 diesel cars were fitted with particulate filters. Euro 5 further tightened the limits on particulate emissions from diesel engines and all diesel cars needed particulate filters to meet the new requirements. There was some tightening of NOx limits too (28% reduction compared to Euro 4) as well as, for the first time, a particulates limit for petrol engines – applicable to direct injection engines only. Addressing the effects of very fine particle emissions, In addition to emission limit for PM mass, EURO 6 regulation has included a standard for total particle number. The limit is set to 6 x 1011 part/km for diesel and petrol cars. The emission standards were different for passenger cars, light commercial vehicles and heavy duty vehicles and busses.

Emissions are tested over a chassis dynamometer test cycle and different test procedures were approved over time by EU to verify compliance with emission standard.

The 2000/2005 standards were accompanied by an introduction of more stringent fuel regulations (minimum diesel cetane number of 51 in 2000, maximum diesel sulfur content of 350 ppm in 2000 and 50 ppm in 2005, maximum petrol sulfur content of 150 ppm in 2000 and 50 ppm in 2005, “Sulfur-free” diesel and gasoline fuels mandatory from 2009).

Figure 2.1 compares car emission limits for the different pollutants as defined by EU standards from EURO 1 to EURO 6.

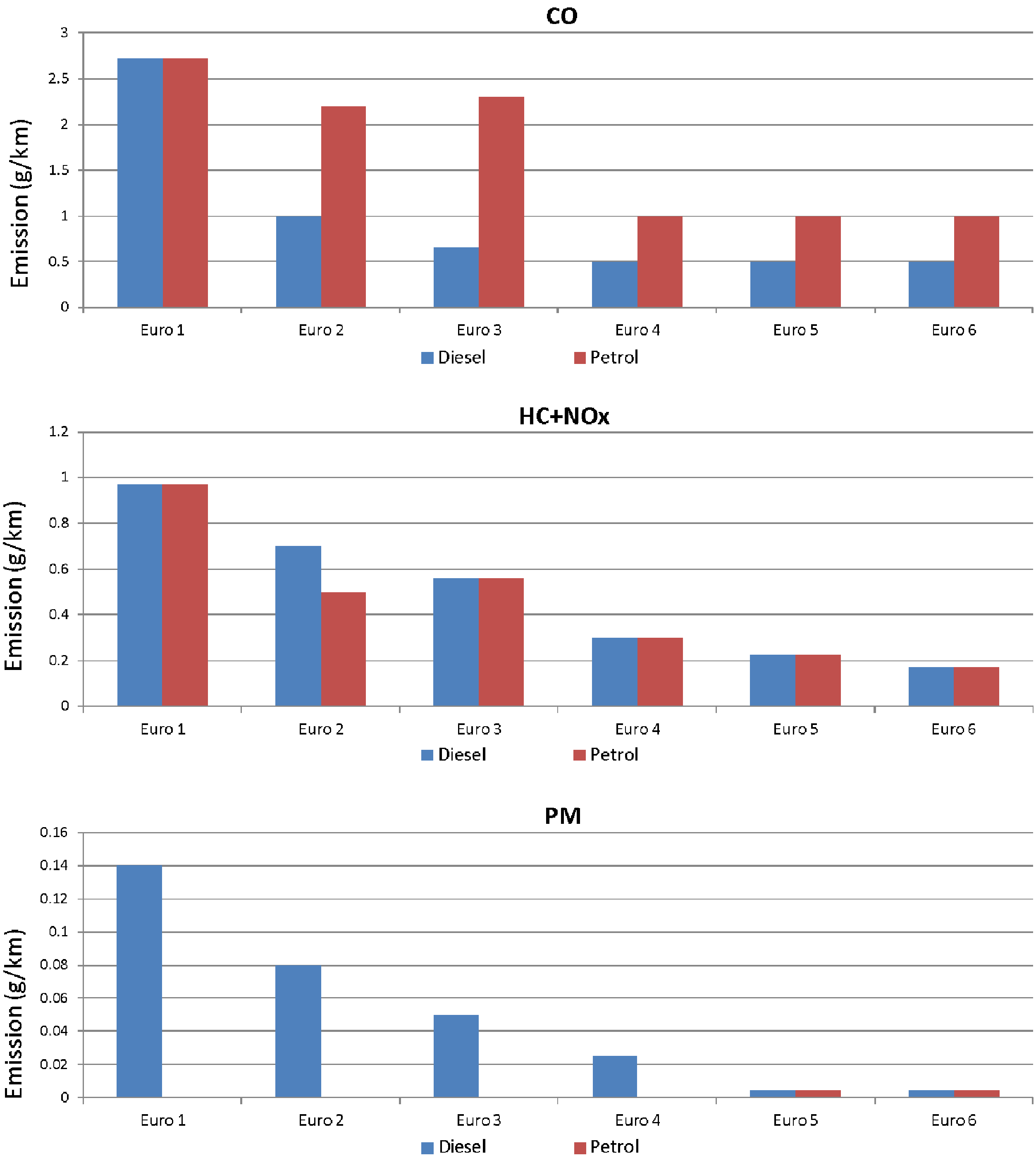

Fig. 2.1. Emission limits for cars set by EU for some pollutants

A similar path for abatement of pollutant emissions was laid down by EU authorities for heavy duty vehicles and busses. For heavy duty vehicles there are two sets of emission standards, with different type of testing requirements: Steady-State Testing and Transient Testing. Table 2.1 shows the impressive reduction of emissions from the first to the last standards for Steady State Testing.

Stage	Date	CO	HC	NOx	PM
		g/kWh			
Euro I	1993, ≤ 85 kW	4.5	1.1	8	0.612
	1993, > 85 kW	4.5	1.1	8	0.36
Euro II	1997	4	1.1	7	0.25
	1999	4	1.1	7	0.15
Euro III	2001	2.1	0.66	5	0.1
Euro IV	2006	1.5	0.46	3.5	0.02
Euro V	2009	1.5	0.46	2	0.02
Euro VI	2015	1.5	0.13	0.4	0.01

Table 2.1. EU emission standards for PM and NOx for Heaxy Duty Vehicles and Buses

2.1.1. Standards on emissions under real driving conditions

The Diesel emissions scandal that involved several car manufacturers in 2014 underlined the importance of the large differences that may be found comparing laboratory and real driving emission tests. Software manipulating air pollution tests was discovered in vehicles from some car makers. The software recognized when the standardized emissions test was being done and adjusted the engine to emit less during the test. The cars emitted much higher levels of pollution under real-world driving conditions (figure 2.2). Some cars emissions were higher even though there was no manipulated software. Scandals relating to higher-than-reported emissions from diesel engines began when the International Council on Clean Transportation (ICCT) reported discrepancies between European and US models of vehicles, beginning with the Volkswagen emissions scandal. Independent tests carried out by the German car club ADAC proved that, under normal driving conditions, diesel vehicles exceeded legal European emission limits for nitrogen oxide (NOx) by more than 10 times.

Also following the 2014 diesel emission scandal the regulatory emission test cycles have been changed and emissions are now tested over the Worldwide harmonized Light vehicles Test Cycle (WLTC) chassis dynamometer procedure, which has replaced the earlier NEDC test. In addition, Real Driving Emissions (RDE) testing requirements have been phased-in from 2017 to control vehicle emissions in real operation, outside of the laboratory emission test. So nowadays vehicle emissions must be tested on the road, in addition to laboratory testing.

Non-exhaust emissions

Non-exhaust emissions (NEE) from road traffic refers to particles released into the air from brake wear, tyre wear, road surface wear and resuspension of road dust during on-road vehicle usage. These emissions arise regardless of the type of vehicle and its mode of power, and contribute to the total ambient particulate matter burden associated with human illness and premature mortality. No legislation is currently in place specifically to limit or reduce NEE particles, so whilst legislation has been effective at driving down emissions of particles from the exhausts of internal-combustion-engine vehicles, the NEE proportion of road traffic emissions has increased.

Data from the UK National Atmospheric Emissions Inventory (https://naei.beis.gov.uk/) indicate that particles from brake wear, tyre wear and road surface wear currently constitute 60% and 73% (by mass), respectively, of primary PM2.5 and PM10 emissions from road transport, and will become more dominant in the future (7.4% and 8.5% of all-sectors UK primary PM2.5 and PM10 emissions). Data from London Marylebone Road indicate a NEE contribution (including resuspension) of 4-5 µg/m^3 to the roadside increment in PM, mostly in the coarse particle fraction (PM10-2.5). Other studies, including dispersion modelling, also indicate total NEE contributions, including resuspension, of up to several μg/m³ of PM10 at busy roadsides, and in the region 1-2 μg/m³ for urban background.

Therefore, to achieve further gains in PM2.5 and PM10 air quality in relation to road transport sources requires attention to reducing non-exhaust emissions, not solely a focus on lowering exhaust emissions.

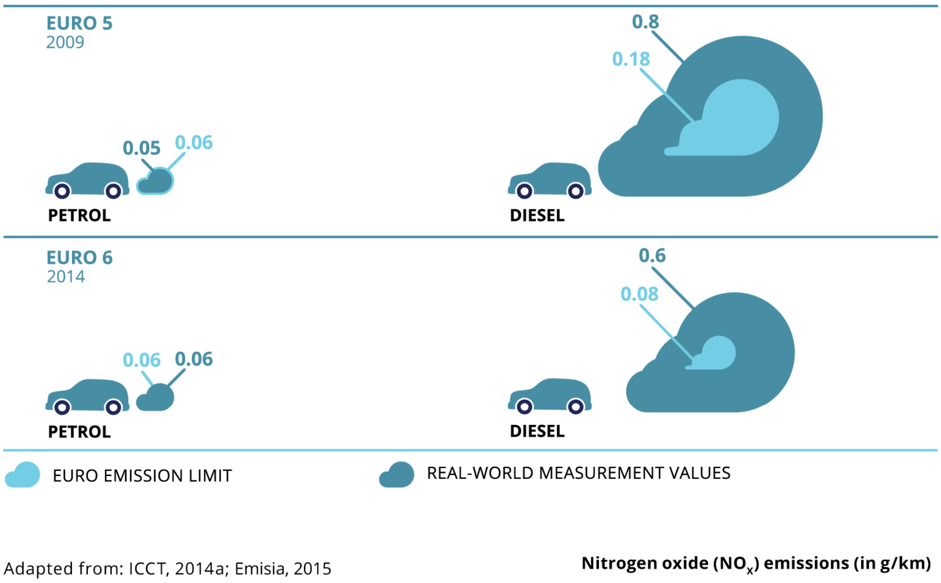

Figure 2.2. Differences between regulatory and real world emissions

The magnitudes of non-exhaust emissions are, however, highly uncertain, particularly when compared to data for exhaust emissions. Emissions vary widely according to brake, tyre and road-surface material, and with driving style. The NEE emission factors used in inventories have a wide span of uncertainty – greater than a factor of two is typical – including uncertainty in splits between PM10 and PM2.5 size fractions. The emission factors are also largely based on data from the 1990s and have not changed as vehicle designs and fleet composition have changed, in contrast to the regularly updated factors used for exhaust emissions.

The available data indicate that brake, tyre and road-surface wear contribute approximately equally to sources of NEE. NEE particles are also an important source of metals to the atmosphere; the UK national inventory estimates NEE contributions of 47% and 21% for Cu and Zn, primarily associated with brake and tyre wear, respectively. The national inventory does not include estimates of road dust resuspension.

NEE are especially important in urban environments. Approximately half of NEE occurs on urban roads, owing to the greater braking per km than on non-urban roads. Emissions may also be high in areas such as trunk-road exits. Tyre-wear emissions are estimated to be greatest on high-traffic trunk roads and motorways (both urban and rural).

The most effective mitigation strategies for NEE are to reduce the overall volume of traffic, lower the speed where traffic is free-flowing (e.g. trunk roads and motorways), and promote driving behaviour that reduces braking and higher-speed cornering. Resuspension of particles from the road surface can be lowered by reducing the material that is tracked onto public road surfaces by vehicle movements in and out of construction, waste-management and similar sites; and potentially by road sweeping, street washing and application of dust suppressants to street surfaces, although the impacts on airborne PM from trials of these latter approaches have so far proven inconsistent and any benefits have been short-lived.

Regenerative braking does not rely on frictional wear of brake materials so vehicles using regenerative braking totally or partially, for example electric vehicles, should have lower brake wear emissions. However, tyre and road wear emissions increase with vehicle mass, which has implications for any vehicle with a powertrain that is heavier (for example due to additional battery and hardware mass) than the equivalent internal-combustion-engine vehicle it replaces. The net balance between reductions in brake wear emissions and potential increases in tyre and road wear emissions and resuspension for vehicles with regenerative braking remains unquantified, and will depend upon road type and driving mode, as both influence the balance between the different sources of emissions. In locations where brake wear makes a major contribution to overall NEE, it seems likely that there will be a net benefit, but this has yet to be demonstrated. Other yet unproven technological mitigation methods include trapping brake wear particles prior to emission, and mandating formulation of low-wear/low-emission tyres, brake pads and road surfaces.

Several national environmental agencies have recommended as an immediate priority that NEE are recognised as a source of ambient concentrations of airborne PM, even for vehicles with zero exhaust emissions of particles. A further priority is to work towards a consistent approach internationally for measurement of NEE and to update and narrow the uncertainties in their emission factors. Such a programme of work could form the basis for subsequently including criteria on brake and tyre wear emissions in future type approvals and regulations governing formulation. Further studies need to be conducted to quantify the efficacy of technical solutions on NEE reductions; in particular, to understand gains from use of regenerative braking versus potential increased tyre and road wear due to additional mass of vehicles incorporating such braking.

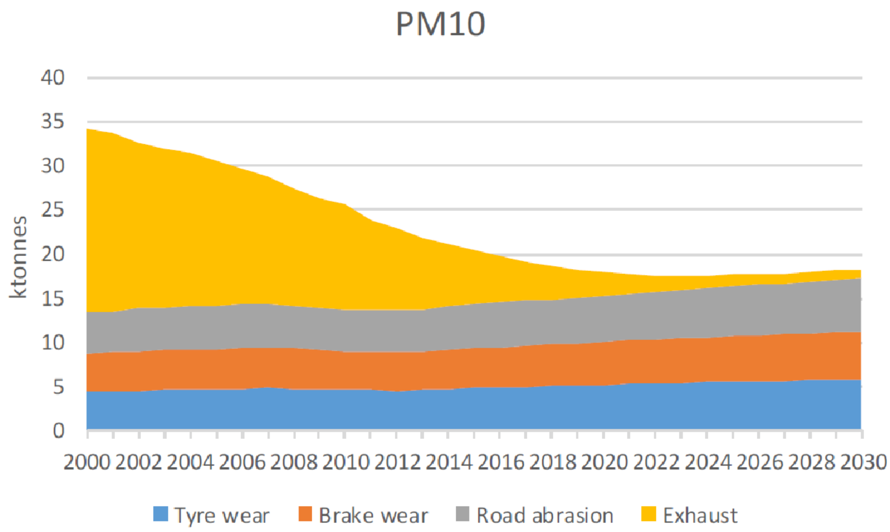

Figure 2.3. UK exhaust and non exhaust emissions from road transport. Source: Non-Exhaust Emissions from Road Traffic. Air Quality Expert Group for Department for Environment, Food and Rural Affair, UK.

2.2. Contribution of transport to air pollution

2.2.1. Methodology to estimate emissions from transport

To calculate air pollutant emissions from road transport, EEA has financed the development of COPERT (https://www.emisia.com/utilities/copert-data/). The software has been developed in the framework of the activities of the European Topic Centre on Air Pollution and Climate Change Mitigation (ETC/ACM) and scientific research underpinning the model is supported by the European Commission's Joint Research

Centre (JRC). COPERT, now available in its 4th version, has been developed for use by national experts to estimate emissions from road transport to be included in official annual national inventories. However, it is available and free for use in any other research, scientific and academic applications. It uses vehicle population, mileage, speed, and other data such as ambient temperature and calculates emissions and energy consumption for a specific country or region.

2.2.2. Emissions from transport

The transport sector and road transport in particular is one of the main contributor to total air pollutants emissions. EEA estimates of emissions by sectors (https://www.eea.europa.eu/publications/air-quality-in-europe-2021/sources-and-emissions-of-air) shows that this is especially true for CO, NOx, Benzene. The primary emission of PM10 and PM2.5 from transport are relevant as well but surely underestimate the role of transport in relation to PM concentration in EU countries. This is due to the key role of secondary processes in PM formation, i.e. the role of gas-gas and gas-particle recombination in air in producing new particles. In CE area secondary processes account for 40 to 60% of airborne PM. In this chapter we will focus on NOx and PM10 emissions due to their high concentrations in many CE urban areas.

In an overall framework showing a reduction of air pollutant emissions, transport sector has followed the general trend with a percentage contribution almost constant at 46-47% for NOx and at 12-15% for primary PM10 (period 200-2019).

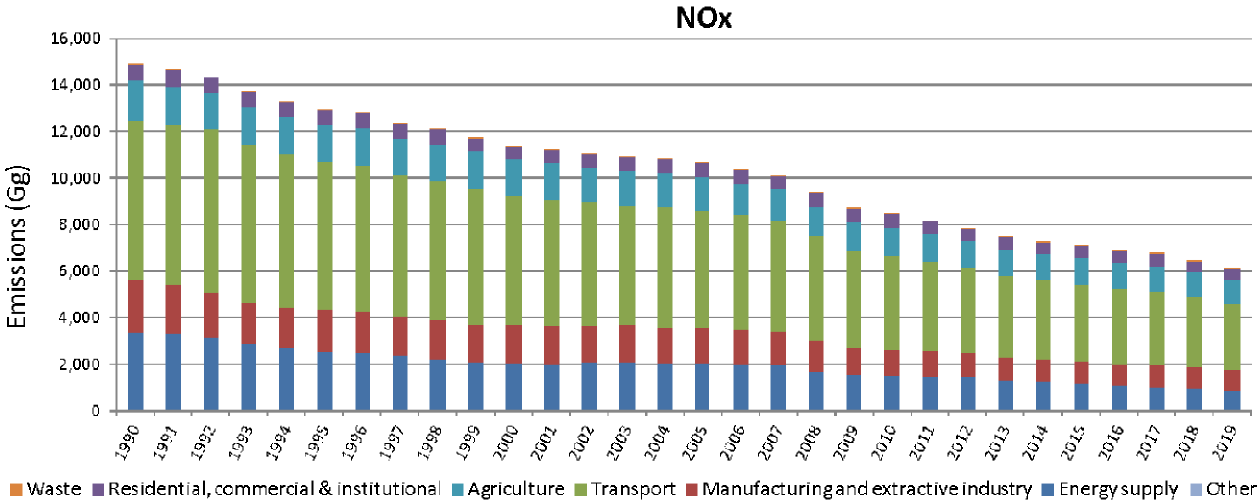

Figure 2.4. Time trend of contribution to NOx emissions by sector in EU28 (Source EEA).

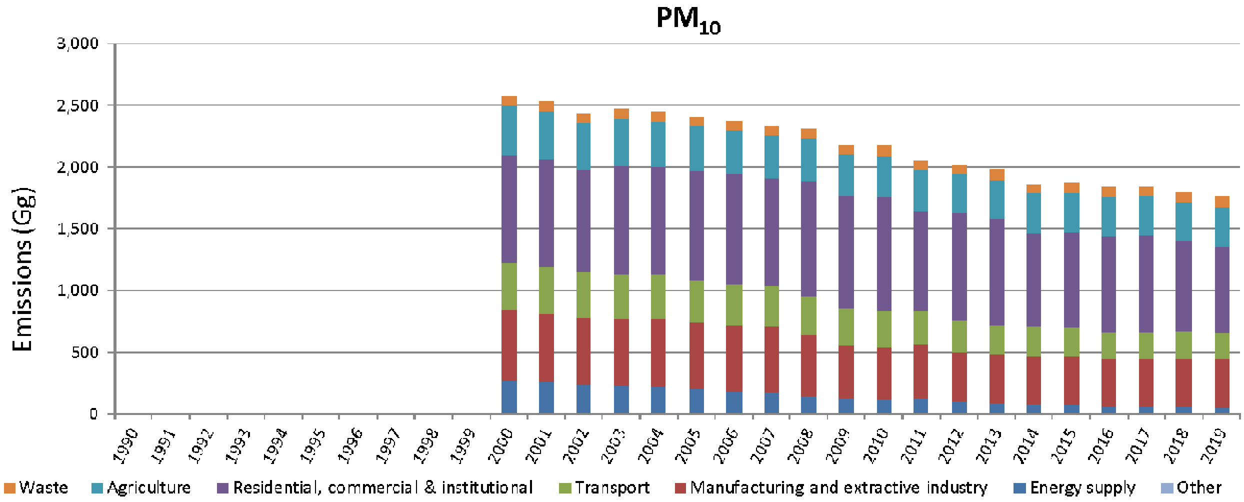

Figure 2.5. Time trend of contribution to PM10 emissions by sector in EU28 (Source EEA)

With regards to the specific subsectors of transport, the most relevant sources of NOx are due to the road transport passengers cars and heavy duty vehicles/busses. Their total quota dropped from 78% in 1990 to 69% in 2019. Also for PM10, road transport is the transport subsector contributing most to total transport emissions. The main difference with NOx is related to the significant emission quotas also due to subsectors different from passenger cars and heavy duty vehicles and in particular the light duty vehicles and "other road transport". The latter in particular is becoming more and more important with a percentage of 57%.

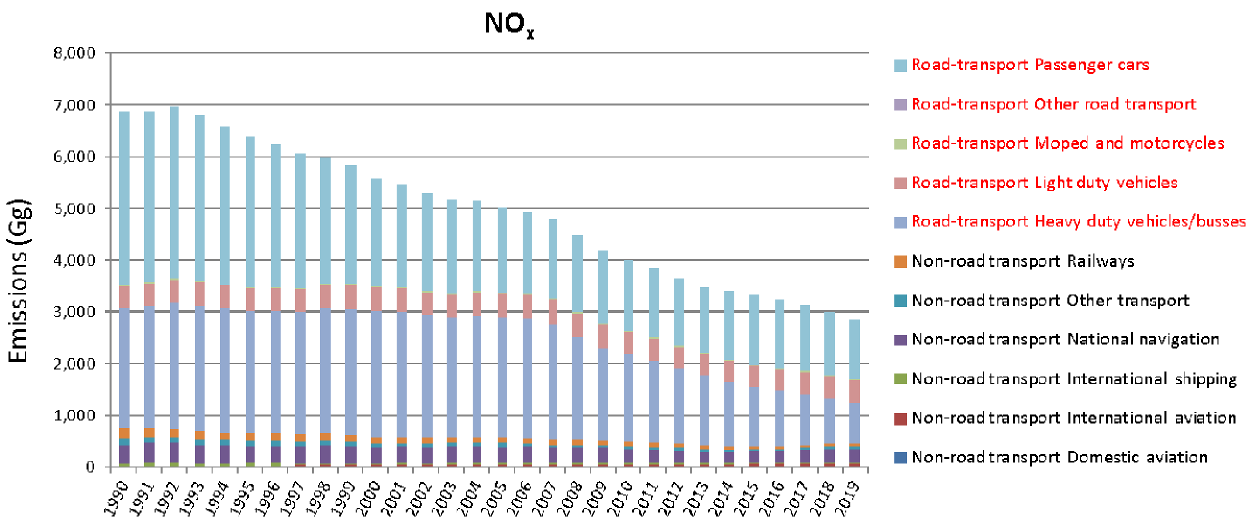

Figure 2.6. Time trend of contribution to NOx emissions by transport subsector in EU28 (Source EEA).

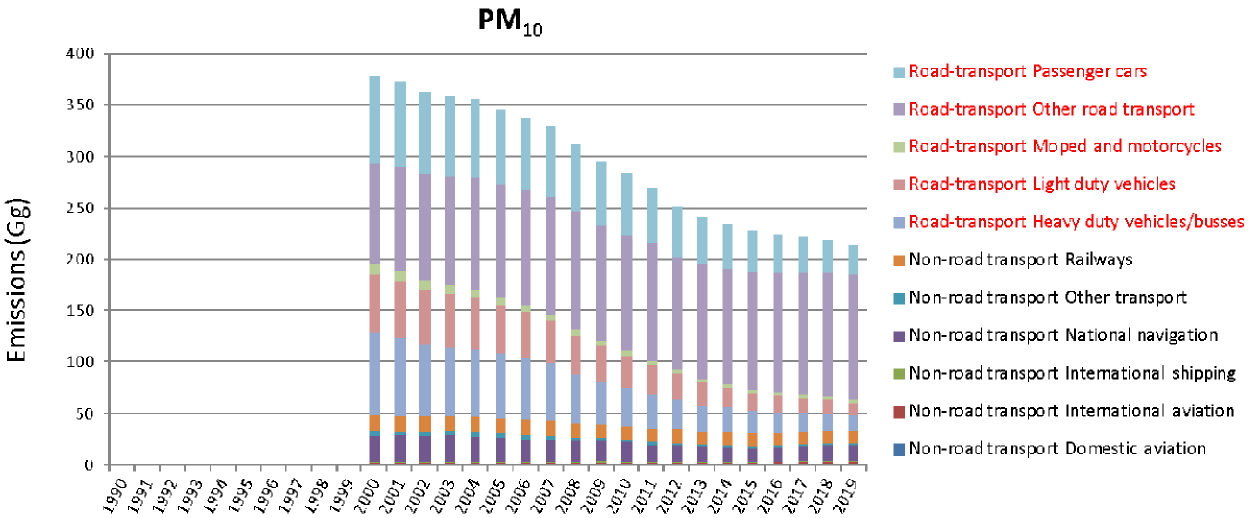

Figure 2.7. Time trend of contribution to NOx emissions by tran sport subsector in EU28 (Source EEA)

Transport sector is important not only for toxic pollutants but also for greenhouse gases (https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer). Figure 2.8 shows that road transportation became in 2019 the second largest contributors to total GHG emissions (following Energy supply). It is worth to note that the transport-related sources (International aviation and road transportation) are the only two sectors showing and increase in GHG emissions. Looking at transport sector in detail it arises that passenger cars are the main sources (15%) followed by heavy duty vehicles (trucks and buses – 5%), marine navigation and aviation (4% each).

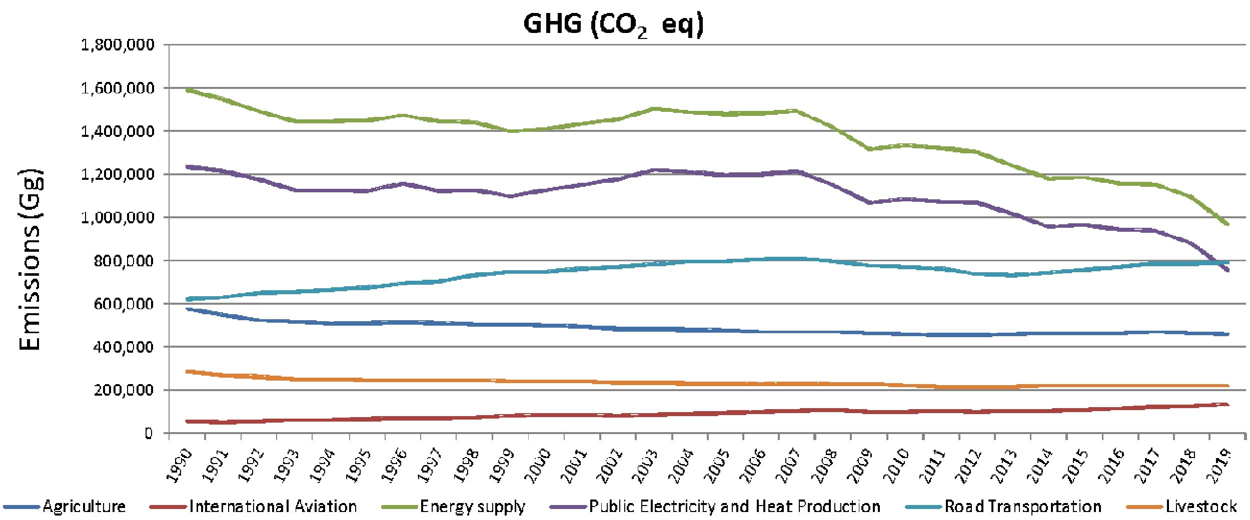

Figure 2.8. Contribution to GHG emissions by sector in EU28

2.3. Next emission standards and low/zero emission vehicles

2.3.1. Towards Euro 7 standards

Euro 6 emission standards were only introduced in 2015, but EU regulators are already working on the rules for Euro 7. It is expected that Euro 7 will be the final Euro emission standard prior to all cars becoming zero-emission. Completed proposals for Euro 7 are due to be presented to the European parliament in 2022 and would likely come into force around 2025.

While emission performance of vehicles has significantly improved thanks to Euro 6 standards, as seen before, road transport continues to represent one of the main causes of air pollution in European cities. There are also other factors affecting the emissions of air pollutants from road transport (e.g. increases in vehicle fleet numbers, overall kilometres driven, driving behaviour, poor maintenance). However, the current standards do not sufficiently contribute to the decrease in air pollutant emissions emerging from road transport, required for the move towards zero-pollution in Europe and the protection of human health from air pollutant emissions, with particular emphasis to urban settings.

The general objective of the post-Euro 6/VI initiative is to reduce the complexity and compliance costs of the existing Euro 6/VI vehicle emission standards, to provide appropriate and up-to-date limits for all air pollutant emissions. Furthermore, it shall ensure that new vehicles keep their air pollutant emissions under control throughout their entire lifetime and in all conditions of use. The Commission has identified the following preliminary set of policy options to achieve the specified objectives. They will be revised once all the results of the evaluations/studies are available. These options were designed using input from the Advisory Group on Vehicle Emission Standards (AGVES). The baseline scenario will consider no legislative changes to Euro 6/VI:

- Option 1 will consider a narrow revision of Euro 6/VI and addresses key simplification and coherence challenges in an increasingly complex environment. This option would involve setting up a single air pollutant emissions standard for cars, vans, lorries, and buses. It would also involve simplifying the existing emission tests while keeping a focus on real-world testing.
- Option 2 will consider a wider revision of Euro 6/VI by including, in addition to the measures in option 1, more stringent air pollutant emission limits for all vehicles. This would involve stricter emission limits for regulated air pollutants and/or new emission limits for currently non-regulated air pollutants, including non-CO2 greenhouse gas emissions.
- Option 3 will consider a comprehensive revision of Euro 6/VI by introducing, in addition to the measures in option 2, real-world emission monitoring over the entire lifetime of a vehicle. Data on air pollutant emissions collected through on-board monitoring (OBM) would subsequently support market surveillance and in-service conformity testing. These data may also be used for roadworthiness tests (i.e. periodic technical inspections and technical roadside inspections), and/or for automatically enabling a zero-emission mode depending on the location of a vehicle (“geo-fencing”).

In option 1, simplified emission testing is expected to only moderately decrease emissions caused by road transport. Option 2 would have a more extensive impact since it would include new and stricter limits on regulated and non-regulated emissions with a considerable effect on human health, the environment, and the climate. The benefits for air quality and climate change would likely be significantly more extensive in option 3. Option 3 combines the previous options with continuous real-world emission monitoring to ensure compliance, robustness against tampering, and enforcement over the entire lifetime of the vehicle. Furthermore, lower emissions of air pollutants such as NOx, ultrafine particles or NH3 would also improve air quality in urban areas and reduce total national pollutant emissions.

2.3.2. Hybrid and electric vehicles

Vehicle manufacturers currently use five main types of electric vehicle technology. These technologies vary in the way the on-board electricity is generated and/or recharged, and the way the internal electric motor and combustion engine are coupled. The mix of battery capacities, charging capabilities and technological complexity provides consumers with a choice of options when it comes to vehicle ranges, refuelling options and price. The main electric vehicle types are (EEA, 2016a):

• Battery electric vehicles (BEVs), powered solely by an electric motor, using electricity stored in an on-board battery.

• Plug-in hybrid electric vehicles (PHEVs), powered by an electric motor and an internal combustion engine that work together or separately.

• Range extended electric vehicles (REEVs), with a serial hybrid configuration in which their internal combustion engine has no direct link to the wheels. Instead, the combustion engine acts as an electricity generator and is used to power the electric motor or recharge the battery when it is low. The battery can also be charged from the grid.

• Hybrid electric vehicles (HEVs), combining an internal combustion engine and an electric motor that assists the conventional engine, for example during vehicle acceleration.

• Fuel cell electric vehicles (FCEVs), entirely propelled by electricity. The electric energy is provided by a fuel cell 'stack' that uses hydrogen from an on-board tank combined with oxygen from the air.

2.3.3. Environmental impact of electric vehicles

In the following chapter, we will compare electric vehicles and conventional internal combustion vehicles considering battery electric vehicles (BEV) based on the assumption that this will be the final step towards green mobility. The environmental impact of hybrid vehicles should be in an intermediate position between BEV and conventional vehicles

Impact on local air quality

BEVs can offer local air quality benefits due to zero exhaust emissions, e.g. nitrogen oxides (NOx) and particulate matter (PM). However, BEVs still emit PM locally from road, tyre, and brake wear, as all motor vehicles do. For local PM emissions, there is a great deal of uncertainty and variation in the results, depending on the assumptions made around ICEV emissions and on the different estimation methods for non-exhaust emissions. In addition, electricity generation also produces emissions. Here, the spatial location of emissions is important. Where power stations are located away from population centres, replacing ICEVs with BEVs is likely to lead to an improvement in urban air quality, even in contexts in which the total emissions of the latter may be greater. Under these circumstances, the contribution of power stations to regional background levels of air pollution, which also affect the air quality in cities, will probably be outweighed by a reduction in local emissions. As the proportion of renewable electricity increases and coal combustion decreases in the European electricity mix (EC, 2016) the advantage in terms of air quality of BEVs over ICEVS is likely to increase in tandem.

Impact in terms of Life Cycle Assessment (LCA)

There is an increasing need to understand BEVs from a systems perspective. This involves an in-depth consideration of the environmental impact of the product using life cycle assessment (LCA) as well as taking a broader 'circular economy' approach. On the one hand, LCA is a means of assessing the environmental impact associated with all stages of a product's life from cradle to grave: from raw material extraction and processing to the product's manufacture to its use in everyday life and finally to its end of life. Overall, across its life cycle, a typical BEV in Europe offers a reduction in greenhouse gas (GHG) emissions compared with its ICEV equivalent (e.g. EEA, 2019; Uwe Titge, 2017). The extent of the difference can depend on a number of factors, including the size of vehicle considered, the electricity mix and whether the BEV is compared with a petrol or diesel conventional vehicle.

Hawkins et al. (2013) reported life-cycle GHG emissions from BEVs charged using the average European electricity mix, 17-21 % and 26-30 % lower than similar diesel and petrol vehicles, respectively (detailed in Figure 6.1). This is broadly in line with more recent assessments based on the average European electricity mix. GHG emissions from raw material and production LCA phases are typically higher for a BEV than for its ICEV equivalent. This is related to the energy requirements for raw material extraction and processing as well as producing the batteries. For the end-of-life stage GHG emissions from both BEVS and ICEVS are low in terms of the overall life cycle; however, there is much uncertainty around the data. The potential for reuse and recycling of vehicle components is a key area of further research and development. The largest potential reduction in GHG emissions between a BEV and an ICEV occurs in the in-use phase, which can more than offset the higher impact of the raw materials extraction and production phases. However, the extent to which the GHG emissions advantage is realised during the in-use stage of BEVs depends strongly on the electricity mix. BEVs charged with electricity generated from coal currently have higher life-cycle emissions than ICEVs, whereas the life-cycle emissions of a BEV could be almost 90 % lower than an equivalent ICEV (IEA, 2017a) using electricity generated from wind power. In future, with greater use of lower carbon electricity in the European mix the typical GHG emissions saving of BEVs relative to ICEVs will increase. A key parameter to be considered in assessing the GHG life cycle impact of BEV is the Energy mix, i.e. the energy production methods used. The figure 2.9 compares the GHG total emissions of a medium size car using the energy mix of several EU countries (but the estimates for the production of batteries and cars are based on EU Energy mix).

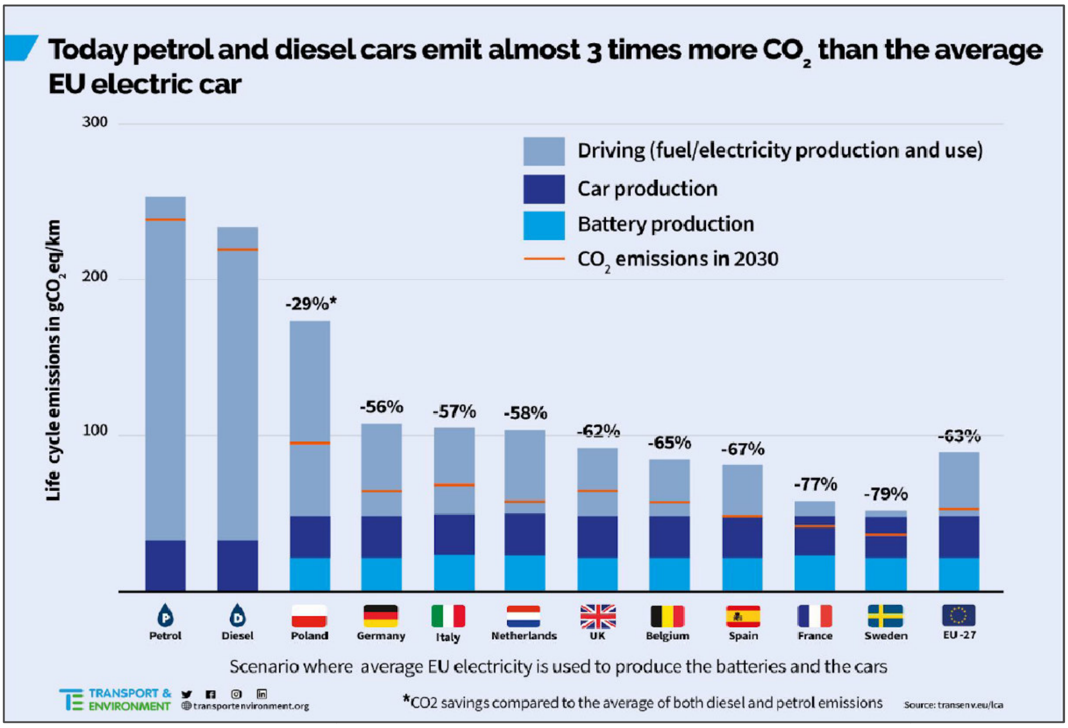

Figure 2.9. GHG emissions from BEV and internal combustion vehicles taking into account the entire life cycle. (EEA Report No 19/2020)

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3. Mobility information useful for air quality assessment

3.1. Traffic flow, emission classes of vehicles, origin-destination matrix

3.1.1. Traffic flow

Traffic flow means the number of vehicles passing through a given section, it is a variable number for both composition and characteristics. The determination of traffic flows is an indispensable parameter for the estimation of transport demand defined by the volume of traffic, its composition, and its average flow rate. The number of vehicles passing in a given period of time varies according to the type of road (highway, fast-moving, local, etc.), location (suburban, urban), vocation (industrial, commercial, residential) time considered (hour, all day, nocturnal, diurnal, working days, holidays, seasonal, etc.)

Taking the average parameters of traffic in large cities, Monday presents the highest traffic volume while it remains almost stationary in the days from Tuesday to Thursday. On Fridays there is a slight decrease that is accentuated on Saturday and Sunday. Measurements of the nearest-to-average traffic volumes shall be made on the middle days of the week.

The hourly variations are very consistent especially in the urban area where there are rush hours with maximum values and hours with low flows. There is a further variation between morning, afternoon, evening and night traffic volumes with flows reduced to zero. Flow measurements can be carried out manually or automatically through traffic meters (e.g. pressure, magnetic, photocell meters). Flow counts can be periodically repeated to allow for the assessment of fluctuations in demand over different time periods. The analysis of traffic flows also allows us to know the distribution of traffic, average speed, and journey times. The most modern tools to decongest traffic allow "real time" control of traffic volumes, this represents a significant advantage for the fluidisation of road traffic and for the choices to be made to optimise the use of infrastructure.

Road traffic is variable in relation to the geographical context and time period, any modification of a road artery or of the whole road network will affect the journey time, the speed of vehicles and the fluxes affecting emissions and concentrations of pollution in the atmosphere. Traffic flow detection takes place at defined points along the road network. The number of points and the location of the stations are defined according to the type of road network.

Fig. 3.1 – Monitoring station in Municipality of Parma

In many cities traffic flows are monitored continuously over the 24 hours and in many situations it is possible to consult the data online. The monitoring of flows during the peak period allows to derive the daily average traffic volumes (TGM = veh/day).

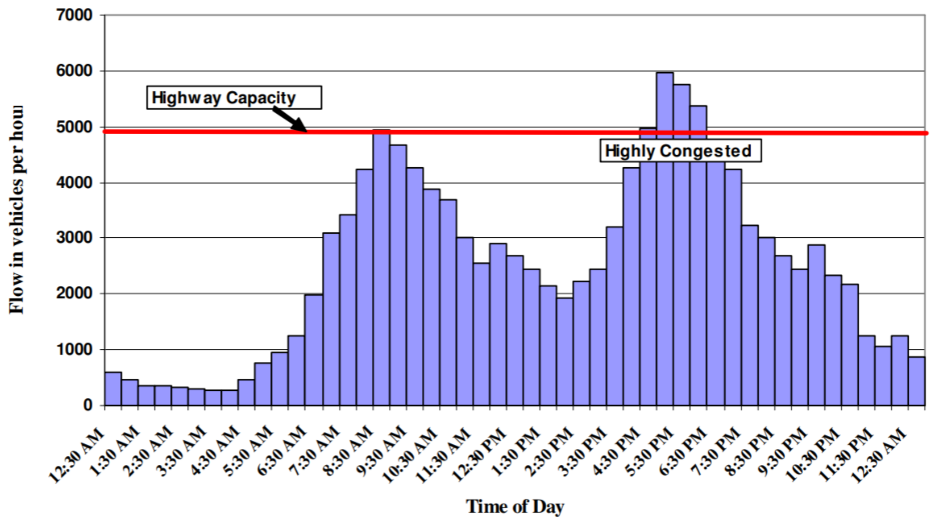


Fig. 3.2 – Vehicular flow distribution on 24 hours

The monitoring of traffic flows allows to analyse:

- vehicle classification (e.g. light vehicles: motor vehicles and cars; heavy vehicles: trucks and buses)
- average speed
- km covered
- travel time

There are various modelling software available that allow you to model the flows in order to make predictions about changes in traffic. The next figure shows the traffic simulation with flows in the morning peak band.

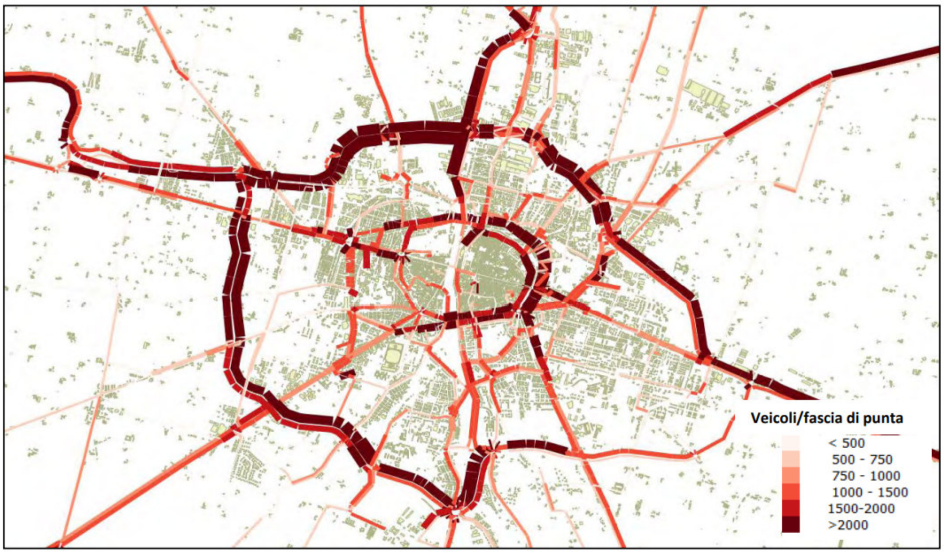


Fig. 3.3 – Flows representation on the road network using a traffic model

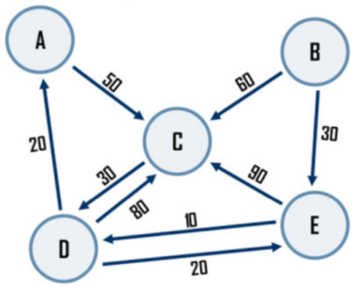
3.1.2. Origin-destination matrix

Thanks to the traffic flow analysis, it is possible to build the matrix Origin - Destination (O/D) useful to feed the traffic simulation model and estimate the transport demand. The transport demand is the total movement of persons and goods within a given territory and over a period of time.

In order to construct the O/D matrix it is necessary to identify the actors of the journeys and the motivation. Usually the O/D matrix concerns the journeys made by private motor vehicles to go to work, in fact it is the commuters who mainly and usually engage the network in certain time slots. The temporal characterisation concerns most often the peak hour on a weekday of a month free of holidays or free extended holiday periods. Then it is necessary to establish the spatial characteristics of the demand through the definition of the areas in which the production and destination of the journeys are supposed to be concentrated. Zoning divides the territory into smaller portions to avoid considering the displacements between all points of the area. This operation considers all points within each zone as a single point called "centroid" to which all the attributes and properties of the area are associated. Notice the number of movements attracted and generated from each zone to each other it is possible to derive the matrix O/D. It's convenient to build smaller areas close to the city centre by expanding them as you progress to the outlying areas. The O/D matrix can be defined by the type of zone by origin and destination:

- Internal travel: origin and destination are within the study area;
- Exchange movements: origin and destination are one internal and the other external to the study area;
- Crossing movements: origin and destination are both outside the study area.

Spatial Interactions



O/D Matrix

	A	B	C	D	E	Ti
A	0	0	50	0	0	50
B	0	0	60	0	30	90
C	0	0	0	30	0	30
D	20	0	80	0	20	120
E	0	0	90	10	0	100
Tj	20	0	280	40	50	**390**

Figure 1. A conceptual diagram of an origin-destination matrix. Source: Dr. Jean-Paul Rodrigue, Dept. of Global Studies & Geography , Hofstra University, New York, USA.

Fig. 3.4 – conceptual diagram of an origin-destination matrix

The O/D matrix flows allow to simulate the traffic and the emissions to the atmosphere deriving from it thanks to the use of simulation models. The models are based on a graph that simplifies the road network into arcs and nodes to which are assigned the characteristics of the network and the detected flow at the cross-section points. Thanks to the O/D matrix and a mathematical model it is possible to assign the traffic volumes to all the rest of the road network. Generally, the flows are represented by the thickness of the arc which is proportional to the size of the passages. The simulation models represent the state of fact and give the possibility to predict the behaviour of users on the network in case of changes, interruptions or congestion.

Traffic simulation is an important tool for modelling the operations of dynamic traffic systems. Although microscopic simulation models provide a detailed representation of the traffic process, macroscopic and mesoscopic models capture the traffic dynamics of large networks in less detail but without the problems of application and calibration of microscopic models. Dynamic Simulation Models (DTA) are used to make evaluations during project implementation and testing, they allow to represent on a small scale the effects and consequences of a new project (a road, a parking area, a bridge, etc.). The objective of DTA is to assess the variation of flows over time in order to identify critical situations, this is not possible with the use of static models. DTA differs in theoretical approach, allocation method and graphical interface, as well as in the level of detail of scenario description. Thanks to the use of models it is possible to represent numerous dynamic phenomena with three levels of detail:

- **Macroscopic simulation models:** Macroscopic models are based on continuous traffic simulation providing information on average speed, flow and vehicle density. In these models the individual vehicle is not followed, as happens in microscopic models, but simply the evolution of the entire vehicular flow on the fluid dynamics rules.
- **Mesoscopic simulation models:** These models focus on the behaviour of groups of users and the outputs are referred to groups and not to individual vehicles as in microsimulation. Each group consists of vehicles that have the same origin, the same destination and the same strategy of choice (route, speed, etc.). The smaller the size of the group, the closer the solution of the model is to the microscopic type
- **Microscopic simulation models:** The microscopic models simulate the movement and trajectories of the individual vehicles allowing to represent in a precise and specific way the traffic and its evolution, moment after moment. These simulation models represent road traffic at a very high level of detail and allow simulating the displacement of each vehicle and its interactions with other vehicles in the road network.

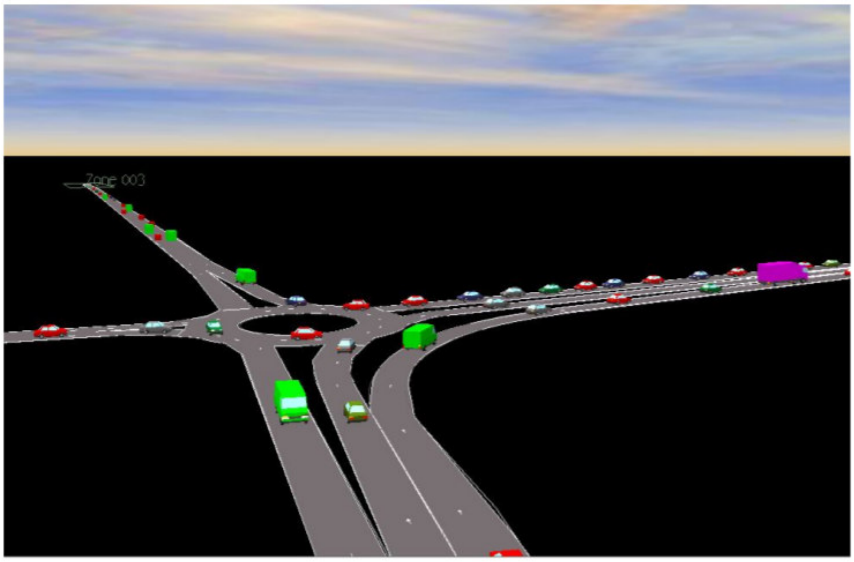


Fig. 3.5 – Microscopic simulation model in a roundabout

3.2. Use of the different means of transport - modal split

The modal split is a common and widespread indicator in transportation engineering to evaluate transportation behaviour. In brief, the modal split shows the percentage of travellers using a particular mode of transport compared to the ratio of all trips made. For example a higher modal split number of bicycle users indicates a more sustainable city. If we count the volumes of each mode, and compare them to each other, we get a very valuable ratio, the modal split. This property varies from city to city and is applied to evaluate current conditions or development in transportation. Modal split data are generally obtained from travel surveys usually referring to systematic home-work travel.

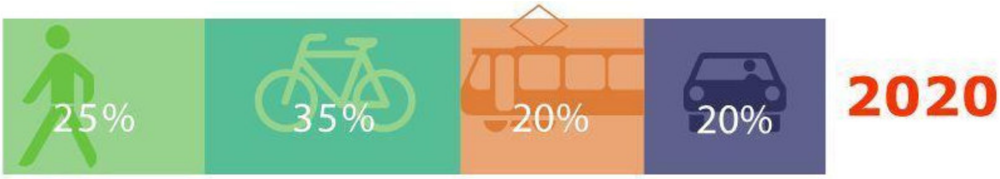


Fig. 3.6 - Modal split in Freiburg

The modal split depends on the geographical, economic, and social context. In recent years, also due to the COVID-19 pandemic, there is a modal shift towards forms of sustainable active mobility (walking, cycling, micro mobility) and sharing mobility. Shared mobility, the shared use of a motor vehicle or bicycle, is an innovative transportation strategy that enables users to gain short-term access to transportation on an as-needed basis rather than through ownership. The term “shared mobility” includes various forms of carsharing, bike-sharing, scooter sharing and others. Several European cities have developed programs that successfully improved mobility and reduced drive-alone trips.

In fact, shared mobility services have soared in popularity due to advances in technology and evolving social and economic perspectives toward transportation, car ownership, and urban lifestyles — especially among the younger generation.

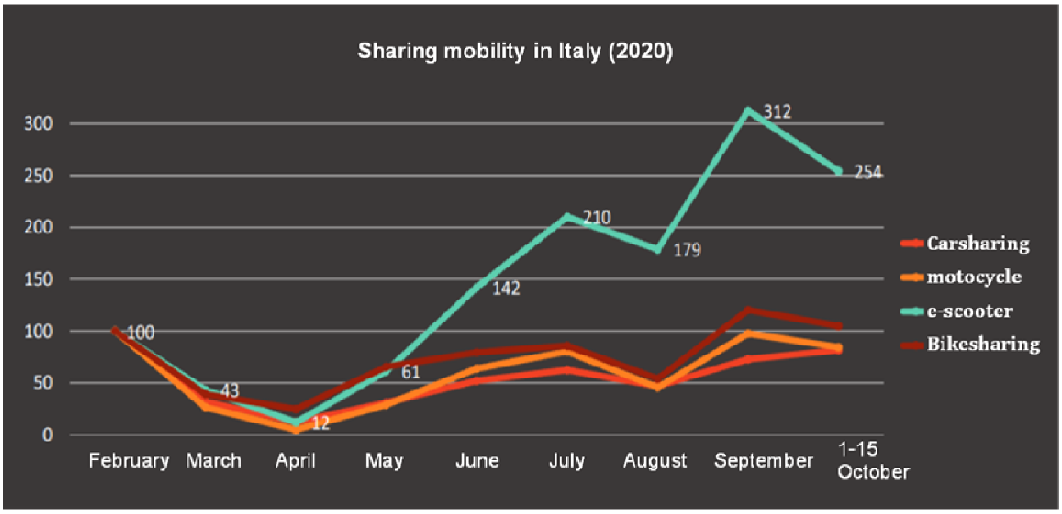


Fig. 3.7 - Average daily rental of sharing services in Italy (2020)

Mobility planning can no longer be the traditional one to achieve greater fluidity, the goal must change to bring the demand for mobility to more sustainable forms of alternative to private cars. The EU provided a guiding framework for these so-called ‘Sustainable Urban Mobility Plans’ (SUMPs), a theoretical approach enshrined in the "Guidelines for developing and implementing a Sustainable Urban Mobility Plan", which introduce a change of approach in the drafting of strategic plans in the mobility sector. The European Commission strongly recommends that European towns and cities of all sizes should embrace the concept of SUMPs, as they can vastly improve the overall quality of life for residents by addressing major challenges such as congestion, air pollution, climate change, road accidents and the integration of new mobility services.

A SUMP considers the whole functional urban area, and foresees cooperation across different policy areas, across different levels of government, and with residents and other principal stakeholders. It ensures a variety of sustainable transport options for the safe, healthy, and fluid passage of people and goods, with all due consideration for fellow residents and the urban environment. Seven out of the top ten liveable cities in the EU are cities with Sustainable Urban Mobility Plans.

3.3. The characteristics of urban mobility in the Dynaxibility4CE partners' areas

Some useful indicators have been defined to describe the areas involved in the Dynaxibility project from the point of view of urban mobility. The indicators should be referred to the municipality or to the metropolitan area; in case of unavailability, data could be provided at a larger scale. For example, Stuttgart is differently referred to as the Stuttgart Region, with 2.700.000 inhabitants or in other cases to Baden-Württemberg with 11.100.394 inhabitants. Data referring to 2019 or the most recent year. Data from the city of Koprivnica is not available.

Partner	Index	Area	Populatior	Year
Budapest	402	Municipality	1756000	2018
Graz	464	Municipality	328276	2016
Krakow	660	Municipality	779115	2019
Leipzig	391	Municipality	587857	2019
Parma	607	Municipality	198292	2019
Stuttgart	597	**Baden-Würt	11100394	2019
Koprivnica	not available			

Table 3.1 – characteristics of FUAs.

The list of the mobility indicators is the following:

- Motorisation rate
- Car fleet according to fuel type
- Car fleet according to emission standard
- Modal split
- Average distance for commuting
- Sharing mobility supply
- Bus fleet according to fuel type
- Bus fleet according to emission standard

Below are the data in table and graphic format accompanied by a comment.

Motorisation rate is the number of passenger cars per thousand inhabitants (Figure 3.8). In 2019, Krakow had the highest motorization index with 660 passenger cars per thousand inhabitants. In the same year in Europe the motorization rate was 524 passenger cars for 1000 people. Leipzig, Budapest and Graz have a motorization index lower than the European average.

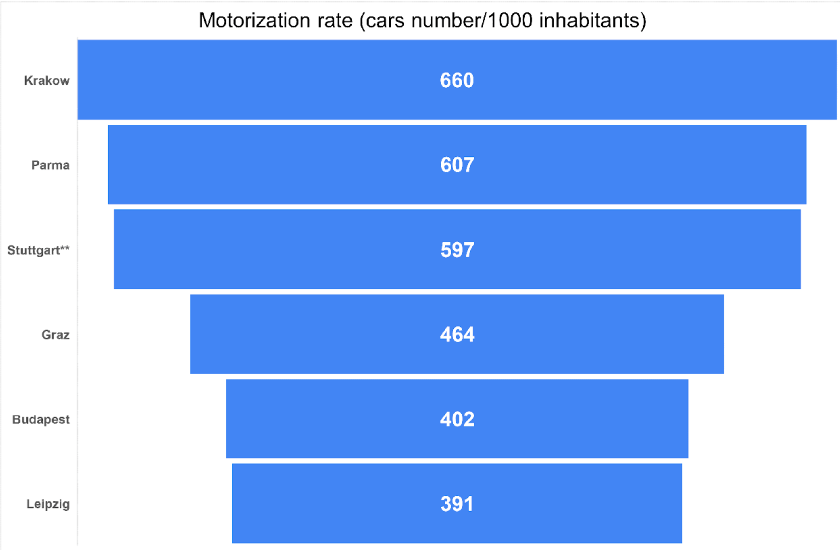
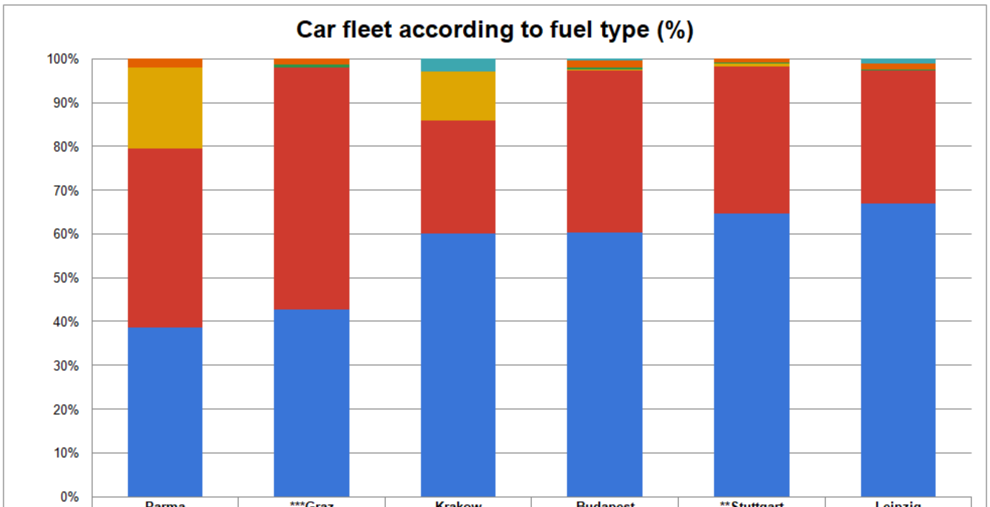


Fig. 3.8 – Motorization rate (cars number/1000 inhabitants). Note: Budapest 2018 instead 2019; Graz 2016 instead 2019. Koprivnica not available. (**) Baden-Württemberg.

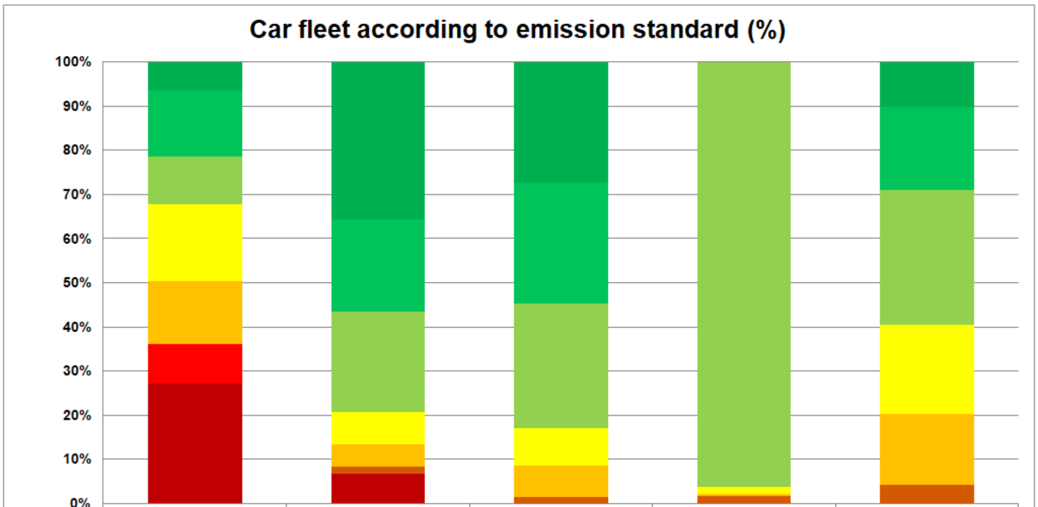
In April 2019, the European Parliament and Council adopted Regulation (EU) 2019/631 introducing CO2 emission standards for new passenger cars in the European Union. This regulation set reduction targets of -15% and -37.5% for the tailpipe CO2 emissions of newly-registered cars for the years 2025 and 2030 respectively. In 2020 more than one in ten cars registered in the EU was electrically chargeable. As for conventionally powered vehicles that use fossil fuels (diesel and petrol) it is possible to observe (Figure 3.9) that the Municipality of Parma has the car fleet with less gasoline powered cars (38.59%) while Leipzig has more than twice (67.01%). Regarding Diesel, Graz has the highest percentage of passenger vehicles with this type of fuel, in this case the number refers to the Federal State of Styria which has 1.243.000 inhabitants. Concerning (compressed or liquified) natural gas-powered vehicles it is possible to observe a percentage of 18.67% in Parma and 11% in Krakow while in other areas natural gas vehicles are almost non-existent. As for hybrid vehicles, the largest percentage is in Parma with 1.91%. Finally in all project areas there are low percentages of Electric vehicles, no one reaches 1%.



	Parma	***Graz	Krakow	Budapest	**Stuttgart	Leipzig
Other	0,00	0,00	3,00	0,50	0,02	1,04
Hybrid	1,91	1,27	0,00	1,60	0,78	1,34
Electric	0,00	0,80	0,00	0,30	0,24	0,33
Gas	18,67	0,03	11,00	0,20	0,69	0,00
Diesel	40,83	55,10	26,00	37,00	33,62	30,28
Petrol	38,59	42,70	60,00	60,40	64,64	67,01

Fig. 3.9 – Car fleet according to fuel type (%). Note: Budapest 2018 instead 2019; Graz 2020 instead 2019. Koprivnica not available. (**) Baden-Württemberg. (***) Province of Styria.

Krakow has the oldest car fleet compared to all other project areas (Figure 3.10), in fact vehicles with standards from Euro 0 to Euro 3 represent 67.80% of the entire car fleet, with a percentage of Euro 0 equal to 27.20%. Also, Parma has around 7% of vehicles of Euro 0 categorisation but has the highest percentage of Euro 6 vehicles (35.65%) compared to other areas. Stuttgart has the technologically most advanced car fleet of all assessed areas with 81.85% of vehicles that can be categorised between Euro 4 and Euro 6. Finally, Leipzig has a car fleet concentrated in Euro 4 (96.26%) because it doesn't differentiate between Euro 4-6 according to the statistics.



	Krakow	Parma	**Stuttgart	Leipzig	Budapest
EURO VI	6,40	35,65	27,08	0,00	10,10
EURO V	15,00	20,85	26,93	0,00	18,70
EURO IV	10,70	22,66	27,84	96,26	30,50
EURO III	17,60	7,46	8,23	1,63	19,90
EURO II	14,10	5,02	7,16	0,33	16,10
EURO I	8,90	1,54	1,39	1,79	4,20
EURO 0	27,20	6,82	0,00	0,00	0,00

Fig. 3.10 – Car fleet according to emission standard (%). Note: Budapest 2018 instead 2019; Krakow 2015 instead 2019. (**) Baden-Württemberg. Koprivnica and Graz: not available.

The next figure presents the modal split for areas involved in the Dynaxibility project (Figure 3.11). Modal split in areas is different, although the car maintains a stable market position. In Stuttgart, 58% of urban trips are completed by car, as the area of analysis also includes the Stuttgart region, which includes an area with the radius of 10-20 km from Stuttgart city centre. Followed by Parma with 56% urban trips by car and Krakow (39,94%), it can be said that motorisation rate seems a key factor of transport mode choice. The difference in modal split morphology lies in the share of other forms of travelling, such as public transport, cycling and walking. In Budapest and Krakow there are good percentages of public transport (33,40% and 30,03%), in both countries this is the second most used mode. Parma is the municipality with a large percentage of cyclability (20%) and Leipzig is more walkability (27,30%).

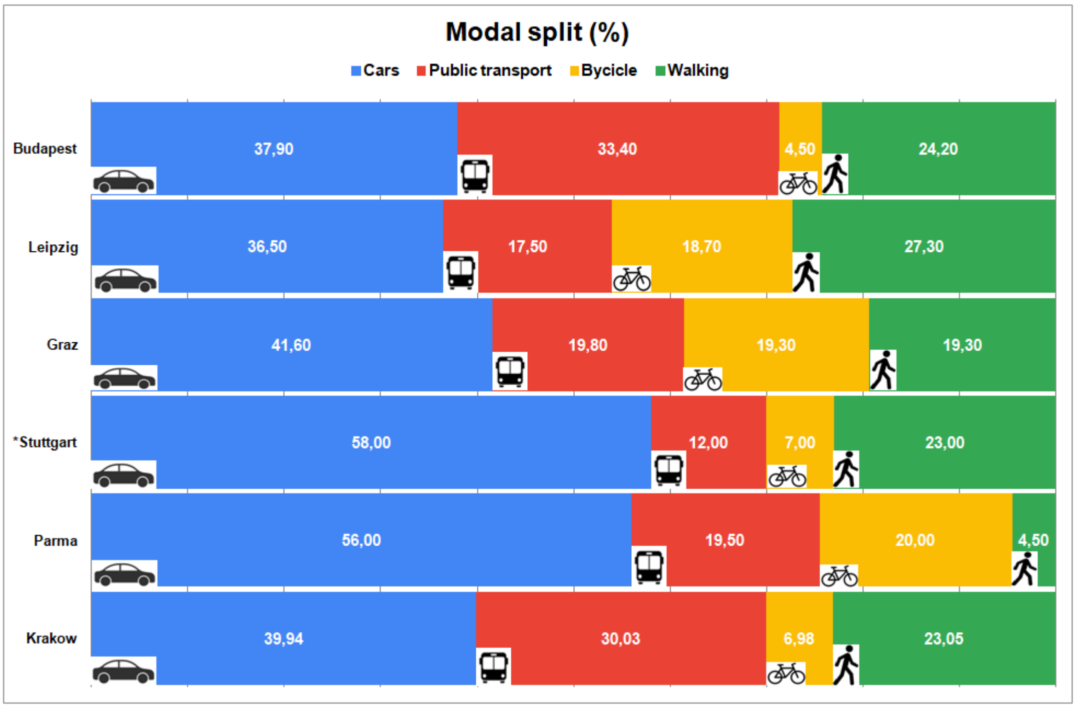


Fig. 3.11 – Modal split (%). Note: Stuttgart 2017 instead 2019; Krakow, Graz and Leipzig 2018 instead 2019. (*) Stuttgart Region. Koprivnica: not available.

The next figure represents the average commuting distance for daily travel for work or other reasons (Figure 3.12). Usually in urban areas the majority of the systematic displacements are between the 5 and the 10 Km of length. In the cities of Graz, Krakow and Leipzig, which have similar extensions, the average distance is about 6 Km. These distances are easily accessible by bicycle and this can be appreciated in the cycling percentage of the previous indicator. The average travel length in Stuttgart is the highest (12.2 km) as the area of interest is the Stuttgart-Region.

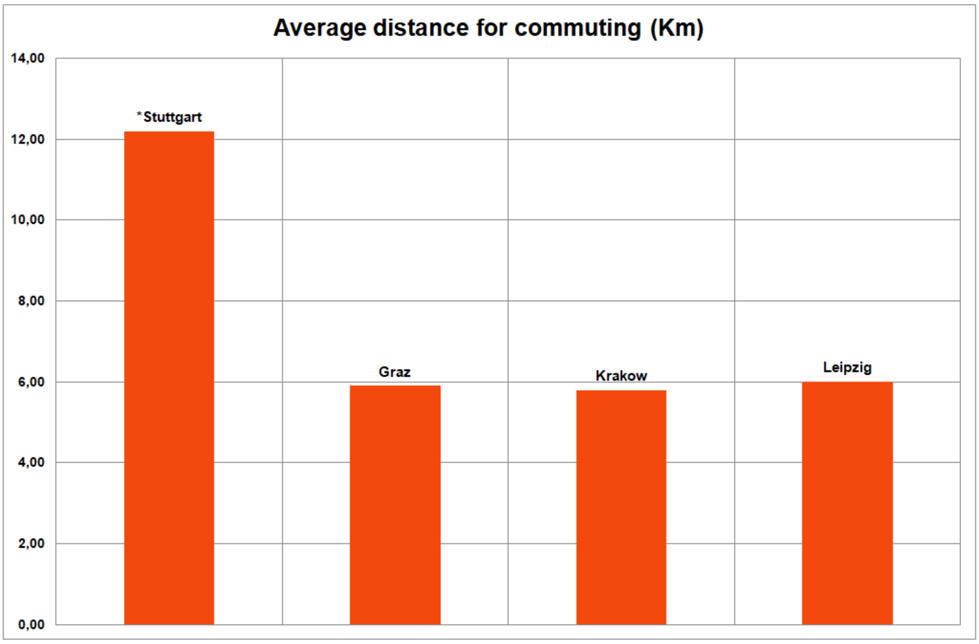
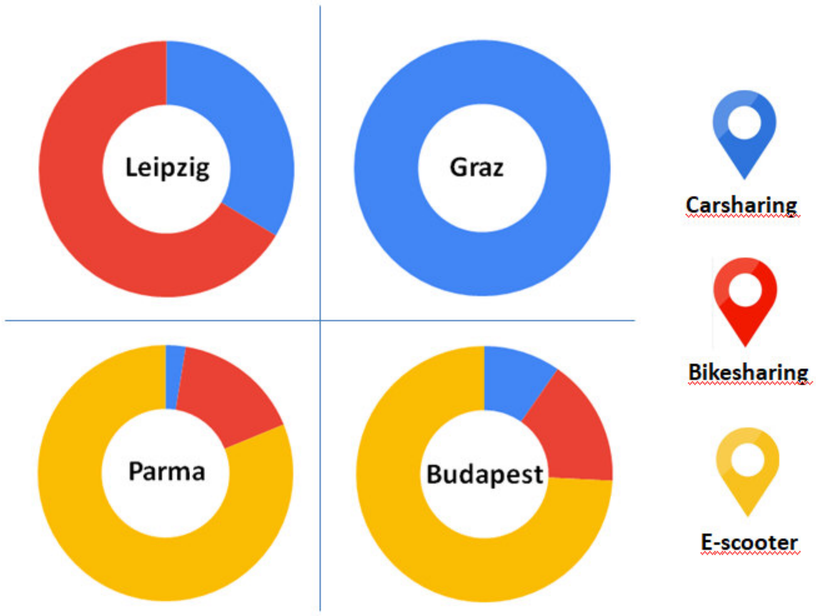


Fig. 3.12 – Average distance of commuting (Km). Note: Stuttgart 2017 instead 2019; Krakow and Leipzig 2018 instead 2019. (*) Stuttgart Region. Budapest, Koprivnica and Parma: not available.

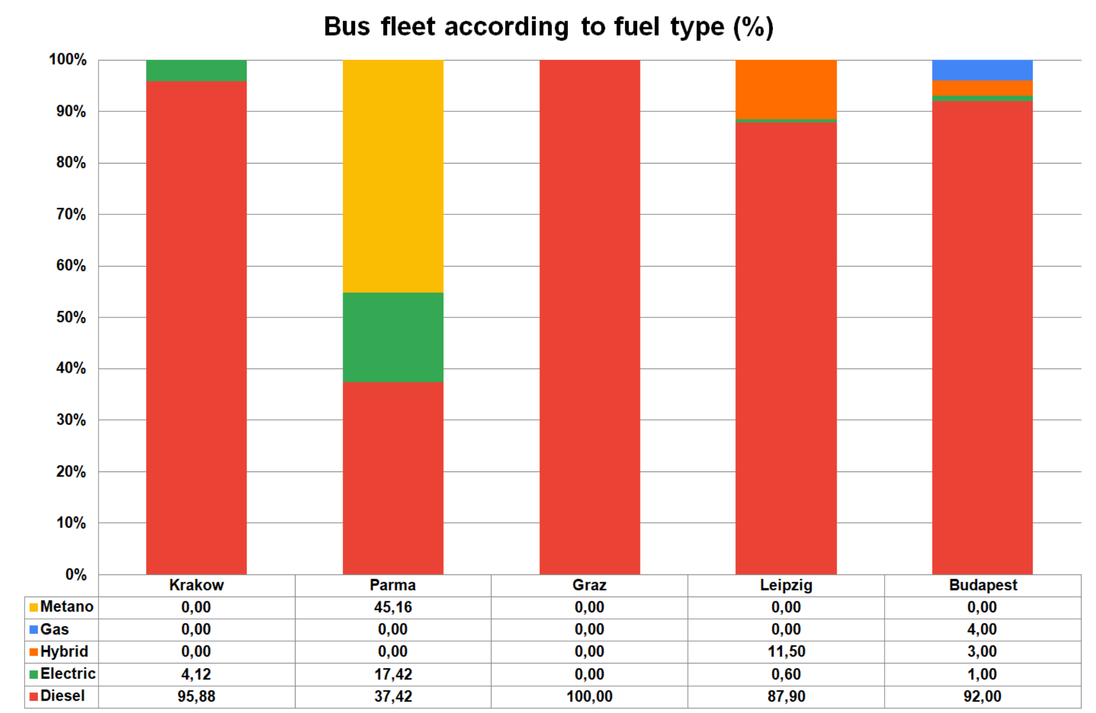
As for sharing mobility indicators, many partners were unable to provide data have not available data (Figure 3.13). Despite this, it is possible to see for the four areas in the table that the services that have the greatest availability of vehicles is the e-scooters sharing: in Budapest it represents 74.19% and in Parma 81.23%. This service is having great success in recent years for ease of booking and use. Even bike sharing is widespread in northern Europe, in the Dynaxibility partner cities there is an availability of one bike per 1000 inhabitants, more than all Leipzig with 66.31%. In the city of Graz carsharing is the only mobility sharing service available.



	Carsharing	Bikesharing	e-scoter
Parma	2,53	16,25	81,23
Graz	100,00	0,00	0,00
Leipzig	33,69	66,31	not available
Budapest	9,68	16,13	74,19

Fig. 3.13 – Sharing mobility supply (%). Note: Koprivnica, Krakow and Stuttgart: not available.

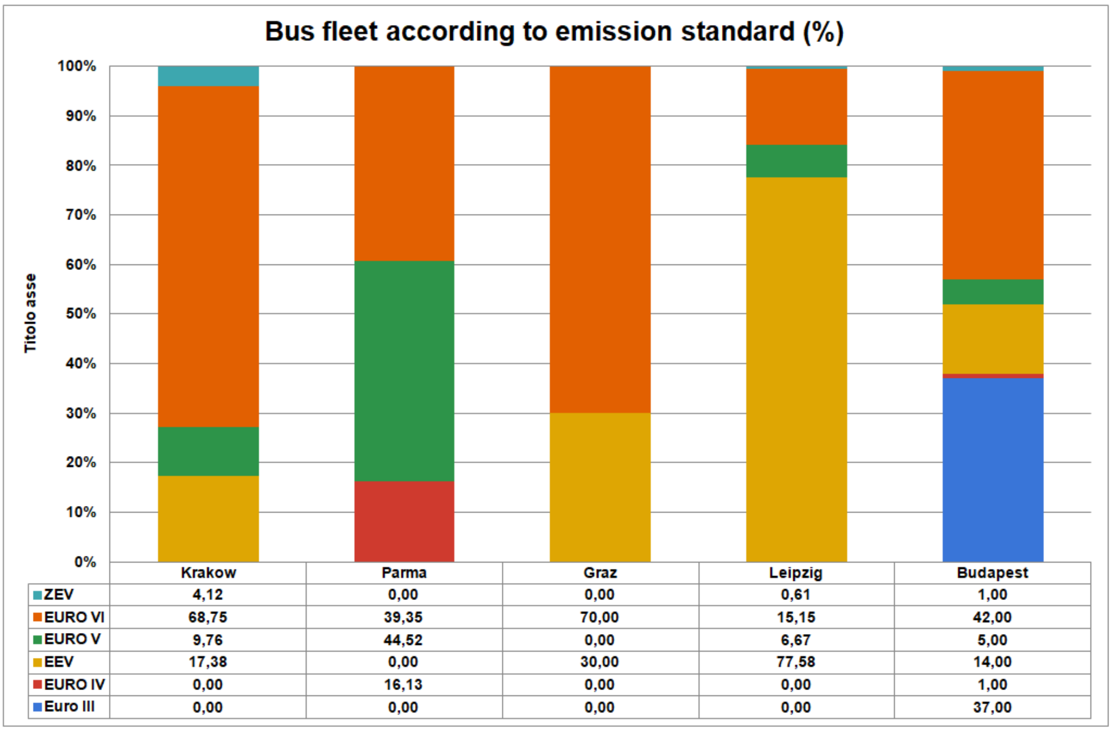
The last two indicators describe the characteristics of the public transport fleet related to buses. About the bus fleet according to fuel type (Figure 3.14 and 3.15). It is possible to note that, except for Parma, in all areas of the project at least 90% of the buses are powered with Diesel, in particular in Graz the 100% of the bus fleet is Diesel. In all areas there are small percentages of Electric buses except in Parma where they represent 17.42% of the total. In Parma there are 45.16% Methane buses. In Leipzig there are 11.50% Hybrid buses.



	Krakow	Parma	Graz	Leipzig	Budapest
Metano	0,00	45,16	0,00	0,00	0,00
Gas	0,00	0,00	0,00	0,00	4,00
Hybrid	0,00	0,00	0,00	11,50	3,00
Electric	4,12	17,42	0,00	0,60	1,00
Diesel	95,88	37,42	100,00	87,90	92,00

Fig. 3.14 -Bus fleet according to fuel type (%). Note: Graz 2021 instead 2019. Koprivnica and Stuttgart: not available.

The composition of the bus fleet from the point of view of emissions to the atmosphere. The city of Parma has the bus fleet with lower emissions since 83.87% is formed by vehicles Euro V and Euro VI despite still retaining 16% of vehicles Euro IV. The city of Budapest has the oldest bus fleet with 37% of vehicles under Euro III. Graz has 30% of EEV (Enhanced Environmental Friendly Vehicle standard) vehicles and the remaining 70% Euro V and Krakow has the largest percentage of Zero Emission Vehicle - ZEV (4.12%).



	Krakow	Parma	Graz	Leipzig	Budapest
ZEV	4,12	0,00	0,00	0,61	1,00
EURO VI	68,75	39,35	70,00	15,15	42,00
EURO V	9,76	44,52	0,00	6,67	5,00
EEV	17,38	0,00	30,00	77,58	14,00
EURO IV	0,00	16,13	0,00	0,00	1,00
Euro III	0,00	0,00	0,00	0,00	37,00

Fig. 3.15 - Bus fleet according to emission standard (%). Note: Budapest 2021 instead 2019. Koprivnica and Stuttgart: not available.

References

- Guidelines for developing and implementing a Sustainable Urban Mobility Plan (2nd edition) - https://www.eltis.org/guidelines/second-edition-sump-guidelines
- Budapest Mobility Plan 2014-2030, Vol. 1 Objectives and Measures, pp 16 - http://www.sump-challenges.eu/sites/www.sump-challenges.eu/files/bmt2016_eng_v3.pdf
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- 17° Rapporto sulla mobilità degli italiani. Tra gestione del presente e strategie per il futuro.
- Osservatorio Nazionale Sharing Mobility http://osservatoriosharingmobility.it/
- Matrice O/D Dr. Jean-Paul Rodrigue, Dept. of Global Studies & Geography , Hofstra University, New York, USA.
- Acea driving mobility for Europe https://www.acea.auto/

4. Reference approaches for air pollutants monitoring

4.1. Background

Air pollution is associated with a range of diseases, symptoms and conditions that impair health and despite a significant decrease in the concentrations of some air pollutants observed in many developed countries over the last decades, air quality still represents a major public concern with people living in urban and suburban areas where they are exposed to high levels of pollution.

Air quality assessment is regulated by national and international legislation. In Europe the framework and legal requirements for assessment and management of ambient air quality are defined in the Air Quality Directive 2008/50/EC, but similar regulations in other countries outside Europe are available. The Directive defines the criteria for air quality monitoring and the reference measurement methods that every Member State shall apply when monitoring air quality. Historically, air quality monitoring and assessment has been carried out for regulatory purposes and has been a prerogative of government agencies that manage monitoring networks of fixed and mobile stations under strict quality assurance and control (QA/QC) protocols that guarantees high accuracy of measurements. The primary role is assigned to fixed monitoring station networks that are subject to a strict routine of maintenance and calibration of the instruments, to ensure high data quality and comparability between stations and regions.

However, the high costs of installation and maintenance of reference monitoring stations result in relatively sparse monitoring, which provides accurate data but only for a small number of locations thus not providing information about localized gradients of potential importance for health protection and not meeting the increasing demand for detailed air quality information neither by citizens and associations, nor the needs for population exposure assessment in epidemiological studies.

One of the most common supplementary techniques is mobile monitoring which consists of vehicles having the same line of instrumentation as the fixed monitoring stations, but also the same maintenance and calibration routines. However, due to their high costs and deployment issues (power supply, …) mobile monitoring cannot significantly increase spatial sampling density.

The most promising answers to the increasing demand for detailed air quality information by citizens is represented by sensor based instruments, which will be dealt with in one of the following sections. The underlying idea is that a cost-effective approach for air quality monitoring would be the implementation of mixed networks involving both reference-grade monitors as well as emerging sensor based technologies. This possibility relies on the fact that field calibration of sensor based equipment will be carried out at reference monitoring stations in order to ensure at the highest the comparability of measurements from the two different sources.

4.2. Air quality standards

The reference legislation related to air quality addresses the issue according to two fundamental aspects, namely, the control of pollutant emission from specific sources and the establishment of air quality standards to be achieved (mainly for health protection).

The discussion of policies related to the control of emissions goes beyond the scope of this document: at the lowest level, policies regarding the pollutant emission related to mobility are mainly dealing with the adoption of traffic restrictions and/or limitations soon after the onset of severe air pollution events. Other short- and also long-term policies may be considered in the framework of the revision of urban and peri-urban mobility (such as MaaS, UVAR, and so on), also introducing new mobility standard as well as renewing private and public fleets of vehicles circulating inside and outside our cities.

Nevertheless, the definition of emission limits is the most important way to control pollutant emission. The reference legislation for the protection of health addresses this issue according to the fundamental aspect of defining of air quality standard values, which have been set in the European Union through the EU Ambient Air Quality Directives. Table 4.1 summarizes the air quality standard values aiming at the protection of health. All the pollutants are measured on a standalone basis, except for BaP[1], Pb, As, Cd, Ni which are measured as content in PM_{10}.

A remarkable difference should be underlined between "limit value" and "target value" in Table 4.1: in EU legislation, in fact, "a limit value is legally binding from the date it enters into force subject to any exceedances permitted by the legislation", while for a target value "the obligation is to take all necessary measures not entailing disproportionate costs to ensure that it is attained, and so it is less strict than a limit value". For some pollutants (both subject and not subject to the EU legislation the evidence base is sometimes insufficient to set a certain level to provide a basis for legally binding limit values. In this respect, the adoption of a target (or a standard) in the form of a concentration reduction obligation might be a good instrument to force local actions on the pollutant reduction.

Another key point is related to "alert threshold" and "information threshold". The first is associated to atmospheric concentrations beyond which there is a risk to human health in case of short-term exposure for the population as a whole. When an alert threshold is reached, actions must be taken immediately. On the other hand, "information threshold" is associated to a risk to human health for certain sensitive groups of the population: also in this case actions in order to ensure adequate and timely information must be taken.

PM_{10}	daily mean less than 50 µg/m^3 (limit value) not to be exceeded on more than 35 days per year annual mean less than 40 µg/m^3(limit value)
$PM_{2.5}$	annual mean less than 25 µg/m^3 (limit value)
O_3	maximum daily 8-hour mean less than 120 µg/m^3 (target value) not to be exceeded on more than 25 days per year hourly mean less than 180 µg/m^3(information threshold) and less than 240 µg/m^3(alert threshold)
NO_2	hourly mean less than 200 µg/m^3 (limit value) not to be exceeded on more than 18 hours per year and less than 400 µg/m^3 (alert threshold) annual mean less than 40 µg/m^3 (limit value)
SO_2	hourly mean less than 350 µg/m^3(limit value) not to be exceeded on more than 24 hours per year and less than 500 µg/m^3(alert threshold) daily mean less than 125 µg/m^3 (limit value) not to be exceeded on more than 3 days per year
CO	maximum daily 8-hour mean less than 10 mg/m^3 (limit value)
C_6H_6	annual mean less than 5 µg/m^3 (limit value)
BaP	annual mean less than 1 ng/m^3 (target value)
Pb	annual mean less than 0.5 µg/m^3 (limit value)

[1]Benzo[a]pyrene.

As	annual mean less than 6 ng/m^3 (target value)
Cd	annual mean less than 5 ng/m^3 (target value)
Ni	annual mean less than 20 ng/m^3 (target value)

Table 4.1 - Air quality standards for the protection of health, as given in the most recent EU Ambient Air Quality Directives.

On the other hand, Table 4.2 summarizes World Health Organization (WHO) air quality guidelines (AQGs) and the estimated reference levels (RLs). WHO last published the guidelines in 2006 (WHO 2006), providing health-based guideline levels for the major health-damaging air pollutants and having a significant impact on the definition of pollution abatement strategies. More than 15 years have passed since the initial publication and during this time there has been a marked increase in evidence on the adverse health effect of air pollution , built on advances in air pollution measurement and exposure assessment and an expanded global database of air pollution measurements. This is the reason why WHO recently updates the global air quality guidelines, modifying the AQG levels, introducing some new ones. One of the most relevant difference in WHO approach is the introduction of "interim targets" that is concentration levels of atmospheric pollutants beyond AQGs to allow governments in highly polluted areas to define pollution abatement policies which could be achieved in a reasonable period of time. These interim targets may then be considered as steps toward the AGQs.

	WHO 2006	**WHO 2021**
PM_{10}	daily mean less than 50 $\mu g/m^3$ (AGQ) annual mean less than 20 $\mu g/m^3$ (AGQ)	daily mean less than 45 $\mu g/m^3$ (AGQ) annual mean less than 15 $\mu g/m^3$ (AGQ)
$PM_{2.5}$	daily mean less than 25 $\mu g/m^3$ (AGQ) annual mean less than 10 $\mu g/m^3$ (AGQ)	daily mean less than 15 $\mu g/m^3$ (AGQ) annual mean less than 5 $\mu g/m^3$ (AGQ)
O_3	maximum daily 8-hour mean less than 100 $\mu g/m^3$ (AGQ)	idem in addition, peak season less than 60 $\mu g/m^3$ (AGQ)
NO_2	hourly mean less than 200 $\mu g/m^3$ (AGQ) annual mean less than 40 $\mu g/m^3$ (AGQ)	hourly mean less than 200 $\mu g/m^3$ (AGQ) annual mean less than 10 $\mu g/m^3$ (AGQ) in addition, daily mean less than 25 $\mu g/m^3$ (AGQ)
SO_2	10-minute mean less than 500 $\mu g/m^3$ (AGQ) daily mean less than 40 $\mu g/m^3$ (AGQ)	idem daily mean less than 20 $\mu g/m^3$ (AGQ)
CO	hourly mean less than 30 mg/m^3 (AGQ) maximum daily 8-hour mean less than 10 mg/m^3 (AGQ)	instead, daily mean less than 4 mg/m^3 (AGQ)
C_6H_6	annual mean less than 1.7 $\mu g/m^3$ (RL)	idem
BaP	annual mean less than 0.12 ng/m^3 (RL)	idem

Pb	annual mean less than 0.5 µg/m^3 (AGQ)	idem
As	annual mean less than 6.6 ng/m^3 (RL)	idem
Cd	annual mean less than 5 ng/m^3 (AGQ)	idem
Ni	annual mean less than 25 ng/m^3 (RL)	idem

Table 4.2 - World Health Organization (WHO) air quality guidelines (AQGs) and the estimated reference levels (RLs).

4.3. Type and number of fixed site and mobile monitoring stations

The definition of exposure limits is clearly not enough: any target related to air quality aiming at the protection of human health and the environment must also define the monitoring quality standards with common methods and criteria. In addition, the assessment of clear evaluation protocols is a fundamental aspect of the issue.

The analysis of pollutant concentrations in relation to the defined EU and WHO standards shown in the previous section is based on measurements at fixed sampling points, officially reported by the Member States. Fixed sampling points in Europe are situated at different locations and include various rules for macro- and micro-scale placing, as stated in (EU 2004; EU 2008; EU 2011). Briefly, depending on the predominant emission sources, stations are classified as follows:

- traffic stations: located in close proximity to a single major road;
- industrial stations: located in close proximity to an industrial area or a specific industrial source or other relevant infrastructures;
- background stations: where pollution levels are representative of the average exposure of the general population.

Depending on the distribution/density of buildings, the area surrounding the stations is classified as follows:

- urban: continuously built-up urban area;
- suburban: largely built-up urban area;
- rural: all other areas.

The following photos represent two reference stations belonging to Arpae Emilia-Romagna air quality network inside Parma urban area, namely “Montebello” (Picture 4.1), which is the urban traffic station, and “Cittadella” (Picture 4.2), which is the background station according to European Environment Agency classification.

For most of the pollutants (SO_2, NO_2, O_3, PM, and CO) monitoring stations must fulfil the criterion of reporting more than 75% of valid data out of all the possible data in a year to be included in the assessment. The Ambient Air Quality Directive (EU 2008) sets, for compliance purposes, the objective of a minimum data capture of 90% for monitoring stations, but, for assessment purposes, a coverage of 75% allows more stations to be taken into account without a significant increase in monitoring uncertainties. Instead, the required percentages drop to the 50% of valid data for benzene and to 14% for toxic metal and BaP according to (EU 2004; EU 2008).

Data collected from air quality reference stations are generally disseminated to the public on a daily basis. For each pollutant monitored by the reference air quality network, the daily indicators required by current legislation are given together with limit values and eventually the updated count of the number of exceedances of the limit value during the calendar year compared to the number of allowed exceedances. Before the publication, data collected from the reference stations are subject to a daily validation process.

The calibration of the monitoring equipment and reference instruments are an essential and time-intensive aspect in the maintenance of these stations and can only be executed by trained professionals. In fact, for each pollutant associated to a limit value set by the legislation a specific technical standard UNI EN is prescribed for the maintenance service and for the calibration of instruments. This clearly indicates the flaws of the system, as monitoring remains stationary and has high operating and maintenance costs. Nevertheless, the possibility of monitoring strategic locations in a certain area and above all for specific time intervals, eventually moving the laboratory to another (strategic) locations in a short time. The relocation could be associated to the occurrence of sudden air quality threat or specific temporary needs somewhere in the territory as a result of local pollution problems as well as in relation to the presence/absence of fixed-site monitoring stations.

Thus, a suitable alternative could be the use of mobile stations, as they could cover a wider area and therefore significantly increase the amount of available air quality data.

Figure 4.1 - The reference monitoring station in Viale Montebello (traffic site) inside Parma urban area.

Figure 4.2 - The reference monitoring station in Parco Cittadella (background site) inside Parma urban area.

Figure 4.3 - Example of a reference mobile stations.

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5. Modelling tools for air quality assessment

5.1. Background

Generally speaking, air quality conditions at a certain location depend on two main factors: the emission of pollutants in the atmosphere according to the different sources within a surrounding area and the meteorological conditions driving air masses motion, and particles of the various atmospheric pollutants as a consequence.

If we aim to describe air quality conditions in a certain area in detail, it is essential to obtain access to a realistic inventory of all the natural and anthropogenic pollution sources at the desired location. Furthermore, the local land use and development level is also essential (urban or suburban or rural; background, industrial or residential area, local traffic flows).

From the meteorological point of view, some parameters show a prominent effect on the diffusion of pollutants. Wind speed and direction are fundamental in driving the paths of pollutants dispersion as well as their rate of diffusion. Temperature and humidity determine the stability conditions of the atmosphere eventually favouring the accumulation (dispersion) of pollutants and their changing concentrations. Atmospheric precipitation has a relevant effect in modifying the local pollutant concentration, at least in the transient stage of washing the atmosphere. The complexity of ground features and terrain elevation have an effect on the local meteorological conditions, particularly on the wind field and on the pattern of precipitation.

Therefore, it is clear that the assessment of air quality conditions at a certain location is a very complex issue relying on different sources of information. A fundamental aspect in this scope is related to the concept of “surroundings”, since it may assume a manifold meaning ranging from the areas in the proximity of the location to the large-scale (continental) air mass motion.

The presence of monitoring stations, although fundamental, is not fully satisfactory to describe in detail the air quality conditions of a certain area. It is then necessary to integrate all the possible information at the different spatial and temporal scales involved. The way to take care of the previously mentioned items is to use numerical models.

The word “model” in the framework of air quality may refer to a variety of different approaches. It is possible to dynamically represent the motion of a pollutant particle starting from the point where it is emitted in the atmosphere and following its path driven by the movement of air masses. The overall effect of the motions of pollutant particles may then be associated with the ground-based information, that is measurements from the reference monitoring stations, land-use, etc.).

Another possible approach is to make use of the historical measurements records at a certain location and to analyse the statistical (in a broad sense) behaviour of the associated time series. Although substantially different under a methodological point of view, both approaches, allow a representation of pollutant concentration at a certain location resulting in the usual categorization of air quality numerical models as follows:

- deterministic models, which are based on the fundamental laws of fluid dynamics applied to the atmosphere, where air pollution (the effect) is generated by some causes (emission processes): this kind of models are mainly deriving from modules originally developed for numerical weather forecasting and involves the numerical solutions of partial differential equations;
- statistical models, which are based on the definition of semi-empirical relationships between measurements and some user defined predictors: this kind of model relies basically on various data mining techniques.

The approach to the issue is totally different, since deterministic models are “dynamic” in the sense they reproduce the motion inside the atmosphere, pointing out the dynamics of particles starting from the emission from a source and the following motion throughout the atmosphere. On the other hand, statistical models are “static” in the sense that they reproduce the relationships between data and measurements assuming that a relationship exists. A careful analysis of the resources available is then necessary to properly define the best tools to be used in any situation.

5.2. Deterministic models

As already stated, the use of deterministic models implies the numerical solution of the set of partial differential equations representing the fundamental laws of fluid dynamics, describing the atmosphere together with the physical and chemical processes and the dispersion of pollutants. The solutions of the set equations relies on appropriate initial and boundary conditions and the results are the pollutant concentrations at some selected receptor locations.

Data required for dispersion models vary in their complexity. At a minimum, most models need meteorological data, emissions data and details about the facilities (such as stack height, gas exit velocity, etc.). Some more complex models require topographic information, individual chemical characteristics and land use data. Insufficient knowledge of pollutant sources and other parameters as well as inaccurate description of physical and chemical processes, can lead to significant bias and error in air quality estimations of models.

Moreover, dispersion is primarily controlled by turbulence in the atmospheric boundary layer. Turbulence is random by nature and thus cannot be precisely described or predicted. As a result, there is spatial and temporal variability that naturally occurs in the observed concentration field. Summarizing, deterministic models are most suitable for long-term planning decisions. These models predict more frequent events quite accurately, extreme events - with less accuracy, due to the complexity and inherent uncertainty associated with turbulent flow.

The most common deterministic models are briefly outlined in the following subsections, with some indications of pros and cons associated with the choice of one model with respect to each other. Readers can refer to (Chang and Hanna, 2004), (Holmes and Morawska, 2006) and (Leelossy at al., 2014) for a more systematic review of these tools.

5.2.1. Box models

The fundamental principle upon which box models are based is the conservation of mass. Models consist of a grid box where pollutants are emitted and undergo physical and chemical processes. No matter what the inner part of the box is, the air mass inside is considered a well-mixed mixture of air and the concentrations of pollutants are uniform throughout.

One advantage of the box model is that it needs only simple meteorological and emission information, which allows to include more detailed chemical reaction schemes as well as an in depth treatment of the aerosol dynamics thus representing at best the physics and chemistry of particles. On the other hand, the box model only simulates the pollutant formation without any information about the local pollutant concentration. Therefore box models are unsuitable for modelling the particle concentrations in a local environment where concentrations are highly influenced by advection from outside the box and by emission.

5.2.2. Gaussian models

These are the most common models used in the framework of air dispersion and assume that the pollutant particles will disperse according to the normal statistical (Gaussian) distribution.

The turbulent diffusion equation is a partial differential equation that can be solved with various numerical methods. Assuming a homogenous, steady-state flow and a steady-state point source, the equation can also be analytically integrated and results in the well-known Gaussian plume distribution.

The main advantage of Gaussian models is their fast runtime and small input data requirement. They can be run without access to gridded meteorological data. However, their accuracy is very limited beyond the spatial distance of a few tens of kilometres or in complex conditions (e.g., orography, wind shear). With only a few input parameters, a single plume can be calculated instantly even on a portable device, making Gaussian models a powerful tool for on-site emergency decision making. On the other hand, they are often applied to estimate the local scale effects of long-term continuous pollution, calculating the sum of single plumes from each hour through several years.

5.2.3. Eulerian models

Eulerian models are a set of second order PDEs in the 3-D space and time independent variables. The solutions of such equations give as a result the spatial and temporal evolution of the concentration. Due to the spatial and temporal variability of the wind velocity and turbulence, the atmospheric transport equation cannot be solved analytically.

The mathematical methods reduce the system of PDE to a system of ODEs having a single independent variable (time). The system of ODEs may then be solved as an initial value problem through several numerical methods and powerful software tools. The most often used technique is the so-called method of lines, which consists of two steps: first, the spatial discretization, and then the time integration of the derived ODEs. The spatial discretization of the atmospheric transport equation is performed on a mesh. This reduces the PDE to a system of ordinary differential equations (ODEs) in time as the independent variable.

5.2.4. Lagrangian models

Lagrangian models provide an alternative method for simulating the atmospheric diffusion. Unlike in the Eulerian approach where the model box doesn’t move, in this case the model box follows the average wind trajectory describing fluid elements which follow the instantaneous flow.

The trajectories of fluid elements are driven by the wind field, buoyancy, and the stochastic turbulent effects. Again, a system of ODEs has to be solved instead of the original system of PDEs avoiding spatial truncation errors and numerical diffusion. The output is the estimation of the concentration field resulting from the final distribution of a large number of particles.

The computational cost of a Lagrangian model depends on the number of particles for which trajectories are calculated. However, the calculation of a few trajectories already provides information on the direction of the dispersion even on large scales. A common practice is to calculate deterministic trajectories considering only the large-scale wind and neglecting the random walk term. This does not allow concentration diagnostics, but provides quick information on the dispersion pathway and the affected areas without the costly solution of an Eulerian model on a large domain or a Lagrangian model with many particles.

Another advantage of Lagrangian models is that the inverse problem (source identification) can be easily formulated using backward trajectories.

5.2.5. Computational Fluid Dynamics (CFD)

CFD tool is designed for computer simulations of fluid flow, heat and mass transport, chemical reactions and other phenomena connected with these issues (such as turbulence). CFD models require the solution of transport equations for mass, momentum, energy and species. The spatial distributions of meteorological fields (i.e. temperature or pressure) and of species are the output of such models.

In general, CFD models consist of four main modules: (a) a mesh generator that splits the computational domain to cells with a user defined resolution; (b) a PDE solver for the selected form of the set of equations; (c) a turbulence module; (d) a visualization tool to create 3D plots and slices of the computed fields.

Because of their flexibility for different purposes, CFD models are widely used in the field of mechanical and environmental engineering as well as micro-scale dispersion modelling.

5.3. Statistical models

To overcome the constraints and limitations of deterministic models, statistical models are employed for air pollution simulation as well. Different algorithms can be used to establish the relationships between routinely measured time series of pollutant data and the various selected predictors.

The major drawback of this approach is the best representation of a specific monitoring station rather than a possible extension to other areas with different environmental conditions. In addition, statistical approaches often require a long time series of measurements under various atmospheric conditions. On the other hand, the statistical approach is generally more appropriate to discover underlying complex site-specific dependencies between concentrations of air pollutants and potential predictors and consequently, they often have a higher accuracy, as compared with deterministic models.

Data mining is the computational process applied to analyze large datasets, discover patterns, extract knowledge and predict outputs of future or unknown events. Methods used in data mining come from a combination of various computational disciplines including artificial intelligence, statistics, mathematics, machine learning and database systems.

There are two major groups of data mining algorithms: prediction and knowledge discovery. Classification and regression are two forms of data analysis that can be used to forecast data trends. Classification predicts categorical labels, the so-called “classes”, while prediction models are used for forecasting continuous variables. Cluster analysis is a technique that tries to identify structures within the data, by finding homogenous groups of cases when the grouping is not previously known.

The most common statistical techniques are briefly outlined in the following subsections. Readers can refer to (Taheri and Sodouidi, 2016) and (Bellinger et a., 2017) for a more systematic review of these tools.

5.3.1. Exploratory Data Analysis

Exploratory Data Analysis (EDA) is an approach for analysis of data sets that employs a variety of techniques and tools. As opposed to traditional hypothesis testing designed to verify a priori hypothesis about relationship between variables, EDA is used to identify systematic relationship between variables without a complete a priori expectations about the nature of those relationships.

Computational EDA methods include both simple basic statistics and more advanced designated multivariate exploratory techniques designed to identify patterns in multivariate data sets. The basic statistical exploratory methods include such techniques as examining distributions of variables, reviewing large correlation matrices or examining multi-way frequency tables. Multivariate exploratory techniques include among others: cluster analysis, factor analysis, distinctive function analysis, multidimensional scaling, log-linear analysis, canonical correlation, correspondence analysis. EDA also includes a large selection of graphical techniques to represent the results.

5.3.2. Time series

A time series is a set of data points indexed in time order. This technique is based on the assumption that successive values in the data set represent consecutive measurements taken at equally spaced time intervals. The main goals of time series analysis is to identify the nature of the phenomenon represented by the sequence of observations and to predict future values of the time series variable based on previously ones.

Time series analysis assumes that data consist of a systematic pattern (a set of components) and random noise (error) which usually makes the pattern difficult to identify. Systematic patterns of time series can be described in terms of two basic classes of components: trend and seasonality. Trend is a general systematic linear or nonlinear component that changes over time and does not repeat. If there is a clear monotonous nonlinear component, the data first have to be transformed to remove the nonlinearity applying a suitable function (logarithmic, exponential, polynomial). Seasonality is the presence of variations that occur at specific regular time intervals (weekly, monthly, quarterly etc.). Seasonality may be caused by various factors (such as weather, holidays) and consists of periodic, repetitive, and generally regular and predictable patterns in the levels of a time series.

Time series methods can be applied in two ways: a “fitting” mode and a “forecasting” mode. In the forecasting mode, one set of measurements determine model parameters, which are then applied to another set of measurements to make the forecast. In the fitting mode, the same set of measurements is used for both parameter estimation and model performance evaluation. Clearly, only the forecasting mode provides an unambiguous evaluation of model performance, while the fitting mode overestimates the forecasting ability of model.

A useful combination of fitting and forecasting can be obtained by applying time series models in an “adaptive” mode, in which the model parameters are re-estimated using the measurements of a “learning” period which maximizes the model performance if the duration of the learning period is appropriate.

5.3.3. Regression

Both linear regression and non-linear regression models have been employed for air quality forecasting. Multiple linear regression explains the relationship between two or more (continuous or categorical) independent variables - the predictors - and one (continuous) dependent variable - the predictand. Relationship between variables is modelled by fitting a linear equation to experimental data.

In general, a lot of potential predictors may be considered since their influence on pollution concentrations, but not all of them are equally important and the detection of the most relevant is required. This procedure may be done using the so-called stepwise regression, which is a method based on successive linear regression, adding or removing a potential predictor at each step according to a specified criterion defining model quality (“forward” selection is associated to the addition of the best potential predictor, “backward” selection to the removal of the worst, both in terms of the improvement of model quality).

In many situations the relationships between air pollution and meteorological parameters determined by means of multiple linear regression are not sufficiently close, since the same meteorological conditions may produce different effects depending on parameters and location of pollution sources. In addition, the relationships between air quality and meteorological conditions are generally non-linear. Therefore non-linear regression models are superior to simple linear regression models because they better reflect reality.

Logarithmic transformations of variables is a common method of modelling a non-linear relationship between the independent and dependent variables.

5.3.4. Clustering

Clustering is a process of knowledge discovery performed via unsupervised learning (there is not a label set for the learning process). Clustering algorithm groups data points into clusters in such a way that points within each cluster will be similar to each other and substantially different from points in other clusters.

The k-means algorithm is one of the most popular clustering techniques. It is often preferred for its simplicity and theoretical foundation. K-means employs an iterative process of updating the cluster centres until convergence. The k in k-means refers to the user-specified number of clusters or to the best value of k from the data set. k-means algorithm is based on the calculation of distances between data points and cluster centres: although different metrics may be used, the classical Euclidean distance is the most common.

Cluster analysis techniques have been applied to identify sources of particulate matter, to perform source apportionment of atmospheric pollutants (i.e. aerosols), explore relationship between climate and air pollutants, find patterns of pollutant distribution.

5.3.5. Artificial Neural Network

Artificial Neural Networks (ANN) are a biologically inspired computing system capable of performing several tasks including regression, clustering and classification. A typical neural network contains a large number of elements (called neurons). Each neuron has many inputs and one output. each input is weighted: the larger the value of a weight, the more relevant is the corresponding input. Upon receiving the signals the weighted inputs are all summed up inside the computing unit. An activation function converts the weighted sum of the signals to form the output of the neuron.

The neural network learns from subset of the whole data set by iteratively adjusting weights to obtain the output. ANN may overcome the absence of information about the analytical relationship between input and output data: in fact, ANNs are a very important tool for modelling complex unknown relationships between variables.

In environmental protection, ANNs are used to provide tentative missing data from environmental monitoring, predicting air and water pollution levels and sound levels, automatic image analysis and interpretation of biological monitoring results, environmental impact assessment and many other issues.

There are many types of the artificial neural networks which differ in structure and principle of operation, e.g. the fully connected feed-forward networks known as multi-layer perceptron (MLP) or the radial basis function networks (RBF). The basic structure of the artificial neural network consists of 3 types of layers of neurons (interconnected nodes). The first is the input layer where data is introduced. The second is the hidden layer where data are processed in order to extract the intermediate data required to determine the final solution. The hidden layer may be one or more than one. The third type of layers is the output layer, where the results are produced.

There are several learning algorithms used to determine the best weights in the input layer: the most popular algorithm of MLP learning is the back-propagation algorithm, which works by adjusting the weights to minimize the error between the actual and the desired outputs. This simple algorithm is quite slow, but very effective. The sum squared error function is often used in this algorithm.

5.3.6. Decision tree and random forest

Decision tree is a type of supervised learning algorithm that is used in classification and in regression problems. It breaks down a dataset into smaller and smaller homogenous subsets based on selected features (which best divides the training cases according to their labels).

The name “tree” is associated to the fact that this technique is based on a flowchart showing the various outcomes from a series of decisions whose main parts are a root node, leaf nodes and branches. The root node is the starting point of the tree, and both root and leaf nodes contain questions or criteria to be answered. Branches are arrows connecting nodes, showing the flow from question to answer. Each node typically has two or more nodes extending from it.

Simple tree predictors may create a collection called random forest (RF) in order to use multiple learning models to gain better predictive results. In the case of random forest, the model is created based on uncorrelated decision trees to arrive at the best possible answer. For classification problems, the ensemble of simple trees vote for the most popular class. In the regression issue, their responses are averaged to obtain an estimate of the dependent variable. Using collection of trees can lead to significant improvement in prediction accuracy.

Decision trees as well as random forest have been applied in great deal of research to predict air quality, identify air pollution sources, improve accuracy of common air pollution sensors, assess impact of different factors (weather, traffic etc.) on air pollution.

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6. New monitoring approaches

In order to increase the understanding of the spatio-temporal distribution of air pollution, supplementary techniques have been proposed and also in some way recognized by regulatory bodies. One of the most common supplementary techniques is mobile monitoring, which consists of vehicles having the same line of instrumentation as the fixed monitoring stations and with the same maintenance and calibration routines. However, due to their high cost and deployment issues (e.g. power supply), mobile monitoring cannot significantly increase spatial sampling density.

Another technique that appeared some decades ago was represented by passive samplers, which have several advantages, such as low costs, easiness to use in field (except for laboratory analysis) and no need of power supply. Nevertheless, a limitation of such solutions is the impossibility of pointing out any temporal pattern is the most relevant.

A third fundamental tool to supplement air quality monitoring consists of air quality models. They can be very useful in spatial mapping of air pollution and can be used also for scenario analysis and air quality forecasting. The problem is that they require a highly specialized knowledge and input data that is not available in all places and that modelled concentrations may also suffer from systematic and stochastic errors, in particular when highly reactive pollutants are considered.

In addition to the above mentioned tools for air quality assessment, during the last decade regulatory bodies such as the European Commission (Karagulian, 2019) and US-American Environmental Protection Agency (EPA) have recognised the importance of new monitoring technologies based on different type of sensors. Air quality sensors have produced such high expectations to the point of making some researchers talk about “paradigm shift of air pollution monitoring”. The main advantages are related to the fact that they are small and portable, apparently easy to use and deploy, and often low cost or at least much less expensive than reference instruments.

6.1. Sensor systems

6.1.1. Overview of sensor systems

For classification and understanding of sensor deployment, one should distinguish between the sole sensor detector produced by Original Equipment Manufacturer (OEM sensors) and sensor systems (SSys), which include OEM sensors together with a protective box, sampling system, power system, electronic hardware, and software for data acquisition, analogue to digital conversion, data treatment and data transfer. There is a limited number of companies that presently manufacture air quality sensors (less than ten) while there is a large and rapidly growing number of companies selling sensor systems.

The operation of all the identified PM sensors is based on the light scattering principle. The aerosols are carried in the air flow across a focused beam of visible or infrared light and the intensity of the scattered light in a selected direction is monitored by a photo-detector. PM sensors are classified into two types: volume scattering devices and optical particle counters (OPCs). In the former the light is scattered from the ensemble of particles. On the other hand, OPCs count and estimate the sizes of individual particles, following which the readings are converted to a particle mass concentration, based on the assumption that the particles are spherical and of consistent bulk density and refractive index.

Various sensor devices are available on the market also for gases. Electrochemical gas sensors are used for measuring the concentration of a target gas by oxidizing or reducing the gas at an electrode and measuring the resulting current. The sensor consists of two or three electrodes that are in contact with an electrolyte. The electrodes are made of porous hydrophobic membrane fixed with a high surface area precious metal. Electrochemical sensors are operated based on the diffusion of gas of interest into the sensor, which results in the production of an electrical signal that is proportional to the gas concentration. A typical gas sensor consists of a sensing layer, deposited on a transducing platform, which is in contact with the environment, together with a transducer that produces a measurable output signal. Electrochemical gas sensors measure currents of electrons of several possible redox reactions, and hence several possible species. Other types of sensors are the metal-oxide sensors that measure the conductance of charges on semiconductor material of species undergoing either reduction or oxidation with reactive oxygen.

6.1.2. Applications

Five main air quality monitoring applications have been proposed for sensor technologies:

1. Supplementing routine ambient air monitoring networks
2. Mobile monitoring
3. Monitoring at the source
4. Monitoring personal exposure
5. Participatory sensing, Citizen Science

Supplementing routine ambient air quality monitoring networks

This is the most obvious application of the new sensor platforms. Supplementing routine networks with sensor platforms may be valuable not only due to their lower cost, but also based on the fact that sensors are often small battery-operated devices and can be mounted on existing infrastructure, such as street lamps and traffic signs. The combination of these factors would allow for a much wider spatial coverage than provided by current air quality monitoring stations. Nevertheless, sensor networks would need to operate in parallel with conventional stations, and the data provided by the sensors would need to be compared and corrected with regards to conventional reference monitors from the stations.

The assessment of pollutant levels through these different types of sensors should cover the entire zone and not only the spots where fixed stations exist. Indicative measurements may be less accurate but micro-sensors may allow to assess the spatial and temporal distribution of pollutant concentrations in a variety of environments where fixed measurement data is not available, to identify areas where elevated pollutant concentrations may occur. For example, sensors may provide estimations of air pollutant concentrations at interest points such as schools, hospitals or a particular road intersection.

Figure 6.1. Example of use of air quality sensor system in locations where fixed site stations cannot be deployed

Mobile monitoring

Sensors may also be mounted on mobile platforms such as bicycles, cars, public transport. The fact that the sensors usually include a GPS receiver to track the sensors facilitates the generation of air quality maps at street level. Mobile platforms cannot trace the temporal variability in the same way as fixed stations but can provide pollution levels within the “street environment”. However, with mobile networks it is possible to generate maps of air pollution aggregated over time (for instance, all the mobile platforms which have been traversing one specific street during the last 24 hours), or to compare pollution at different streets or parts of the city at a given moment in time. These kinds of assessments might allow for the development of new types of studies of urban pollutants that assess personal exposure while moving through a city, small-scale variations due to street canyon effects and sources and pollutant dispersion at much more detailed scale.

Figure 6.2. Example of use of air quality sensor system for mobile monitoring

Monitoring at the source

Another possible use of AQ sensors is monitoring at the source where air pollutant concentrations and sensor performance may be higher. For instance, new sensing technologies can be used to build dense surveillance networks for industries, both at the source level, within industrial halls, as well as outdoors in the vicinity of the industrial plants. Although the sensitivity and accuracy is still not at the level of the required for regulatory emissions or ambient monitoring, the data can supplement the existing networks and provide ubiquitous monitoring to better capture, e.g., industrial incidents as chemical releases, fugitive emissions, worker exposure, etc. In this context sensors can be also used to verify the results of model simulations.

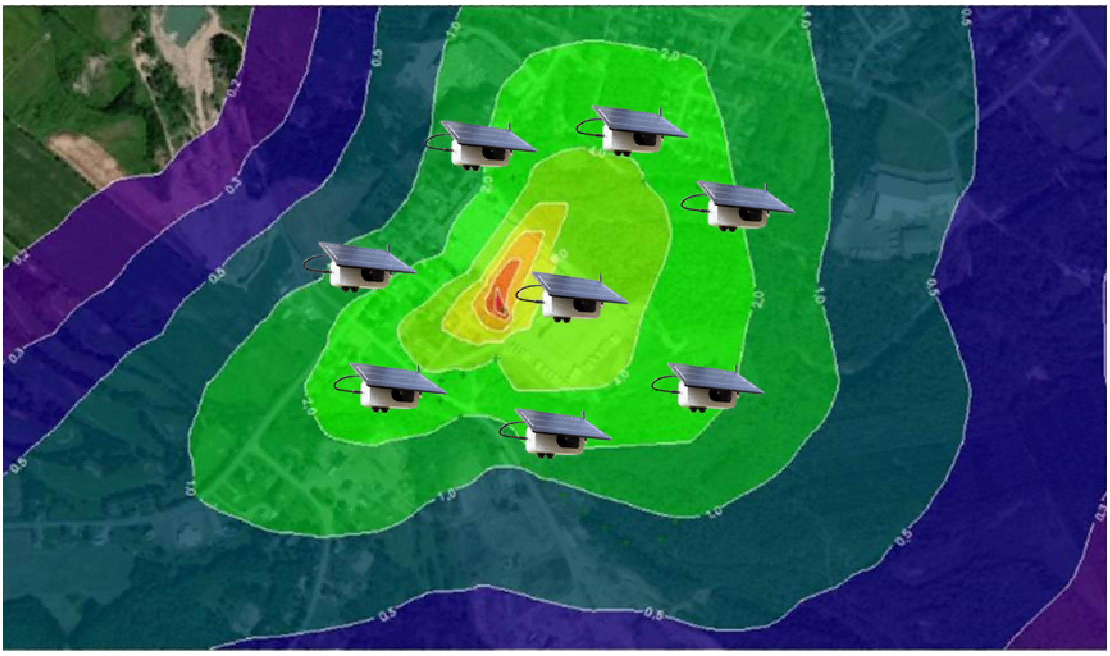


Figure 6.3. Example of use of air quality sensor system for point source impact assessments

Monitoring personal exposure

Personal exposure to air pollution links air quality with health effects. The protection of human health is one of the main reasons why air quality monitoring is regulated by European legislation. However, estimating personal exposures and attributing exposure to sources presents significant challenges because of the spatial and temporal variability and the difficulty in estimating time-activity patterns, i.e., the time individuals spend in different environments (office, commuting, working out outdoors, etc.). Attempts have been made to measure personal exposure combining sensors and GPS functionality embedded in smartphones. One of the advantages of this type of indirect sensing is that it reduces costs, and that it is not necessary for the user to carry additional sensors to the ones already integrated in cell phones. Indirect sensing uses the location data from the phone and merges it with exposure models making possible to estimate exposures at multiple locations per person rather than only at the residence location.

Another way to provide citizens with an estimation of their exposure is based on body-worn sensor nodes carried by users during their everyday activities. Sensor nodes provide information about air pollution in the surroundings of the user, and it is also possible to evaluate personal exposure along a route. Recently, integrative USB pluggable sensors are built for mobile phones to obtain air quality information. Sensors integrated into mobile phones have the advantage of mobility, co-location with people, pre-built network and power infrastructure, and potentially, ubiquity. These characteristics, however, also present significant challenges. Mobility means non-uniform sampling in space, and constrains the size and weight of the sensors. However mobile sensing has the theoretical potential to provide an individual's exposure at a specific place and time.

Despite the challenges of personal monitoring, improving estimates of personal exposure may prove an asset for epidemiological studies, which often rely on limited ambient air monitoring data as input. Additionally, air pollution sensors can be linked with physiological sensors, thus providing a better estimate of human exposure.

Figure 6.4. Example of use of air quality sensor system for personal monitoring

Participatory sensing

Participatory air quality monitoring is taking place in several cities around the world (see section 4 below) and this use of sensors can be considered an additional and growing application of air quality sensors. Participatory sensing refers to the vision of distributed data collection and analysis at the personal, urban, and global scale, in which participants make key decisions about what, when and where to sense. It emphasizes the involvement of individuals and community groups. A revolutionary aspect of this new monitoring strategy is the change in who is measuring air pollution and the purpose for which it is being measured. Until now, air pollution measurement has primarily been in the hands of trained scientists, experts and technicians employing reference instruments. New low-cost easy-to-use sensors are making it possible for any individual to measure air pollution and share the data (US-EPA, 2013). This, however, presents strong limitations regarding data quality and comparability as will be discussed below.

In some of the cases, participatory sensing has not been promoted under specific research projects or by governmental organizations, but instead has surged from a sector of the population concerned by air quality. Currently, there is a growing number of “Do It Yourself” (DIY) projects which allow citizens to easily build air quality sensors. One of the most well-known is the Air Quality Egg, but there are also other DIY projects related to air quality monitoring in urban areas. Indeed, the attraction toward low-cost sensors is sufficiently great that, even before sensor performance has been characterized, widespread data collection and data sharing using new sensors is already occurring. It must be stressed that this is, by far, the largest risk of participatory sensing given that data are in no way quality-checked before they are shared. Thus, these projects raise the question about the importance of quality data and assessing uncertainty levels. Poor quality data or unknown uncertainty levels lead to data misinterpretation and erroneous conclusions. Administrations have already expressed their concerns on how to respond to citizens reporting data from sensors while information on data quality is unavailable (US-EPA, 2013). Guidance documents and advice on sensor use and data interpretation are essential to help communities and individuals to effectively take advantage of this new technology.

There is also a growing interest in the scientific community about the use of citizen collected data for scientific purposes which is the real meaning of “Citizen Science”. Examples are the recently funded projects by the European Commission under the call FP7-ENV.2012.6.5-1 "Developing community-based environmental monitoring and information systems using innovative and novel earth observation applications".

Figure 6.5. Example of use of air quality sensor system for indoor and citizen science experiences

6.1.3. Practical use of sensors

One of the issues to be faced when using sensor systems is the transmission of measured data. Some of the low cost sensors don't include a transmission module and data can only be visualized on a screen installed on the device. Other systems are equipped with a transmission module based on wifi connection, i.e. an internet connection to a server. Finally, the most advanced systems include a GSM system that enable a communication between the instrument and a server. Wi-fi and GSM systems are often complemented by a web platform for data visualization and download.

Another important issue related to the use of sensor systems is the field calibration. Main current calibration solutions from the manufactures are limited to sensor testing in the laboratory under controlled conditions. This approach often provides unsatisfactory results during ambient air monitoring making the field calibration a necessary phase when using air quality sensors. However, field calibration is associated with problems related to the generalizability of calibration parameters calculated under specific ambient conditions. The issue is relevant when sensors are calibrated and used at the same place because of the limited range of environmental conditions experienced during the calibration period. But the problem becomes significantly more important when sensors are calibrated in a site and used for monitoring campaigns in other sites. Indeed, calibration parameters may be site-specific with an additional possible influence of sensor handling and transport. Unfortunately, while multiple relocation is the most useful use of the air quality sensors in real world applications almost all published studies analyzed sensor performance considering calibration and testing at the same site.

The effect of relocation is important also in relation to the choice of calibration approach. Several algorithms have been tested for sensor calibration spanning from univariate or multivariate linear regression models to machine learning techniques such as Artificial Neural Networks, Support Vector Machine, Random Forest and Hybrid models. Findings from literature show that calibration procedures involving non-linear methods generally outperform those using classical statistics, and better capturing the effects of environmental factors on sensor response.

In conclusion, despite the high expectations and potential pros, research and regulatory bodies have raised several issues related to the accuracy of such monitors including problems of stability, cross-sensitivity, repeatability and reproducibility. The use of air quality data collected by low-cost sensors requires reproducibility and assessment of uncertainty of measurements. In this respect, it is necessary to define technical specifications for performance of these low cost sensors, since manufacturers generally provide insufficient information in terms of data quality and stability over time (essential for long term field campaign). This situation gives rise to doubts about the adequacy of the sensors for the specific purpose of the user who acquired the system. The European Committee for Standardization (CEN/TC264/WG42) and EPA have been working on the definition of some technical specifications of statistical indicators and methods to be used for laboratory and field testing of air quality sensors.

6.1.4. Costs

Sensor systems are often referred to as “low cost” instruments. However, the term “low cost” is relative, depending on user and the specific purposes, and has been used loosely in the literature. For example, a sensor system of 2000-5000€ could be low cost for a regulatory authority but unaffordable for community monitoring. Additionally, the term “sensor/monitor” was sometimes used to refer to both the measuring component, as well as the whole monitoring systems, including one or multiple sensors/monitors, enclosure, data display (optional), battery or other power source connection, and varying components for data storage, transmission, and retrieval. Sensor alone have generally costs varying between 10 to 300€. However, since the “sensor” alone will be of little use without the supporting components, it is more useful to provide information about sensor systems. As for sensor systems, basic models (without internal memory, with data transmission via wi-fi connection and very simple enclosure) may cost as low as a few tens of euros while high end instruments (with data transmission via GSM, equipped with multiple sensors, with >IPx6 enclosure, powered with solar panel or grid) may cost more than 10000 €. It is important to highlight that low cost sensor systems may be purchased on the internet while most high end sensor systems use is often binded to a contract for data transmission, access and control.

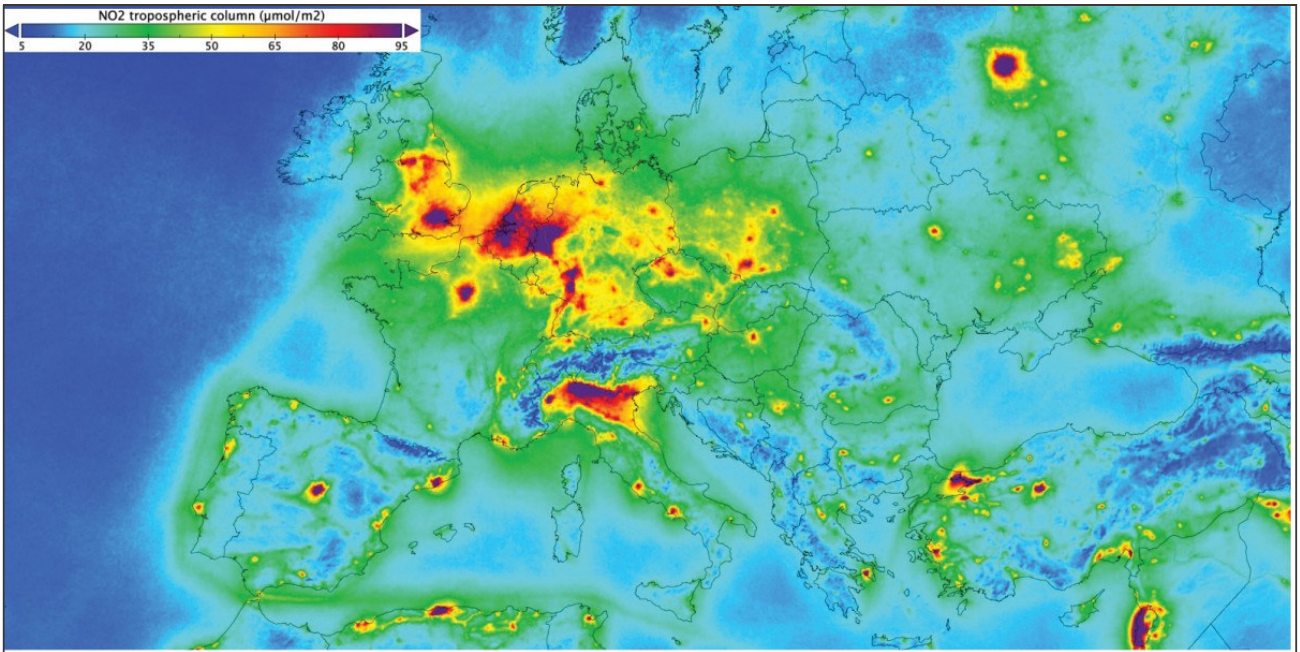
6.2. Satellites

As already said, fixed site monitoring networks provide frequent measurements while often lacking in spatial coverage. Another possibility to overcome this drawback can be represented by space-borne air pollution monitoring: satellites equipped with spectrometers measure the abundance of select molecules in the form of atmospheric column densities. While their position in Earth's orbit allows satellites to frequently map most locations on Earth, remote sensing spectrometers currently only provide spatial resolutions in the kilometres range and with little information about the pollutant's vertical distribution. Specifically, the estimation of concentrations near the surface, where these pollutants originate from, is a non-trivial task.

The main strengths in satellites data are the possibility of having information about the horizontal transport of pollutants on short and long timescales, of advance warning for air quality events, especially wildfires and dust storms and of collecting air quality information in areas where there are no ground-based monitors.

However, some problems are related to the use of air quality data from satellites. The first one is the lack of specificity for some pollutants. In this sense the most useful and reliable data from satellites have been obtained for $NO2$ and $PM2.5$. The second problem is the already mentioned spatial and temporal resolution that are not appropriate for some applications. Another problem is the presence of clouds that precludes the measurement of many satellite products, making them essentially unavailable in cloudy days. In conclusion, satellites data alone cannot provide accurate and detailed information about air pollutant distribution at urban and suburban scale. However, satellite data prove to be especially powerful when combined with other data, such as ground-based monitor measurements and land use information (see section 6.4).

During the last decades EU has promoted a research and development programme in the field of use of satellites to monitor the environment and the air quality. The Sentinel-5 mission is part of the European Earth Observation Programme "Copernicus" which is a coordinated and managed by the European Commission (EC). The space component of the Copernicus observation infrastructure is developed under the aegis of the European Space Agency (ESA).



According to the Air Quality in Europe report published in 2018 by the European Environment Agency (EEA), 19 EU Member States recorded nitrogen dioxide concentration above the annual permissible limit. Imagery from Sentinel-5P

Figure 6.6. Example of use of satellite data for air quality assessment

The Copernicus Space Component comprises a series of space-borne missions called 'Sentinels' that are developed and procured by the European Space Agency. The missions Sentinel-4, -5 and -5 precursor (S4, S5, S5P, respectively) are conceived as complementary elements of a constellation serving the specific needs of the Copernicus Atmospheric Monitoring Services (CAMS). These services will provide coherent information on atmospheric variables in support of European policies and for the benefit of European citizens and will cover ozone and surface UV, air quality, and climate applications. Sentinel-5 is focused on air quality and composition-climate interaction with the main data products being O3, NO2, SO2, HCHO, CHOCHO and aerosols. Additionally Sentinel-5 will also deliver quality parameters for CO, CH4, and stratospheric O3 with daily global coverage for climate, air quality, and ozone/surface UV applications.

6.3. Drones

Unmanned Aerial Vehicles (UAVs) technology has gained popularity over the years also for air quality monitoring also because taking measurements close to pollutant sources may not always be possible and it could be too dangerous. Several reasons encourage the use of small, lightweight UAVs for a wide range of applications including applications in urban settings. Small, lightweight UAVs can provide more accurate information on air pollutant vertical distribution throughout the atmosphere, which is needed to understand air quality and composition in specific atmospheric layers. They are being used in various air quality control methods for measuring particulate matter and VOCs as well as measurements relating to meteorology such as temperature, humidity, pressure and winds. In addition, UAVs are quickly deployable, cover large areas and can monitor remote, dangerous or inaccessible locations, increasing operational flexibility and resolution over land-based methods. Therefore, UAVs may be a viable option for air quality data collection. A wide range of sensors, improvements in data post-processing, and continuing evolution of the drones themselves are expanding the potential uses.

Figure 6.7. Example of use of air quality sensor system installed on drones

The potential of UAVs for studies on air quality has been identified, but several issues still need to be resolved which includes flight longevity, payload capability, sensor sizes/precision, and sensor reactivity. The difficulties, however, are not just technical, but at present time, policies and laws, which vary from country to country, symbolize the major challenge to the extensive use of UAVs in the air quality/ monitoring studies. UAV systems are flexible, allowing various sensors to be transported and operated in distinct flight modes. Due to the capacity and flexibility of these robotic systems, UAVs have a promising future for air quality measurement and its applications.

6.4. Combined use of models and monitoring systems and high resolution AQ mapping

As already said, many studies have documented large spatial contrasts in air pollution in European and US cities. Land Use Regression (LUR) modelling has become a popular method for explaining the observed contrasts, as well as estimating outdoor pollution concentrations at the homes of participants of large epidemiological studies. LUR relies on a spatially dense air pollution monitoring network, with each site characterized by a set of potential “predictor variables”, which are generally derived from Geographic Information Systems (GIS). In LUR, a regression model is developed which links the air pollution concentrations observed in the network to the most predictive environmental characteristics, such as traffic, land use and population. Depending on the pollutant, LUR modeling has been able to explain a moderate to large amount of spatial variability in concentration for a growing arsenal of pollutants.

LUR models are based on data measured in different ways. Large scale LUR models (e.g. models with spatial domain from the regional to the European scale) can rely on fixed site monitoring station data. In this case, the spatial resolution of the model output is usually of the order of the 10s of kilometres. These models are often coupled with satellite data which provide estimates with similar spatial resolution. Several studies have produced accurate concentration maps mainly for NO2 and PM2.5 adopting this approach.

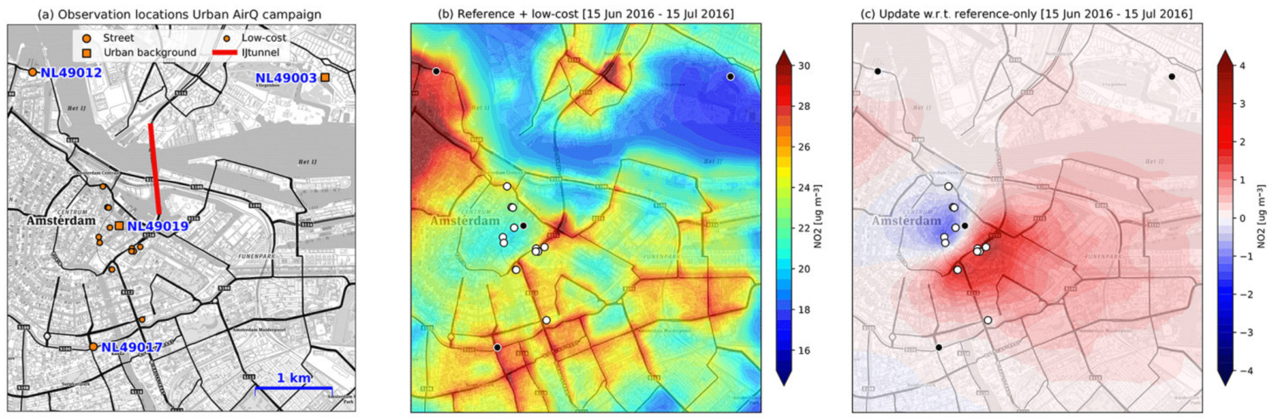


Figure 6.8. Example of use of air quality sensor system to feed Land Use Regression models

When LUR models are built to assess spatial variability of air pollutants at finer scale (metropolitan, urban or suburban scale) fixed site monitoring stations are too sparse and inadequate for model construction. It is therefore necessary to plan measurement campaigns with portable devices such as passive samplers or sensors.

As already mentioned, passive samplers, also called diffusive samplers, are light weight, inexpensive and do not need maintenance, on-site power and pumping. Therefore passive samplers which offer a simple, cost effective means of measuring air pollutants have been performed for the monitoring of ambient NO2, CO, Benzene and other pollutants' level worldwide. These earlier tubes used triethanolamine (TEA) as absorber. With the time several different types of passive samplers been developed using different absorbers. Passive samplers are generally designed either in a tube-type configuration with one end open (so-called "Palmes tubes"); or in a shorter badge-type configuration, where the open end is protected by a membrane filter or other wind screen. In either case, the closed end contains an absorber for the gaseous species to be monitored. Several different types of commercial diffusion tubes are there in market in recent time. The basic principle on which diffusion tube samplers operate is that of molecular diffusion, with molecules of a gas diffusing from a region of high concentration (open end of the sampler) to a region of low concentration (absorber end of the sampler). The movement of molecules of gas is governed by Fick's law, which states that the flux is proportional to the concentration gradient.

The accuracy of passive samplers is quite good (higher than the threshold established for indicative measurements) but it is important to highlight that data provided by passive samplers are time-integrated, i.e. refer to the mean value of pollutant concentration in a time window that typically spans from some days to 2 weeks.

Recently sensor systems have complemented and progressively replaced passive samplers. The strengths of sensor systems are related to the possibility of collecting time resolved data (down to 1 min measures) and to measure also particulate matter.

A few recent LUR studies have also modelled ultrafine particles variability, mostly based on mobile or short period monitoring. Long-term, spatially resolved monitoring campaigns for ultrafine particles (UFP) have been uncommon because the condensation particle counters which are typically used for measurements are costly and require daily maintenance.

Typically, LUR models are developed for single cities, metropolitan areas or regions, and applied within the same geographical parameters. Some attempts have been presented to combine study areas, or transfer LUR models between areas. Most studies conclude that locally developed models are favourable over combined-area or transferred models. However, it has been mentioned that combined-area models may allow epidemiological studies to pool epidemiological data from different areas and better exploit the between area contrasts, which would substantially increase the exposure range for some pollutants.

The background concentration difference between areas is often mentioned as a source of over- or under-prediction when applying these combined-area models, and has been addressed by including indicator variables, area-specific regional background or recently satellite-observed background concentration, or larger scale dispersion models.

LUR models were originally linear models but during the last years non linear approaches have successfully tested with a wide use of artificial intelligence (IA) techniques. In particular several studies have tried to integrate information from fixed site reference station data with data from spatially dense network of sensor systems.

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