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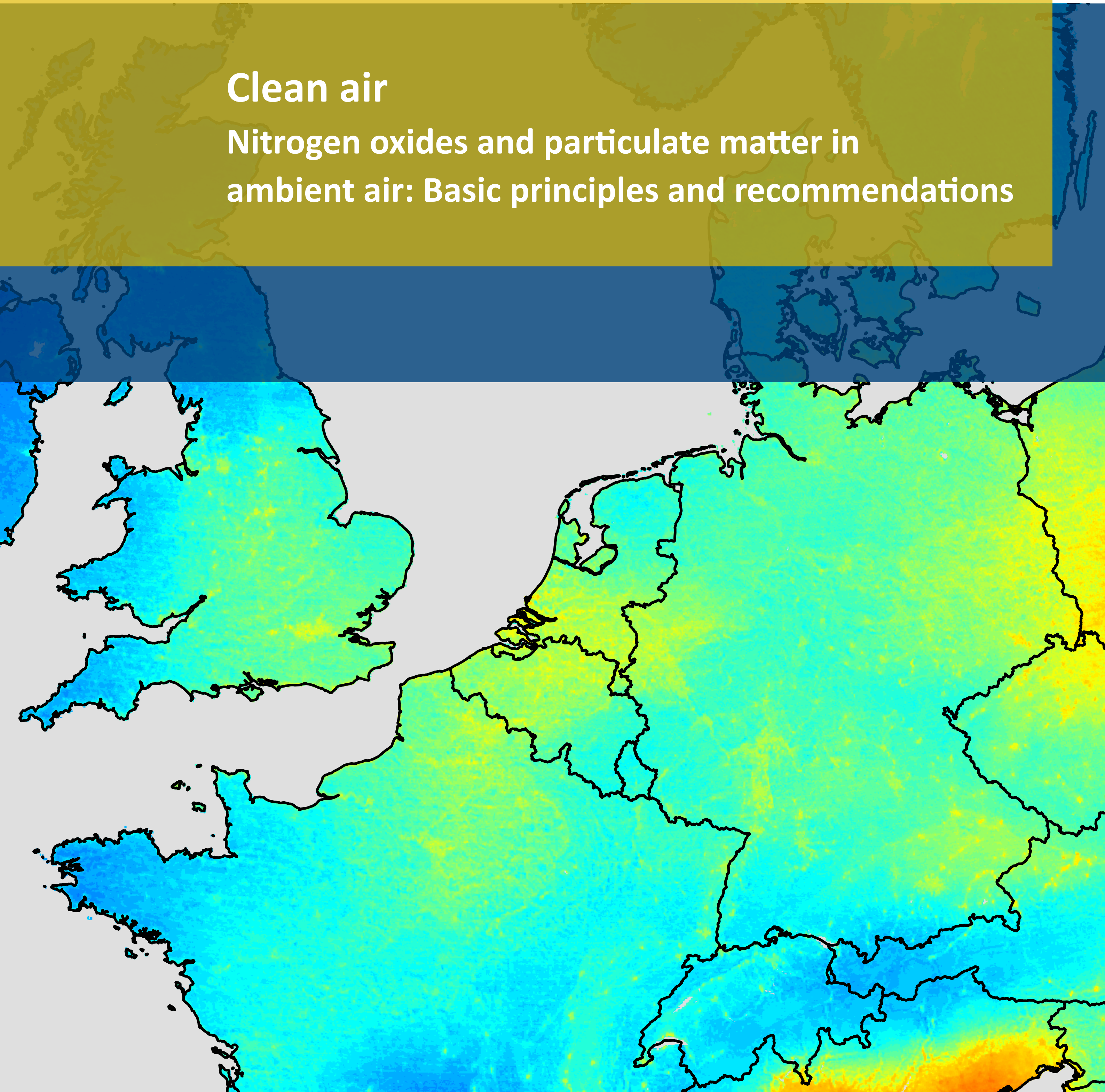
Clean air

Nitrogen oxides and particulate matter in ambient air: Basic principles and recommendations



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Particulate matter in Germany and adjacent countries. For more information see p. 58.
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Nitrogen oxides and particulate matter in ambient air: Basic principles and recommendations

Contents

Preliminary remarks

Today, extreme air pollution and smog are primarily associated with megacities such as Delhi, Beijing and Cairo. In Europe, they have become a matter of the past. But many people still remember the Great Smog of London, which killed around 12,000 people in the winter of 1952. Ten years later, in December 1962, the Ruhr district experienced the worst ever smog crisis in Germany.

A lot has changed since then. Thanks to improved filter technology in power stations and the introduction of catalytic converters and unleaded petrol for cars, air pollutant levels in Germany have fallen considerably. Political action provided the framework for this, for example through the German Federal Immission Control Act and limit values for air pollutants on a national and European level. The smog regulations adopted by some federal states were abolished during the 1990s as they were no longer necessary. Today, the air in Germany is nowhere near as polluted as it was several decades ago. It is now virtually unthinkable for concentrations of sulphur dioxide, carbon monoxide, benzene and lead to exceed the EU limit values. Pollution from particulate matter and nitrogen dioxide is also showing a downward trend.

Such examples demonstrate that it is possible to control air pollution. This is also true for the persistently problematic substances nitrogen dioxide, particulate matter and ozone, which are a particular cause for concern in metropolitan areas and areas with heavy traffic and industry.

There are many factors to consider when analysing the impact of air pollutants on health, and there are some questions to which there is still no final answer. But regardless of this, legislators are expected to set limit values for emissions and pollution. This is done on the basis of the precautionary principle, which applies throughout Europe and aims to prevent or considerably reduce potential dangers to the environment and human health. Our statement expands on this approach by relating the expected benefits to the anticipated societal costs.

Clean air is a public good which is vital for life. Responsible environmental and health policy must make the campaign against air pollution a priority. It is therefore a good sign that the right track to air quality management is being debated with such passion in a highly developed industrial society such as Germany. It will only be possible to reconcile our mobility needs and environmental protection in the long term through measures which are supported by as many people as possible.

The current debate centres around the standardised EU limit value for nitrogen dioxide (NO_2) and the suitability of short-term measures such as diesel car bans in order to meet this limit value. A major question under discussion is the scientific basis to set limit values for air pollution.

It was against this backdrop that, at the end of January 2019, Chancellor Angela Merkel asked the National Academy of Sciences Leopoldina as a provider of science-based advice for politicians and the general public to look into air pollution – particularly by NO_2 – and the resulting impact on human health. In February 2019, the Leopoldina established an interdisciplinary working group to take up this issue.

The working group started out, as requested, by looking at the scientific evidence on air pollution from nitrogen oxides (particularly NO_2). It explored this topic in conjunction with the much more harmful pollution of ambient air by particulate matter. But it has also incorporated an even more important aspect: the emission of greenhouse gases, most notably carbon dioxide (CO_2). All of these aspects must be considered in an integrated approach, as measures which may appear wise from a single perspective may nonetheless turn out to result in net harm.

This ad hoc statement presents the results of the discussions in the working group. It includes information on the latest scientific knowledge as well as recommendations for the next steps to achieving cleaner air.

We would like to express our heartfelt thanks to all of the scientists who were actively involved as members of the working group or who provided their expertise, either in a consultation or in writing. The Leopoldina views this ad hoc statement as its first contribution to the ongoing debate and intends to devote more of its efforts to wide-reaching scientific questions concerning the development of a mobility system which is socially, economically and ecologically sustainable.

Martin Lohse
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President

The statement in brief

- The EU Directive 2008/50/EC on ambient air quality and cleaner air for Europe, adopted in 2008, provides the legal basis for German air quality management policy. It establishes a narrow framework for national measures.
- The **pollutant load in air** has decreased significantly in recent decades. This includes **nitrogen dioxide** and **particulate matter**. Nonetheless, the limit values are still sometimes exceeded – frequently for nitrogen dioxide and rarely for particulate matter. Particulate matter originates not only from direct emissions. A significant proportion is formed by gases such as nitrogen dioxide and ammonia; this fraction has not yet been systematically recorded.
- Particulate matter poses a much greater risk to health than nitrogen dioxide. In view of the comparably low health impact of nitrogen dioxide, from a scientific perspective, it does not seem urgent to revise the existing limit value downwards. In contrast, a further **reduction in particulate matter pollution** should be an urgent priority – even if the current levels measured in Germany are within and sometimes well below the EU limit values, which are less strict than those for nitrogen dioxide. It should be noted here that there are many sources of particulate matter.
- Localised measures and short-sighted actionism contribute very little to achieving a sustainable improvement in air quality. It is wiser to pursue a longer-term strategy which considers other relevant sources of pollution in addition to road traffic. The aim should be to develop a nationwide, cross-sector **strategy for air quality management** which factors in other pollutants and greenhouse gases from all sources in addition to nitrogen oxides and particulate matter. It should offer orientation and guidance to politicians and industry and form a basis for local and regional air quality management plans.
- Road traffic causes other environmental stresses beyond air pollutants. Germany has committed to a comprehensive **reduction in greenhouse gas emissions**. Under the EU Effort Sharing Regulation, Germany has a binding CO_2 reduction target of 38% by 2030 (compared to 2005 levels) in the sectors of transport, buildings and agriculture. All of these are reasons to focus on the swift development of a concept for a **sustainable transport transition**.
- The development of low-emission forms of transport is e**xtremely important** not only for decreasing traffic-related pollution, but also **for the economy**.
- There is a **need for further research** on air pollutants – on methods for measuring them and modelling their dispersal and effects, on health impacts, particularly from ultrafine particles, on strategies for preventing these pollutants, and on the social costs and benefits associated with any potentially promising measures.
- The **Leopoldina** will establish working groups to prepare and accompany the development and implementation of the recommended measures.

Key declarations and recommendations

Key declarations

Air quality and air pollution in Germany

- Clean air is fundamental to healthy human life. However, in Germany and elsewhere, air quality is negatively impacted by **pollutants** which have a detrimental effect on health and the environment.

- In addition to natural sources, it is primarily combustion processes (in the energy system, households, and traffic) as well as agriculture and industry which **contaminate** the air with pollutants.

- In general, **air pollution in Germany** has decreased considerably in recent decades – even though traffic and industrial production have grown during the same time. Improvements in fuel quality and new technologies for exhaust gas post-treatment have significantly contributed to this decrease. Today, sulphur dioxide, carbon monoxide and lead play only a minor role in air pollution. This shows that air quality can be greatly improved through resolute action.

- Ozone, **nitrogen oxides** – particularly nitrogen dioxide (NO_2) – and **particulate matter** are among the air pollutants which continue to be a problem. Nitrogen dioxide emissions from road traffic are produced primarily by diesel vehicles which do not meet the most recent emissions standards such as Euro 6d-TEMP for passenger cars. Particulate matter generated by human activity largely comes from power stations, industry, agriculture, road traffic, and heating stoves and furnaces. Gases such as volatile organic compounds, nitrogen dioxide, ammonia and sulphur dioxide contribute to the formation of greater quantities of secondary particulate matter than the amounts emitted directly. Modern vehicle engines, regardless of their technology, make a relatively small contribution to the direct particulate matter pollution currently measured. However, particles emitted through wear of tyres and brakes continue to be a significant issue.

Health risks and health protection

- When discussing **health risks**, a distinction is generally made between acute and long-term effects. *Acute effects* are investigated in experiments using relatively high concentrations of clearly defined substances (toxicological studies) as well as population studies in real-life conditions (epidemiological studies). Long-term effects are recorded by epidemiological monitoring of people subject to different levels of exposure over a longer period of time. Needless to say, the conditions for these studies are less strictly defined; on the other hand, everyday exposure can be better assessed. On the basis of epidemiological studies, it is possible to calculate a number of quantitative indicators which complement each other to convey an overall picture of the health risks – for example, of how life expectancy is reduced by the inhalation of certain air pollutants. Of all the environmental factors in Germany which lead to disease and shorten life expectancy, air pollution is the most significant one.

- For people suffering from asthma, spending even a short time in an environment with considerable **nitrogen dioxide** pollution can be sufficient to trigger an acute asthmatic attack. Long-term exposure to nitrogen dioxide can cause respiratory problems such as asthma. All in all, the health effects of the concentrations currently measured in the ambient air are less severe than those of particulate matter. Nitrogen dioxide occurs in the environment in combination with other traffic-related pollutants, making it difficult to determine its independent effects on human health. Furthermore, it contributes to the formation of particulate matter and ozone.

- **Particulate matter** poses a considerably greater risk to health than nitrogen dioxide. Particulate matter enters the lungs via the inhaled air, and the smaller the particles, the deeper in the lungs they are deposited. Particulate matter can increase mortality and cause respiratory and cardiovascular diseases as well as other illnesses such as lung cancer. Ultrafine particles can enter the bloodstream via the lungs, causing a variety of other health problems.

Limit values and measurement of air pollutants

- To ensure precautionary health protection for the general population, political authorities lay down **limit values** for air pollutants on the basis of the latest scientific knowledge. In the case of both nitrogen dioxide and particulate matter, it is not possible to draw a precise line between harmful and harmless, where there are no health effects below a certain threshold. This makes it difficult to weigh precautionary health protection against the resulting economic and societal costs. Among the G20 countries, there are varying limit values for nitrogen dioxide and particulate matter. The limit values laid down by the EU are relatively strict for nitrogen dioxide and less strict for particulate matter.

- Air quality is recorded at approximately 650 **measuring stations** across Germany. The procedures for measuring nitrogen dioxide and particulate matter are standardised and the positioning of measuring stations is regulated by law. Even within this legal framework, measurement results can differ considerably depending on the precise location where the samples are taken. Different positioning conditions apply in countries outside the EU. This limits comparisons of results from around the world. A harmonisation of measuring techniques and positioning conditions would be desirable in the interests of drawing reliable international comparisons.

Recommendations

1. Overall, **nitrogen dioxide** is showing a decreasing trend. The annual mean air quality limits are currently violated at quite a number of roads with high traffic volumes. In these cases, there is a legal obligation to introduce effective countermeasures. In view of the relatively lower health impact of nitrogen dioxide compared to particulate matter, it does not seem urgent from a scientific perspective to revise the existing limit values downwards. In this context it should be considered that nitrogen dioxide pollution, which is currently the focus of attention, will presumably decrease so much over the next five years due to vehicle modernisation that it will mostly be possible to meet the relevant limit values.

2. **Particulate matter** has also displayed a downward trend in Germany for decades. Here, a further **reduction in pollution levels** should be a priority – even though the current levels measured in Germany are within and sometimes well below the relatively moderate EU limit values. It should be noted here that there are many sources of particulate matter.

3. Small-scale and short-term limitations directed against individual sources of nitrogen dioxide pollution are **measures with little benefit** for human health. These include road closures and isolated driving bans which only serve to divert traffic into other urban areas.

4. Human health is highly dependent on the **environment and climate**. Reducing nitrogen dioxide pollution therefore should not contribute to an increase in climate-affecting CO_2 emissions. For the sake of climate protection, among other reasons, it would not be prudent to replace all diesel vehicles with petrol vehicles of the same weight class and engine output. Reducing the emissions per vehicle is not sufficient for reducing the total emissions. Instead, there is a need for new mobility concepts, most notably in large urban areas.

5. A **mixture of short-term and mid-term measures** which complement each other is a particularly promising approach. Completing the planned software updates for diesel vehicles as quickly as possible will generate a significant reduction in nitrogen dioxide pollution from urban traffic. Hardware retrofits might also contribute to such a reduction, and in the short term make particularly sense for buses and municipal vehicles. Socially fair changes to taxation as well as higher fuel prices will help speed up a decrease in total distance travelled by private and commercial vehicles. In the medium term, the development of low-emission public transport, improved traffic control to reduce fuel consumption, and the systematic replacement of older vehicles with low-emission models can be expected to bring about further benefits.

6. Traffic is not the only aspect to be considered when pursuing a further reduction in particulate matter. The aim should be to develop a nationwide, cross-sector **strategy for air quality management** which factors in other pollutants and greenhouse gases from all sources – including agriculture and wood combustion – in addition to nitrogen dioxide and primary and secondary particulate matter.

7. Germany has committed to a comprehensive **reduction in greenhouse gas emissions**. The pressure will increase considerably from 2020 in the context of the EU Effort Sharing Regulation. For Germany, this means a binding CO_2 reduction target of 38% by 2030 (compared to 2005 levels) in the sectors of transport, buildings and agriculture. Failure to meet the annual targets might result in considerable compensatory payments for purchasing emission allowances. These are further reasons to work towards the systematic implementation of a **sustainable transport transition**.

8. Intensified efforts in the fields of e-mobility and alternative technologies to develop **low-emission vehicles** will play a major role in this transition. It will be necessary to interconnect different means of transportation (public transport, passenger cars, bicycles etc.) and build up the associated infrastructure.

9. An accompanying **cost-benefit analysis** should help to bear in mind the societal costs of such interventions. **Research and development** on the topic of air pollutants should also be strengthened, most notably in the following areas: formation, measurement and analysis of pollutants, distribution modelling, mechanisms of adverse health effects, ultrafine particles, and prevention strategies.

10. Germany has made considerable progress in air quality management in recent decades on the basis of scientific knowledge. This allows us to be optimistic that further improvements can be achieved. Now it is time to combine the goals of **high air quality, increased climate protection and sustainable prosperity** and to embark on a suitable strategy.

1. The pollutants

Adults take approximately 20,000 breaths per day, and this figure is even higher for children. When we breathe in, our body takes in vital oxygen, while breathing out releases carbon dioxide. Dry air consists of 21% oxygen (O_2) and 78% nitrogen (N_2). Air pollutants make up considerably less than 1% of the volume of air.

But although they constitute only a tiny proportion of ambient air, these pollutants are highly significant. The air pollutants released in Germany each year weigh more than five million tonnes. They include carbon monoxide, nitrogen oxides, ammonia, sulphur dioxide, non-methane volatile organic compounds (NMVOCs) and particulate matter (dust; PM). Nitrogen dioxide and particulate matter, which are the focus of this statement, play a major role in the overall mixture of pollutants. The emission statistics are based on data collected by the German Federal Environment Agency (UBA) in cooperation with authorities, associations and companies (Table 1.1).

Table 1.1: Pollutant emissions in Germany in 2016 (Source: Federal Environment Agency, 2018).

Pollutant	CO	NO_x	NH_3	SO_2	PM_{10}	$PM_{2,5}$	Soot
in 1000 tonnes	2.858	1.217	663	356	203	101	14

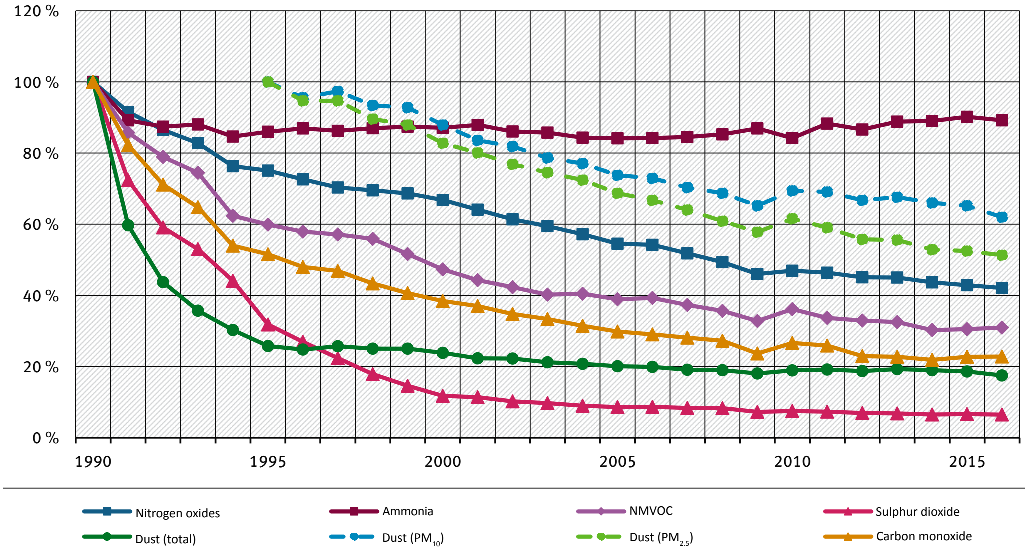

Figure 1.1: Trends in selected air pollutant emissions in Germany (trends since the reference years 1990/1995 in percent; Source: Federal Environment Agency, 2018).

Combustion processes in the energy industry and in vehicle engines contribute significantly to air pollution. Road traffic and coal-fired power plants are major sources of nitrogen oxide and particulate matter emissions, and gas-based power plants also emit nitrogen oxides. Sulphur dioxide emissions are principally caused by coal combustion. Ammonia is primarily released in agriculture and NMVOCs in industry. Nat-

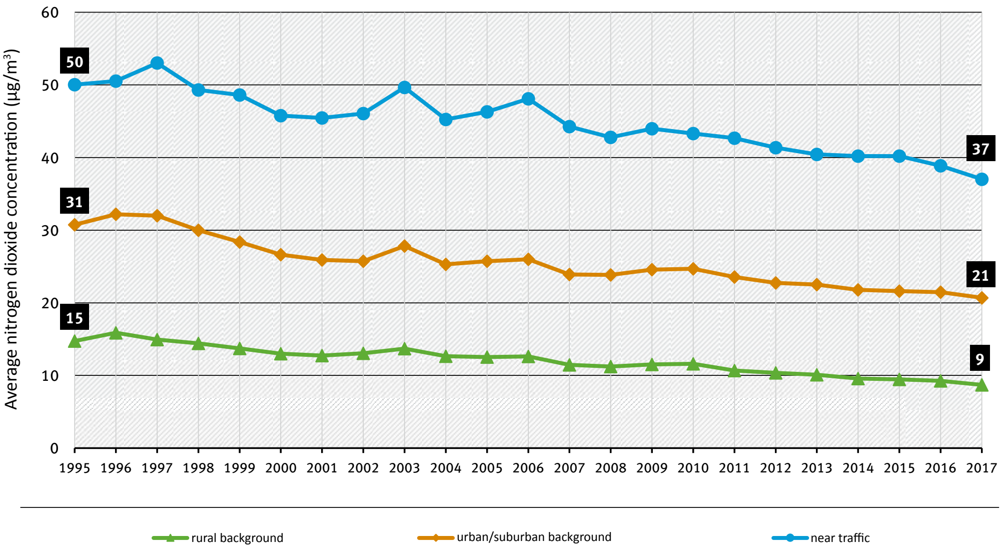

Figure 1.2: Annual mean nitrogen dioxide levels in different environments. Each value was averaged across multiple measuring stations. For localised exceedances at individual stations, see Figure 2.2 (Source: Federal Environment Agency, 2019).

ural sources such as vegetation, soils and waters also emit trace gases and particulate matter.

With the exception of ammonia, overall air pollutant emissions in Germany have been decreasing for years (Figure 1.1). However, particulate matter ($PM_{2.5}$) as well as nitrogen dioxide (NO_2) and ozone (O_3) continue to affect human health. Ozone is not emitted as a pollutant but can form in the atmosphere from volatile organic compounds and nitrogen oxides, and is therefore considered a secondary pollutant.

The collective term **nitrogen oxides** (NO_x) refers to the two gases nitrogen monoxide (NO) and nitrogen dioxide (NO_2). **Nitrogen monoxide** is a colourless, reactive gas. It is primarily formed in combustion processes and is a valuable intermediate product in the chemical industry. It is also present in small amounts as a messenger substance in the human body, where it determines the diameter of blood vessels among other functions. **Nitrogen dioxide** (NO_2) is a red-brown, pungent-smelling gas formed when NO reacts with oxygen (O_2) or ozone (O_3).

Nitrogen oxides actively interact with other pollutants. Chemical conversions in the atmosphere and reactions with ammonia can produce ammonium nitrate, for example. As a secondary organic aerosol, this is a major contributor to particulate matter pollution. Furthermore, nitrogen oxides and volatile organic compounds support the formation of **ozone** and smog close to the ground.

Box 1.1: Nitrogen oxides in exhaust fumes

The gases nitrogen monoxide (NO) and nitrogen dioxide (NO_2) are formed in combustion processes such as gas and coal combustion in the energy industry and fuel combustion in vehicles. In chemical reactions at very high temperatures, the nitrogen in the air (N_2) reacts with oxygen atoms to form nitrogen monoxide (NO). In the exhaust of a gasoline engine, a classic three-way catalytic converter or a storage catalyst can directly convert NO into N_2 and CO_2 through a reaction with the simultaneously present carbon monoxide (CO) as well as unburned hydrocarbons. A diesel engine operates under different combustion conditions (pressure, temperature, inhomogeneous fuel mixture, excess O_2). On account of these differences, particularly the high concentration of O_2 in the exhaust gas, NO_x emissions are generally reduced by a technique using an aqueous urea solution.

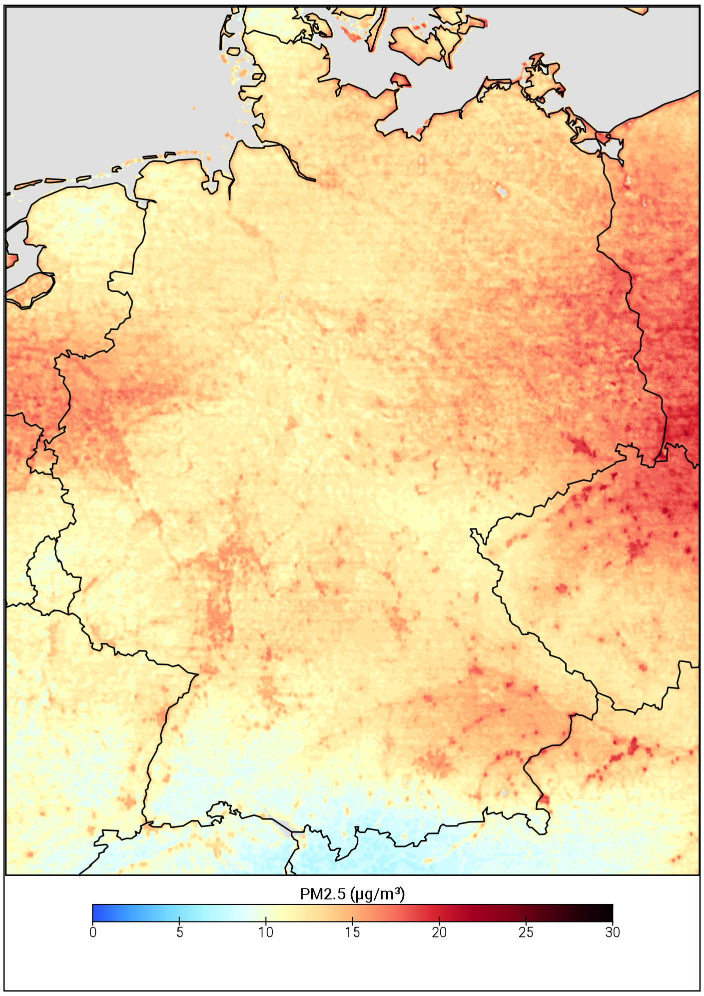

Figure 1.3:
Regional $PM_{2.5}$ particulate matter accumulation in 2016 determined by ground-based and satellite measurements (Source: Van Donkelaar et al., 2016). In the EU, the limit value for the mean annual load is 25 µg/m³.

As shown in Figures 1.1 and 1.2, nitrogen dioxide emissions from combustion processes in Germany have decreased considerably since 1990. This has been made possible by new industrial technologies for combustion management, such as lowering temperatures through exhaust gas recirculation as well as lean-burn and staged combustion. Exhaust gas treatment using catalytic converters to chemically break down nitrogen oxides in vehicles and large combustion plants has also played a major role in the downward trend, though the decline has slowed recently.

Particulate matter is composed of a complex mixture of organic and inorganic substances including acids, salts, soot and non-volatile organic compounds which are suspended in the air as aerosols. With diameters of just a few millionths of a metre (micrometres, µm), these particles are not visible to the naked eye. Particulate matter in the size class $PM_{2.5}$ comprises particles with aerodynamic diameters of up to around 2.5 µm (see Chapter 2). The size class PM_{10} also includes larger particles with diameters of up to around 10 µm. To compare, a human hair has a diameter of about 100 µm. Ultrafine particles measure up to around 0.1 µm in diameter. They are included in the size classes PM_{10} and $PM_{2.5}$ but are not yet recorded separately in routine measurements.

Ground-based measuring stations (see Chapter 2), aircraft measurements, satellite observations and chemical transport models are used to analyse and characterise particulate matter accumulation and the associated atmospheric processes. Figure 1.3 shows the regional distribution of $PM_{2.5}$ pollution in Germany calculated from ground-based and satellite measurement data (annual mean from 2016).

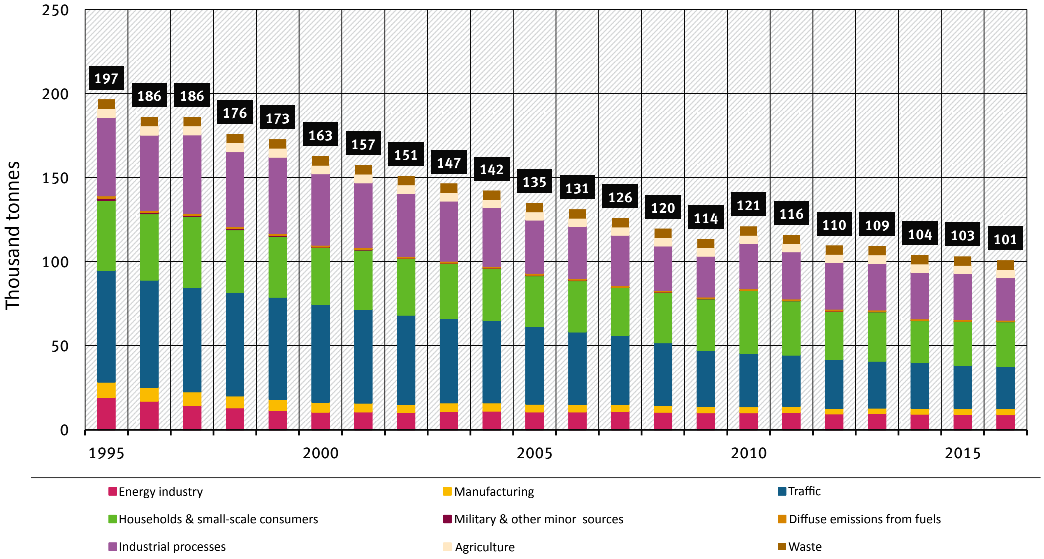

Figure 1.4: Variation in direct emissions (primary emissions) of particulate matter ($PM_{2.5}$) according to source. Please note that secondary organic aerosol formation in the atmosphere, which is responsible for a larger proportion of $PM_{2.5}$ pollution, is not recorded here (Source: Federal Environment Agency, 2018).

Direct particulate matter emissions, also known as primary particulate matter emissions, is mostly released by combustion processes in power stations, waste incinerators, engines and private and industrial furnaces (Figure 1.4). The majority of this particulate matter emission can be removed from the emissions using particle filters. Brake and tyre wear in motor vehicles occurs with all types of engine and increases direct particle emissions. Primary particulate matter is also released in agriculture. Furthermore, secondary organic aerosols, which are responsible for well over half of $PM_{2.5}$ pollution in Germany, are formed by ammonia emissions from fertiliser and liquid manure application as well as by chemical reactions involving NMVOCs in the atmosphere. In addition, eroding soils and deserts, volcanoes and other natural sources release particulate matter into the air, which also contains parts of plants, viruses, bacteria and fungal spores.

The decrease in direct $PM_{2.5}$ emissions shown in Figure 1.4 can primarily be attributed to industrial processes and transport; contributions from other sources remain approximately constant. It should be noted here that the direct $PM_{2.5}$ emissions shown in Figure 1.4 are significantly lower overall than secondary organic aerosol formation in the atmosphere, which is responsible for a larger proportion of $PM_{2.5}$ pollution (more than 50%). In this process, other air pollutants such as nitrogen oxides, sulphur dioxide and ammonia are converted into particulate matter. In total, over 2 million tonnes of these substances are emitted per year (Table 1.1), particularly from traffic (approximately 40% of NO_x) and agriculture (over 90% of NH_3).

The concentration, composition, and particle size distribution of particulate matter is influenced by local and regional pollutant sources as well as the geographical location, the weather and other factors. The mixture of particles can therefore vary significantly. On the whole, the characteristics and sources of particulate matter in Germany are similar to those in many other countries in Central Europe.

Overall, it can be concluded that pollution from traffic-related emissions of nitrogen oxides has decreased considerably in Germany in the past decades. As demonstrated in Chapter 6, emissions can be further reduced by, for example, using the latest vehicle models, updating the software in older diesel models and retrofitting older municipal buses with exhaust gas treatment systems. Downward trends can also be observed in the particulate matter size classes $PM_{2.5}$ and PM_{10}. There is a need for further action and research, in particular with regard to a further reduction in particulate matter load and the interactions between different pollutants.

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2. Measurements und measuring techniques

Shipping container-sized measuring stations for monitoring air quality (Figure 2.1) are found in both rural regions and metropolitan areas and along urban roads with particularly high traffic. There are more than 650 such stations across Germany. The majority of these stations are managed by the respective federal state, which gains an overview of local and regional air pollution from the measurement results. The **German air monitoring network** is supplemented by seven facilities run by the Federal Environment Agency (UBA) which are distributed across the country and also measure air pollutants transported over long distances and across borders. The results from all measuring stations are collected by the station operators, evaluated there and then collated nationally by the Federal Environment Agency. The data is processed and published by the operators (usually state environmental authorities) as well as the Federal Environment Agency.

Figure 2.1: Measuring equipment to monitor air quality – here, at the main road Am Neckartor in Stuttgart (Photo: A. Dittler).

Air quality measurements tend to attract public attention when limit values are exceeded. In Germany, at present only 4 of 18 **limit and target values for air pollutants** continue to be sometimes exceeded. These are:

- particulate matter – the number of days on which the daily mean value for particulate matter in the category PM_{10} may be exceeded,
- nitrogen dioxide (NO_2) – the annual mean value, most notably at traffic-oriented measuring points,

Figure 2.2: Map of Germany displaying all 47 air quality measuring stations which recorded NO$_2$ levels in excess of the limit value in 2018 (Source: Federal Environment Agency, unpublished).

- ozone – the permitted number of days with an eight-hour mean above 120 micrograms per cubic metre of air (µg/m³) has often been exceeded,
- ozone – the target value for the protection of vegetation.

In the case of **particulate matter**, the daily mean value of 50 µg/m³ for the category PM$_{10}$ can legally be exceeded on 35 days per year. In 2018, this limit value was exceeded more frequently – i.e. on 36 days – at only one site in Germany, an industry-oriented measuring station in North Rhine-Westphalia.

For **nitrogen dioxide**, the annual mean value recorded in 2018 exceeded the permissible limit value of 40 µg/m³ at 47 predominantly traffic-oriented measuring points (Figure 2.2).

Box 2.1: Where air samples are collected

In addition to the actual measurement processes, environmental chemical measurements include sampling and the separation and identification of substances for analysis. The quality assurance of measurement methods is governed by prescribed, tried and tested methods. The placement and number of sampling stations is critical for the quality of the results, as the substances to be analysed are not evenly distributed in the air.

Traffic-dependent air pollutants are generated along roads, which can be seen as time-varying line sources with local variations such as at crossings or where traffic jams form. If the traffic is moving, the pollutants are enveloped in turbulence around the road.

Pollutants disperse depending on the surrounding buildings, vegetation, terrain and other local features, as well as on the wind and weather. They do not build up in the atmosphere permanently but instead are repeatedly created and broken down through a variety of chemical and physical processes. These processes vary over time; they generally take place over large areas and only to a lesser extent along roads.

To ensure an accurate evaluation of the measurement results for health and environmental protection, it is therefore important to collect samples close to the sources, in residential areas and in locations with no sources of emissions such as parks – that is, where people actually spend time. In Germany, the placement of state sampling stations complies with these requirements.

Air quality measurements are used for preventive healthcare and can have far-reaching consequences. It is therefore important to ensure reliable **measuring methods**, transparent and comparable measurement conditions and sound quality assurance. Germany’s progress in this area is clear from the examples of nitrogen dioxide and particulate matter.

The basic rules for measuring these and other pollutants are laid out in the EU Directive 2008/50/EC on Ambient Air Quality and Cleaner Air for Europe, which was adopted in 2008 and amended slightly in 2015 by the Directive EU 2015/1480. The 39th Ordinance implementing the German Federal Immission Control Act (39th BImSchV) incorporated the Directive into German law in 2010. Further regulations can be found in the German Technical Instructions on Air Quality Control (TA Luft) and in German and European norms.

Nitrogen dioxide and particulate matter are usually monitored at the same measuring stations. Both substances are subject to the same rules on sampling, which stipulate how and where air samples are collected (see Box 2.1). In both cases, the federal states and the Federal Environment Agency are responsible for **quality assurance**. The federal states are also required to perform quality control on-site; they additionally have to ensure that the suitability of the monitoring equipment is checked. The UBA coordinates such quality assurance measures and serves as the national reference laboratory together with a state office in North Rhine-Westphalia.

The concentration of **nitrogen dioxide** is usually determined using the tried and tested chemiluminescence method. It is specified as a reference method in the EU Directive; the European Norm DIN EN 14211:2012 “Ambient air – Standard method for the measurement of the concentration of nitrogen dioxide and nitrogen monoxide by chemiluminescence” contains specific rules for its application. This method works on the basis that certain chemical reactions, for example between ozone and nitrogen monoxide, emit light in the red and infrared range.

The European Norm additionally contains detailed instructions for calibrating measurement devices with calibration gases and specifies maintenance intervals between

Box 2.2: Size comparison of particulate matter

The measurement of the particulate matter groups PM_{10} and $PM_{2.5}$ is based on the definitions laid down in 39th BImSchV and the DIN EN 12341 norm. In these publications, $PM_{2.5}$ and PM_{10} are defined as follows:

To measure PM_{10} concentration (in µg/m^3), the aerosol is passed through a size-selective inlet where particles with an aerodynamic diameter of 10 µm pass with 50% efficiency. The subsequent filter in the set-up retains a larger fraction of smaller particles and a smaller fraction of larger particles (see Figure 2.3).

Similarly, when measuring $PM_{2.5}$ concentration (in µg/m^3), 50% of the particles with an aerodynamic diameter of 2.5 µm are included in the measurement. Again, the filter retains a larger proportion of smaller particles and a smaller proportion of larger particles, which tends towards zero as particle size increases.

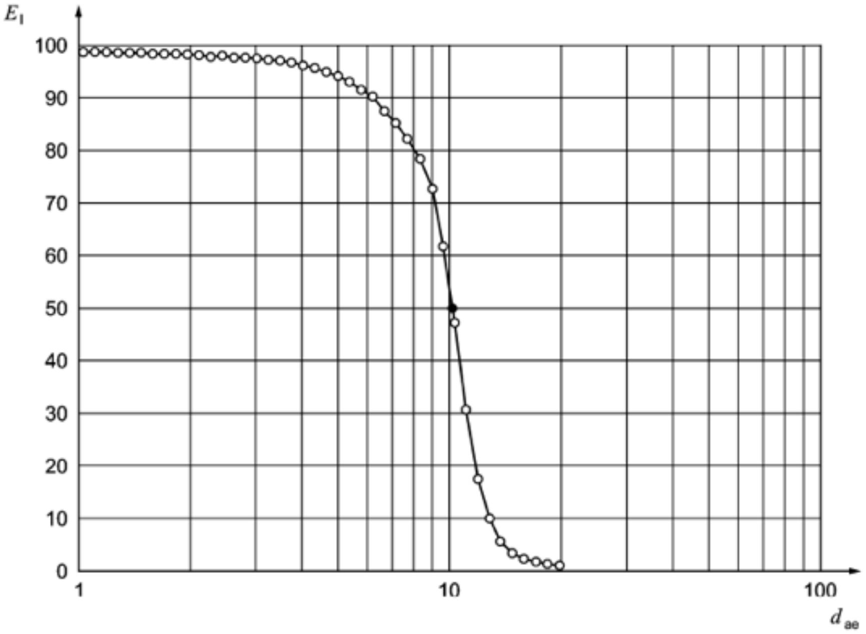

Figure 2.3: Determining PM_{10} concentration with a measuring device. The efficiency level E (the percentage of particles recorded) is displayed in relation to the aerodynamic diameter d of the particles (in µm). (Source: DIN EN 12341)

three months and three years. Measurement errors can occur if nitrogen dioxide reacts with substances deposited on the particle filter of the measuring equipment, for example. The impact of such errors is minimised through a series of quality assurance measures. According to the EU Directive, errors in the actual measurement method may result in a maximum permitted uncertainty of 15%.

The EU Directive stipulates that gravimetric analysis is to be used to measure **particulate matter** in the categories PM_{10} and $PM_{2.5}$ (see Box 2.2; see also Chapter 1). In this procedure, particles are deposited on a filter membrane according to their size (size-selectively) and then weighed at regular intervals under precisely defined laboratory conditions. Up to 25% uncertainty is permitted for this analysis, which is considerably higher than the maximum uncertainty for nitrogen oxides.

Levels of **ultrafine particles** (UFP or $PM_{0.1}$) can be measured using complex methods which are not yet suitable for routine application. These particles are smaller than 0.1 µm and make up less than 5% of the total mass of particulate matter. However, due to the small size and high quantity of ultrafine particles, they can comprise over 90% of the particles in particulate matter. There is currently no guideline value or limit value for ultrafine particles. Assessing ultrafine particles is difficult – the Ger-

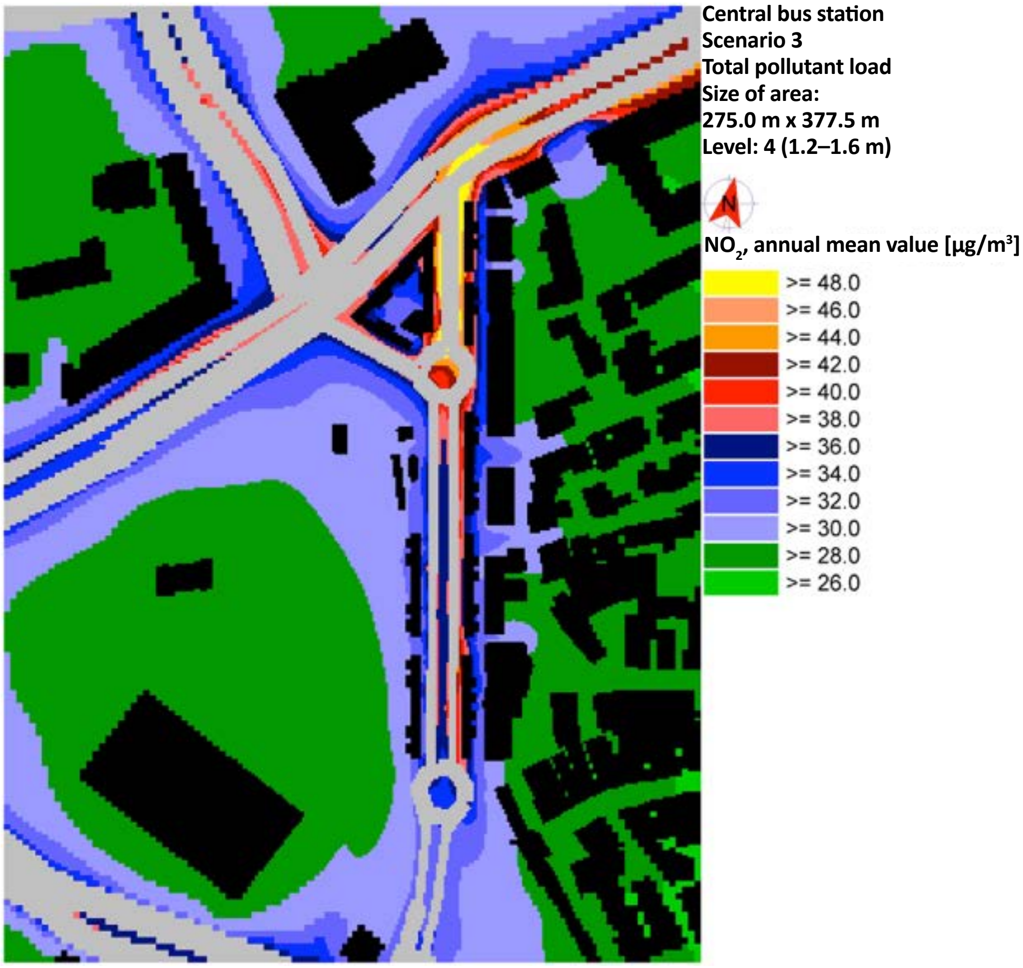

Figure 2.4: Nitrogen dioxide concentrations in a traffic-oriented area in Reutlingen (in 2017; area size 275 m x 377.5 m). This model, produced on the basis of measurement-supported calculations, shows nitrogen dioxide dispersion over a small area. The highest values (over the limit value for the annual mean load of 40 µg/m^3; yellow/red) are found directly at the roadside (Source: Aviso 2017).

man Ultrafine Aerosol Network (GUAN), coordinated by the Federal Environment Agency, is doing pioneering work in this field. Appropriate methods for measurement and quality assurance are still under development.

The **siting of measuring stations** has a considerable influence on the measurement of particulate matter and nitrogen dioxide. The regulations on siting conditions can be found in the Annexes to the Federal Immission Control Act (39th BImSchV). The regulations are not always clear-cut, but allow for a certain flexibility and individual discretion to take location-specific circumstances into account. For example, there must be

Table 2.1: Comparison of selected parameters for the positioning of traffic-related measuring stations in the USA and Germany.

	Distance between station and street		Height of inlet		Source
	Recommendation	max.	min.	max.	
Germany	-	10 m	1,5 m	4 m	39th BImSchV
USA	within 20 m	50 m	2 m	7 m	EPA Technical Document

no obstructions around the air inlet of the monitoring equipment. The inlet sampling probe, i.e. the air intake device, should be positioned “several meters” away from any buildings, trees etc. and at a height of “1.5 to 4 metres” above the ground – and even higher if the measurement needs to cover a large area.

Considering road traffic, it is obvious that pollutant concentrations differ according to the distance from the vehicle exhaust gases and the air circulation in the specific location. Figure 2.4 shows that measurement values taken along a main road can vary over short distances, such that the choice of sampling location can determine whether the measurement results fall below or above the limit value. These are inherent, unavoidable uncertainties which can at best be optimised, as was recently proposed in an Expert Opinion from the European Commission.

Outside the EU, conditions for positioning measuring stations cannot be easily compared. Some countries align their regulations with the EU rules while others allow significantly greater distances between the measuring equipment and the road, for instance. While a maximum distance of 10 metres is permitted in the EU, the USA allows up to 50 metres and recommends a distance of 10 to 20 metres from the road for traffic-oriented stations. And in the USA the maximum permitted measurement height is 7 metres, whereas in Germany it is just 4 metres. This shows how much care must be taken when comparing measurement results. The different measurement conditions have less of an effect on the results for particulate matter than on those for nitrogen dioxide.

If measurement values are to be compared on an international level, there is a need to **harmonise** measurement regulations and positioning conditions for measuring stations.

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3. Health effects

Introduction: How do we gain scientific knowledge about the effects of air pollutants?
Our understanding of the impact of air pollutants is based on

(1) experiments with clearly defined pollutant concentrations on cells, cell cultures and animals,
(2) controlled trials with humans (known as chamber studies) and
(3) epidemiological observational studies of the population with measurements or estimations of the actual pollutant load.

Medical literature currently provides over 71,000 studies on this subject, making air pollutants the most thoroughly researched aspect of environmental pollution.

Experimental studies on cells and animals primarily help us to understand the mechanisms of the effects of pollutants. Such experimental studies enable a systematic comparison of individual pollutants and clean air to ensure that the effects of nitrogen dioxide, for example, are not confounded by the effects of other pollutants. On the basis of such studies, it is therefore possible to establish a causal relationship between exposure and effect. For example, experiments on animals have shown that exposure to high concentrations of nitrogen dioxide over several weeks can cause a sustained inflammatory response, allergic reactions and respiratory hypersensitivity. The doses of pollutants used in animal experiments are generally much higher than the concentrations found in the environment. In addition, results from cell and animal testing may not be fully transferable to humans.

Controlled exposure studies are therefore also carried out on humans (healthy volunteers or patients). These studies are well suited to study acute, temporary effects of individual pollutants in comparison to clean air. On the basis of such chamber studies, volunteers with mild, well-managed asthma have been shown to experience bronchial hyperresponsiveness after a brief exposure to relatively high concentrations of nitrogen dioxide. Chamber studies always involve small, carefully selected groups of volunteers who are exposed to an artificially generated pollutant load. There are major constraints on the transfer of such results to the wider population and to highly sensitive people. Furthermore, for ethical and practical reasons, chamber studies can only be used to investigate short-term and temporary effects.

This highlights the need for epidemiological observational studies of the general population under real environmental conditions. Observational studies can investigate long-standing pollution situations – for example, long-term exposure in homes in year-long cohort studies – or short-term effects of daily fluctuations in air pollution levels. For example, the relationship between daily air pollutant concentration and daily mortality can be explored in a time series study or with medical examinations of repeatedly investigated patients. A major advantage of epidemiological observational studies is the possibility to study the effects on particularly sensitive sectors of the population, i.e. foetuses, babies, children, the elderly and people with medical conditions. A further benefit is that these investigations are carried out in real-life conditions.

When researching the health effects of air pollutants in epidemiological observational studies, it must be taken into account that these pollutants to some extent come from the same sources. As a result, the exposure patterns for different air pollutants can look similar. For example, study participants' exposure to nitrogen dioxide often correlates with their exposure to ultrafine particles and soot. This can make it difficult to disentangle the specific effects of nitrogen dioxide from the effects of other pollutants. When interpreting the health effects of such studies, it is important to bear in mind that the results do not necessarily indicate exclusively the effect of nitrogen dioxide. Instead, other pollutants contribute to such effects to the extent that they correlate with nitrogen dioxide.

In epidemiological studies, it is important to monitor other factors associated with the pollutant load and the illness being analysed. These include the social status and lifestyle of the study participants, such as diet, smoking and physical activity. Failure to account for these may result in confounding. In well-designed studies, this is documented in detail and information on personal characteristics is often collected several times during the observation phase.

Depending on the conditions, research question and variability of the measurements, individual studies may produce different results. As a result, conclusions can only be drawn from an overall evaluation of numerous studies. Such comprehensive analyses are carried out by scientific institutions and by bodies such as the World Health Organisation (WHO), environmental authorities of individual countries (such as the US Environmental Protection Agency, US EPA) and the Permanent Senate Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area (MAK Commission) of the German Research Foundation (DFG). To determine causality, toxicological studies, chamber studies and epidemiological studies are always viewed in conjunction with one another.

3.1 Toxicological evaluation

Nitrogen dioxide

The irritant gas nitrogen dioxide (NO_2) enters the upper and lower respiratory tracts via the nose. When it comes into contact with mucous membranes, it converts into a mixture of nitrogen monoxide, nitrous acid and nitric acid which irritates the bronchi and can trigger an asthma attack. In the lower respiratory tract, it can cause tissue damage and inflammation.

In animal experiments, high concentrations of nitrogen dioxide are required to cause these effects. Biochemical changes were detected above approximately 1,500 micrograms per cubic metre of air ($\mu g/m^3$) and tissue damage at several thousand $\mu g/m^3$. These values are more than 30 times and more than 200 times higher, respectively, than the limit value for the annual means in outdoor and indoor air (see Chapter 4). The changes observed may be stimuli as well as consequences of inflammation. Chronic inflammation of the respiratory tract can have local consequences (asthma, emphysema) and systemic ones (cardiovascular diseases).

From the few laboratory experiments carried out to date with healthy study participants, it has not been possible to determine with sufficient accuracy the nitrogen dioxide concentration above which acute symptoms occur in humans. In an experiment on acute exposure, volunteers inhaled nitrogen dioxide at a concentration of 2850 µg/m³ for a short time. At this high dose, the volunteers exhibited no or only minor symptoms.

In contrast, asthma patients often experience a narrowing of the airways and increased sensitivity to allergens at much lower nitrogen dioxide concentrations. In certain studies, some asthma patients suffered increased sensitivity of the airways within an hour at a nitrogen dioxide concentration of 190 µg/m³. In other investigations, such effects were only observed at concentrations which were two or three times higher. The concentration of 190 µg/m³ is below the one-hour limit value for nitrogen dioxide of 200 µg/m³. Values of 200 µg/m³ are periodically reached or exceeded on many roads with a particularly high traffic volume.

Shortness of breath, chronic bronchitis and damage to the alveoli were observed more frequently in people who inhale nitrogen dioxide over a **longer period**.

In animal experiments, long-term exposure to nitrogen dioxide at a high concentration of over 4,000 µg/m³ caused emphysema, changes in the immune system and an increased susceptibility to infection, though the effects subsided after some months. In other animal experiments, inflammatory responses in the lungs, immunological changes and an increased susceptibility to allergic reactions and infections were observed after exposure to nitrogen dioxide for several weeks to months.

Particulate matter

Particulates are made up of different chemical components and differ in terms of size, shape, chemical composition and solubility in water. Their harmfulness is not so much due to their chemical composition than to their nature as foreign particles which can cause long-term irritation in an organism. Granular biopersistent particles – which cannot be broken down by the body – are particularly harmful. In occupational medicine, they are considered carcinogenic for humans if the maximum permissible workplace concentration is exceeded.

The smaller the particles, the deeper they can penetrate into the body. This is why PM_{10} particles end up in the bronchi while $PM_{2.5}$ particles can be inhaled all the way into the alveoli. Larger airways are equipped with certain cleaning mechanisms which to some extent can get rid of these particles. Small particles are sometimes exhaled again, but they can also remain in the lower respiratory passages for a long time. Ultrafine particles with diameters of 0.1 millionths of a metre (µm) and less can pass from the lungs into the blood vessels. Once transported in the bloodstream, they can cause damage in other organ systems and in the blood itself.

The mechanisms of action of particulate matter have been researched in many studies on cells, animals and people. While the overall picture is not yet clear, important disease mechanisms have already been identified.

Particles cause **inflammation** in the bronchi and lungs. One aspect of this is known as oxidative stress. This refers to the formation of reactive oxygen species which then cause and aggravate inflammation. For particularly sensitive people or those with pre-existing respiratory illnesses, acute pollution exposure can cause narrowing of the bronchi severe enough to trigger coughing and shortness of breath, or even an asthma attack. In the long term, the lungs can become predisposed to allergic reactions and adults may develop asthma or chronic pulmonary diseases. Children experience slower lung growth. Particulate matter itself and accumulations of other air pollutants increase the risk of lung cancer.

Inflammation in the bronchi and alveoli leads to the release of messenger substances which can trigger an inflammatory response in the entire body via the bloodstream. As a result, blood vessel elasticity decreases, the tendency for blood clotting increases, and the body's cells become more resistant to the hormone insulin. Possible consequences include **heart attacks** and **strokes**, which can occur within hours of increased exposure, as well as type 2 **diabetes** and accelerated atherosclerosis in the long term. Inflammatory processes have also been observed in the **brain** and have been linked to more rapid development of dementia in the elderly and delayed intellectual development in children. In addition to causing inflammatory responses, particulate matter can also **damage the cardiovascular system** in other ways. This begins with an activation of the autonomic nervous system, which increases the heart rate and blood pressure. This can cause heart attacks and arrhythmias.

3.2 Epidemiological evaluation

Nitrogen dioxide

What has been conclusively proven on the effects of nitrogen dioxide?

Epidemiological studies show that even short-term exposure (lasting from hours to days) to high concentrations of nitrogen dioxide in the ambient air can provoke **acute respiratory problems** in susceptible people. These include asthma attacks and increased hospital admissions due to asthma, a decline in lung function and an inflammatory response in the lungs. People react differently to short-term exposure to nitrogen dioxide. Healthy people with a functioning immune system tend not to suffer any ill effects from higher concentrations of nitrogen dioxide. However, the same concentrations can trigger an acute asthma attack or frequent bouts of bronchitis in people who are more sensitive, such as children or adults with asthma.

Long-term exposure to nitrogen dioxide is considered a probable **cause of asthma.** This correlation is biologically plausible, as both repeated short-term exposure and long-term exposure cause the development of allergic responses in experimental studies on animals, and it is possible to rule out distortions or effects caused by other pollutants in these studies. The observational studies which indicated a probable causal effect were carried out with nitrogen dioxide concentrations of between 15 and 100 µg/m^3 in the outdoor air. People react differently to long-term exposure and many people do not experience any effects whatsoever. However, it has been proven that some people are more seriously affected, for example if they have certain genetic characteristics. Babies, infants and school-age children also tend to be particularly sensitive as the tissues in their lungs are not fully developed and can therefore be damaged more easily.

Which health effects of nitrogen dioxide are hypothesised but not yet conclusively proven?

There is evidence for a causal relationship between **short-term** nitrogen dioxide exposure and **all-cause mortality** as well as **mortality from pulmonary diseases**.

This correlation is largely unaffected by the concentration of particulate matter present. Furthermore, there are consistent links to **hospital admissions for cardiovascular diseases**, primarily coronary heart disease and heart attacks. It is not clear whether these correlations are indeed causal as there are very few toxicological studies to date which directly investigate the biological mechanisms that may lead to increased mortality or influence the cardiovascular system.

Further health risks that may be associated with **chronic exposure** to nitrogen dioxide include increased **mortality from cardiovascular diseases**, the development of **chronic obstructive pulmonary disease**, the occurrence of **strokes, heart failure** and **hypertension**, and the development of **diabetes mellitu**s. For these risks, too, there is evidence but no conclusive proof of a causal relationship as there are still too few studies on the toxicology of nitrogen dioxide which might explain the biological mechanisms.

Particulate matter

What has been conclusively proven on the effects of particulate matter?

There is a global consensus that particulate matter poses a higher risk to health than nitrogen dioxide. As there are many more epidemiological studies and comprehensive toxicological studies on particulate matter, the health effects have been better characterised and the causality evaluated more clearly than for nitrogen dioxide. Despite the large quantity of data available, it has not yet been possible to identify a lower threshold for such effects. This means that even below the current EU limit values and the considerably lower guideline value of the World Health Organisation, the effects increase with greater exposure.

For **short-term exposure**, the daily **mortality rate** increases by 0.4 to 1.0% for each 10 µg/m³ increase in daily PM_{10} exposure. Furthermore, increasing numbers of people are admitted to hospital due to **asthma attacks**, **heart attacks**, **heart failure and strokes**. After days with high particulate matter concentrations, raised inflammatory markers and an increased tendency to coagulate can be measured in the blood.

Epidemiological studies on **long-term exposure** to particulate matter (over years to decades) indicate significant consequences for human health. Long-term exposure to the particulate matter concentrations now common in Europe causes an increase by approximately 7% in **mortality** (with a variation [confidence interval] of 2% to 13%) per 5 µg/m³ increase in long-term exposure to $PM_{2.5}$. The probability of suffering a **heart attack** increases by around 12% (confidence interval of 1% to 25%). Children display **reduced lung growth**, and improvements in air quality then lead to an increase in lung growth. Particulate matter increases the risk of developing lung cancer. It is now considered to be epidemiologically proven that particulate matter increases the risk of type 2 **diabetes**.

It is important to note that the health effects of particulate matter also occur below the current EU limit value. The effects occurring below the EU limit values and even below the WHO guideline value are currently being investigated in three large studies, each with several million participants, in Europe, the USA and Canada. The first results from the USA demonstrate a linear exposure-effect relationship between particulate matter and mortality at exposures as low as an annual mean of 5 µg/m³. This means that every reduction in exposure has a positive effect on health.

Which health effects of particulate matter are hypothesised but not yet conclusively proven?
Links have been observed between mothers' exposure to high levels of particulate matter during pregnancy and **lower birth weights** in babies. More recent studies suggest that traffic-related pollutants in particular impair **brain development** in children and accelerate the development of **dementia** in the elderly. However, there are not yet enough studies on such health effects to be able to talk of a causal relationship.

Table 3.1: Air pollutants and their health effects (based on published evaluations up to 2016).

Air pollutant	Effects on health	Evaluation	Source
Nitrogen dioxide	Short-term: Worsening of respiratory problems	causal	US EPA (2016) US EPA (2009)
	Long-term: Development of respiratory problems	probably causal	US EPA (2016) US EPA (2009)
Particulate matter ($PM_{2.5}$)	Mortality	causal	US EPA (2009))
	Cardiovascular diseases	causal	US EPA (2009)
	Lung cancers	causal	IARC 2016
	Respiratory problems	probably causal	US EPA (2016) US EPA (2009)

Excursus: Calculating the burden of disease

Burden of disease calculations aim to quantify the extent to which different risk factors affect health and the annual number of disease cases or deaths in the population. A comparison can then show which risk factors are responsible for a particularly high number of disease cases, deaths or years of life lost. This helps to set the right priorities for prevention. Typical risk factors compared in burden of disease calculations include smoking, unhealthy diets, alcohol consumption, lack of exercise, air pollution and noise.

The calculations follow a standard methodology which is also used by institutions such as the World Health Organisation. This typically involves calculating several measures of the total burden of disease in a population. One measure is premature deaths attributable to a certain risk factor, and others are years of life lost (YLL) and disability-adjusted life years (DALYs). These statistics indicate the percentage of mortality (total number of deaths per year) and the years of healthy life lost which can be attributed to a certain risk factor. They can enable a comparison of different risk factors or describe trends over several years.

The US Institute for Health Metrics and Evaluation (IHME) uses this standard methodology in its Global Burden of Disease (GBD) project to calculate disease burdens for the whole world and individual countries at regular intervals. For Germany, the most recent comprehensively analysed data – from 2010 – show a significant overall decrease in the disease burden compared with 1990 (Figure 3.1). Diet-related risk factors have the greatest impact and account for almost 14% of the total burden of disease, followed by high blood pressure, smoking and being overweight. Air pollution causes around 2% of the disease burden for women and 3% for men, meaning it is ranked 8th and 10th respectively of a total of 84 risk factors investigated. Its impact is comparable with that of high cholesterol for women and occupational risks for men (both just under 4%). Of the ten most significant risk factors, air pollution showed the greatest reduction during the observation period (-67%).

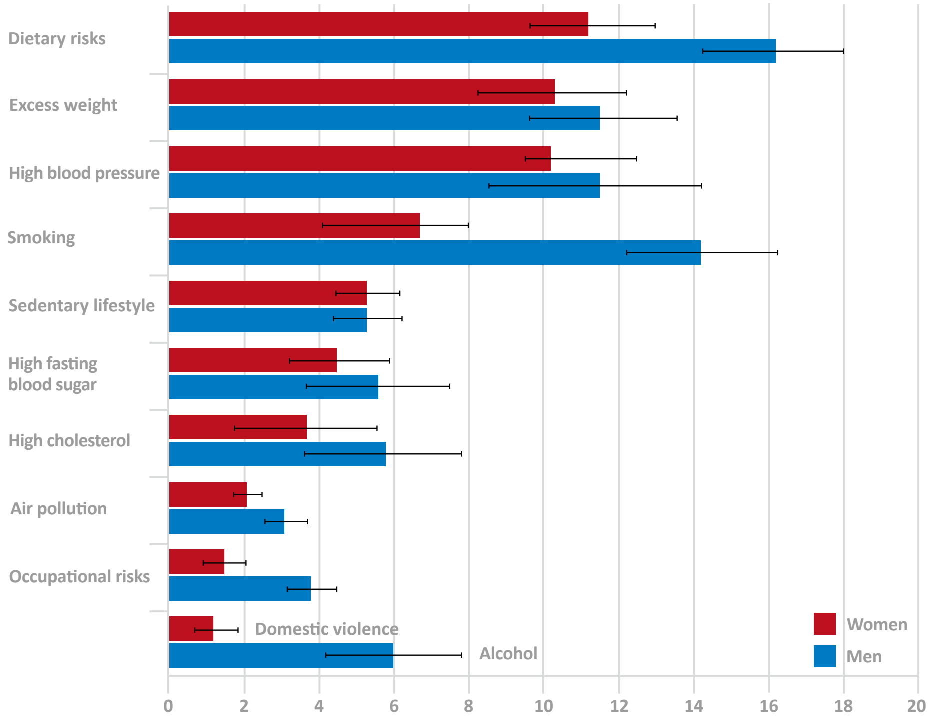

Figure 3.1: Burden of disease calculation for Germany. The most significant risk factors are shown with the disease burden attributable to them (given as % disability-adjusted life years, DALYs); the black lines indicate variation (95% confidence interval). (Source: Plass et al., 2014).

The European Environment Agency also calculates the burden of disease for the air pollutants particulate matter and nitrogen dioxide each year for Europe as a whole and for each member state. According to these calculations, particulate matter is responsible for the largest share of the disease burden in Germany (2015) (approximately 60,000 attributable deaths and 640,000 years of life lost). Around 13,000 deaths and 130,000 years of life lost are attributable to nitrogen dioxide, though these figures have an uncertainty of ±35–45% (95% confidence interval). Current studies by German research institutes are finding similar results for nitrogen dioxide and considerably higher effects for particulate matter based on the latest epidemiological data. A widely discussed study commissioned by the Federal Environment Agency shows that urban and rural background exposure to nitrogen dioxide alone is linked to approximately 6,000 (confidence interval 2,000 to 10,000) attributable deaths and approximately 50,000 (confidence interval 17,000 bis 82,000) years of life lost each year due to cardiovascular disease. There is evidence of a causal relationship between nitrogen dioxide exposure and cardiovascular disease. Overall, the study found a rise in the cardiovascular burden of disease due to nitrogen dioxide which is relatively low in comparison to other risk factors and is generally decreasing but is still measurable.

There are many uncertainties in burden of disease calculations. They estimate the impact of different risk factors on the burden of disease for the entire population. Certain individual deaths may not be taken into account. The attributable mortality is a conservative estimate of the deaths partly or entirely caused by a certain risk factor. It is susceptible to misinterpretation, particularly in view of the fact that it underestimates the actual number of deaths linked to a risk factor. For this reason, some scientists prefer to use years of life lost as a comparative measurement. Others call for a measure which includes the burden of non-fatal illnesses in addition to the attributable deaths.

The advantages and disadvantages of the different measurements are the subject of heated debate. The scientific consensus in epidemiology is that burden of disease calculations are a tried and tested method to compare different risk factors in terms of their effect on the population.

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4. Limit values

Clean air for everyone, every day, for life – there are legally binding limit values for air pollutants to help this objective to be met. These limit values are negotiated as part of a political process and take into account not only scientific knowledge but also technical feasibility and the effort involved in monitoring and maintaining them. Economic aspects, such as protecting jobs, are also important. This means that limit values are a compromise between what is medically desirable and socially possible.

In Germany, the **limit values** and **guideline values** set by the EU for air pollutants apply. There are limit values for "emissions", i.e. the release of pollutants, and limit values for "immissions", i.e. the impact of harmful substances on humans and the environment.

The **EU Directive** 2008/50/EC on Ambient Air Quality and Cleaner Air for Europe, which was adopted by the European Parliament in 2008, provides the legal framework for immissions. It specifies limit values for nitrogen dioxide, particulate matter in two size classes, sulphur dioxide, lead, benzene and carbon monoxide (see Table 4.1). The EU Directive was passed directly into German law in the form of the Federal Immission Control Act in 2010 and was updated in 2015. Since then, the federal, state and local authorities have been required to ensure that the limit values are observed across the board, with few exceptions, and must take effective countermeasures in the event of exceedances (see Chapter 6).

In contrast to limit values, **target values** are not obligatory but are used to provide long-term guidance. For example, there is a target value for ozone as an air pollutant.

The limit values applicable in Europe are subject to the **precautionary principle**. According to this principle, legislative authorities are even required to protect the population from substances which are only possibly harmful to health, i.e. even if their harmfulness cannot be unequivocally proven using scientific methods. Particularly vulnerable people, such as asthmatics, infants and older people, are explicitly mentioned in the EU's Ambient Air Quality Directive. Many countries, including the USA, are not guided by the precautionary principle but rather require clear evidence that a substance is harmful.

The limit and target values listed in Table 4.1 are immission values; they indicate the maximum permissible concentration of each substance in the air we breathe. Legislators also consider the duration of exposure by laying down hourly or daily mean values for short-term immissions and annual mean values for long-term immissions. The aim of this is to protect the entire population around the clock from adverse health effects caused by the regulated substance.

There are two limit values for nitrogen dioxide, for example: the one-hour limit of 200 millionths of a gram per cubic metre of air (µg/m^3) and the annual mean value of 40 µg/

Table 4.1: Pollutants and their immission limit values pursuant to the 39th German Federal Immission Control Ordinance (39th BImSchV).

Pollutant	Immission limit value/guideline value		Parameter	Protects …
Particulate matter – PM$_{10}$	50 µg/m^3	max. 35 exceedances p. a.	daily mean value	human health
	40 µg/m^3		annual mean value	
Particulate matter – PM$_{2.5}$	25 µg/m^3		annual mean value	
NO$_2$	200 µg/m^3	max. 18 exceedances p. a.	1h mean value	human health
	40 µg/m^3		annual mean value	
NO$_x$	30 µg/m^3		annual mean value	vegetation
SO$_2$	350 µg/m^3	max. 24 exceedances p. a.	1h mean value	human health
	125 µg/m^3	max. 3 exceedances p. a.	daily mean value	
	20 µg/m^3		annual mean value	vegetation
Lead	0,5 µg/m^3		annual mean value	human health
Benzene	5 µg/m^3		annual mean value	
CO	10 µg/m^3		8h mean value	
Ozone	120 µg/m^3	max. 25 exceedances p. a.	8h mean value	
	18000 µg/m^3 *h	May–July	Mean value over 5 years	vegetation
Arsenic	6 ng/m^3 (ng = nanogram/ billionth g)		annual mean value	human health & environment
Cadmium	5 ng/m^3			
Nickel	20 ng/m^3			
Benzo(a)pyren	1 ng/m^3			

m^3. The aim of the 200 µg/m^3 limit is to protect the airways from acute damage, while the aim of the 40 µg/m^3 limit is to avoid long-term damage to health. According to this philosophy, each individual value must be kept under 200 µg/m^3; in contrast, the mean annual level of exposure must not exceed 40 µg/m^3.

The European Court of Justice is currently discussing the limits which must be observed in areas where the highest concentrations occur, e.g. along busy roads (see Chapter 5). From a toxicological point of view, it is being argued that the one-hour limit of 200 µg/m^3 should apply in these areas since it cannot be assumed that people spend 24 hours a day in these areas the whole year round.

The precautionary limit values for ambient air are much stricter than the corresponding **occupational exposure limit values** (OELV). To cite just one example, the OELV for nitrogen dioxide stands at 950 µg/m^3. In contrast and as already mentioned, ambient air is subject to a one-hour limit of just 200 µg/m^3 and an annual mean limit of 40 µg/m^3.

In the public debate, this is often seen as a contradiction – which is not correct. This is because, unlike ambient air limit values, which apply to all population groups 24/7, occupational exposure limit values only apply to healthy adults over a 40-hour working week.

The OELV are set by the Committee for Hazardous Substances at the Federal Ministry of Labour and Social Affairs on the basis of **MAK values**. The German acronym MAK stands for maximum workplace concentration; the values are calculated by the German Research Foundation's Permanent Senate Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area.

The MAK value for nitrogen dioxide is largely based on **inhalation studies** conducted on animals and **observations** of human volunteers. During these experiments, substances are administered at different concentrations in order to determine the approximate threshold between harmless and harmful. In one experiment, test animals breathed air with a very high nitrogen dioxide concentration of 4,066 µg/m³, which is about 100 times the annual mean limit value for ambient air. Even after exposure to this high concentration for a period of up to 13 weeks, the animals showed no signs of health problems. The threshold value determined during the animal experiment was used along with the results of experiments on humans to calculate a maximum workplace concentration of nitrogen dioxide of 950 µg/m³ according to the Commission's rules. This value has been checked and confirmed several times since it was first calculated in 2010.

The EU bases its limit values for the general population on recommendations made by the World Health Organisation (WHO) in its air quality guidelines. Instead of specifying limit values, these set **guideline values**. The WHO last updated its air quality guidelines for protecting human health from harmful substances in 2005; a revised version is due to be published in 2020. The guideline values are based on laboratory studies on cells and animals, experiments on humans (chamber experiments) and findings from environmental epidemiological studies compiled and evaluated for the WHO by scientists from around the world. In 2013, a WHO expert group conducted a special evaluation on behalf of the European Commission, which showed that the substances in question had relevant health effects even below the EU limit values in force at that time.

The discrepancies between the EU's limit values and the WHO's guideline values are especially pronounced in relation to **particulate matter**. While the WHO recommends an annual mean value of 20 µg/m³ for the size class PM_{10}, the EU's limit value for this is twice as high at 40 µg/m³. Meanwhile, the WHO's guideline value for $PM_{2.5}$ is 10 µg/m³, which is less than half the EU's limit value of 25 µg/m³. In contrast, the EU's limit value for the mean annual exposure to nitrogen dioxide is exactly the same as the WHO's guideline value, at 40 µg/m³.

As shown by the limit values in Table 4.2, the WHO's recommendations are implemented very differently around the world. The **USA** follows virtually the opposite approach to the EU. At 12 µg/m³, the limit value for $PM_{2.5}$ particulate matter in the USA is similar to the WHO's guideline value. Conversely, at 100 µg/m³, the limit value for nitrogen dioxide is much higher than the WHO's guideline value. On the other hand, the emission limit values are stricter in the USA.

Switzerland has adopted the 2005 WHO recommendations for particulate matter and has even introduced a more stringent limit value of 30 µg/m³ for mean annual ni-

Table 4.2: Limit values for particulate matter ($PM_{2.5}$ and PM_{10}) and nitrogen dioxide (NO_2) in selected countries. (Source: Kutlar Joss et al. 2017).

	Limit values for nitrogen dioxide (NO_2) in µg/m^3			Limit values for particulate matter ($PM_{2.5}$) in µg/m^3		Limit values for particulate matter (PM_{10}) in µg/m^3	
Country	Hourly mean	Daily mean	Annual mean	Daily mean	Annual mean	Daily mean	Annual mean
EU/Germany	200	–	40	–	25	50	40
Argentina	–*	–*	–	–*	–*	–*	–*
Australia	230	–	60	25	8	50	–
Brazil	320	–	100	–	–	150	50
Canada	–	–	–	28	10	–	–
China	200	80	40	75	35	150	50
India	–	80	40	60	40	100	60
Indonesia	–	150	100	–	–	150	–
Japan	–	113	–	35	15	100	–
Mexiko	395	–	100	45	12	75	40
Russia	–*	–	40	35	25	60	40
Saudi Arabia	660	–	100	35	15	340	80
South Africa	200	–	40	65	25	120	50
South Korea	190	115	57	50	25	100	50
Turkey	300	–	–	–	–	100	60
USA	188	–	100	35	12	150	-

* Limit values with different measurement methods

trogen dioxide levels. However, despite the lower annual mean value for NO_2, the actual situation in Switzerland is similar to that in Germany, as the limit value is exceeded along main roads in both countries. For example, in 2016, the mean annual NO_2 level recorded at measuring points near roads in Zurich was around 50 µg/m^3. Austria also has a lower limit value (35 µg/m^3 including a margin of tolerance). To date, seven countries have adopted the WHO's particulate matter guideline values as their limit values. However, in practice, WHO guideline values are exceeded in many regions around the world. The maps in Figure 4.1 provide an overview of the global limit values for particulate matter (PM_{10}) and nitrogen dioxide (NO_2).

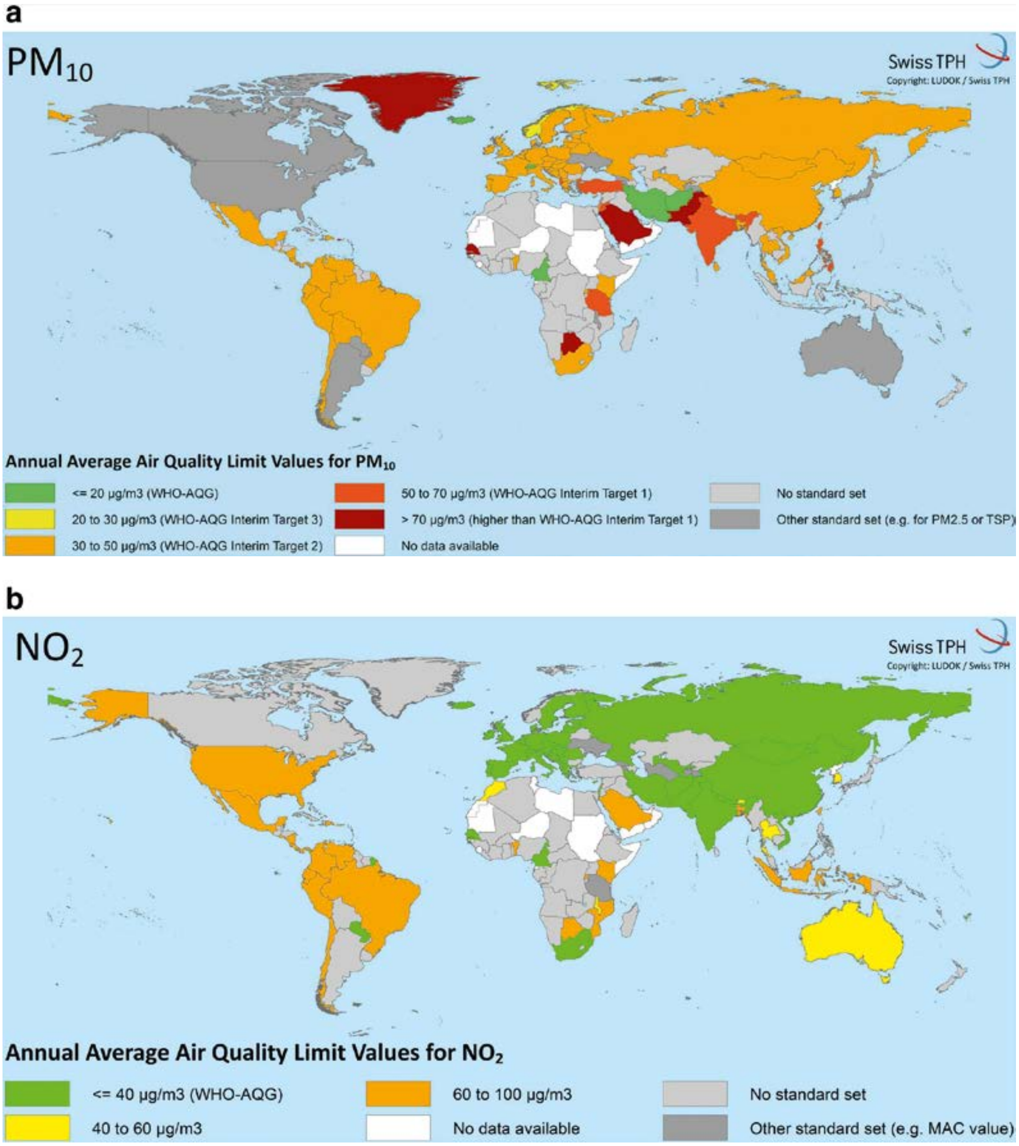

Figure 4.1: Limit values for particulate matter (PM_{10}) and nitrogen dioxide (NO_2) in selected countries (source: Kutlar Joss et al. 2017). Published under Creative Commons licence CC-BY 4.0 (http://creativecommons.org/licenses/by/4.0).

The different rules around the world show how individual countries have their own ways of protection against air pollutants and of evaluating the significance of the various pollutants. For example, the USA's focus on particulate matter as opposed to nitrogen dioxide is in line with the greater impact that particulate matter has on health (as discussed in Chapter 3). On the other hand, the stricter emission limit values in the USA help the country to achieve lower immission values. However, as alluded to in Chapter 2, it is important to note that different measurement conditions make it difficult to draw international comparisons like these.

Pollutants without a known lower threshold of effect, as especially seems to be the case with particulate matter, are particularly problematic. It must be assumed that these substances have an impact on health even below the limit values. The precautionary principle would even aim to reduce the limit values down to the region of background exposure.

However, the potential health effects are not the only factors that influence the setting of limit values. The cost required to comply with the limit value also factors in, as do other possible consequences of the limit value on society and the economy. The objective is to achieve a **balance** between the cost required to reach the limit value and the resulting benefits, i.e. the impact on health, the economy and society. In other words, it is it is about the proportionality of the measures associated with the setting of limit values.

In the case of nitrogen dioxide, for example, it must be questioned whether city centre driving bans are proportionate if they only result in minor improvements in air quality. **Scientific studies** can determine the direct and indirect costs of enforcing limit values and the impacts of reduced health risks, often in numerical terms.

The question of whether the end justifies the means is, however, a **political matter** which in democratic systems must be answered by the legitimised bodies. An informed and open public discussion which takes into account expert advice can contribute to a well-balanced and rationally justifiable decision-making process. The role of scientists is to support this process using the best available knowledge without determining the outcome in advance.

However, once the **limit values** have been set, they are binding. At this point, considerations of proportionality can only be taken into account to a limited extent. This is particularly true for the European limit values adopted by Germany.

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5. The legal framework

As is the case in the other EU countries, Germany's clean air policy is largely determined by **European law**. The EU's limit values for air pollutants must be observed by all member states; broad guidelines on measuring methods and positioning conditions for measuring stations are laid down, and there is a requirement for effective air quality plans to be created if limit values are exceeded. Generally speaking, EU law gives national legislative authorities little freedom to develop their own clean air policies. Their ability to shape policy is largely limited to short-term countermeasures in the event that limit values are exceeded. It is not uncommon for this to lead to certain inconsistencies in practice.

European clean air legislation is underpinned by the Maastricht Treaty (Treaty on European Union), the Charter of Fundamental Rights and the Treaty on the Functioning of the European Union (TFEU), which has been in force since 2009. Article 191 TFEU makes the EU responsible for contributing to the protection of the environment and human health. The precautionary principle and its high level of protection play a guiding role here. This principle aims to minimise risks and justifies regulations even below the risk threshold. In this spirit, EU legislators first passed an Ambient Air Quality Directive in 1996. This was replaced by Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on Ambient Air Quality and Cleaner Air for Europe, which was adopted in 2008 and is still in force today (1).

The **directive** has a clear **objective**. Emissions of air pollutants should be avoided, prevented or reduced and appropriate objectives set for ambient air quality, taking into account the WHO guideline values (2). The pollutants cited by the directive for which limit values and procedures are specified are sulphur dioxide, nitrogen dioxide, nitrogen oxides and particulate matter (3). The assessment regime, assessment criteria, sampling points and reference measurement methods are laid down in more detail in the annexes to the directive.

The central element of the directive is the regulation of **limit values** and alert thresholds (e.g. for nitrogen dioxide, particulate matter, lead and benzene) for protecting human health. According to the directive, the member states must ensure that the values measured for the pollutants covered do not exceed the specified limit values anywhere on their national territory. The limit values set by EU law are not simply target values to be used for planning purposes by German legislators. Article 13(1) Sentence 2 clearly states: "limit values ... may not be exceeded (from the dates specified)". The limit values are therefore binding, although national legislative authorities may revise them downwards. Air quality plans for minimising immissions are one of the means laid out in the directive for counteracting exceedances of limit values. It is up to national legislative authorities to decide which measures to include in these plans. Here, legislators have a certain amount of freedom in terms of forecasting and planning.

The positioning of **sampling points** plays a considerable role in determining whether limit values are being exceeded. Related issues are currently the subject of proceedings at the European Court of Justice (4). According to the Advocate General's opinion provided prior to the decision, sampling points are used to identify "areas ... where the highest concentrations occur" (5). Since the case concerns high-level legal interests, such as the right to life and the EU's environmental protection standards, the Advocate General argues that authorities must "in case of doubt ... choose a strategy which reduces the risk of exceedances of limit values not being detected" (6).

Against this backdrop, the correct – from a scientific point of view – positioning of sampling points used to determine the representative mean annual exposure, for which the limit value of 40 µg/m³ must be applied, might become a topic of litigation in administrative courts (see also Chapter 4).

The European clean air legislation was adopted into **German law** in 2010. Since then, the European limit values for pollutants have been implemented in one of the Ordinances of the Federal Immission Control Act (39th BImSchV) (7). If the immission limit values are exceeded, the competent authority must draw up a **clean air plan** in accordance with EU law which specifies the necessary measures for achieving a permanent reduction of air pollution (Section 47(1) of the Federal Immission Control Act – BImSchG). German immission control legislation does not provide for any other measures other than the creation of clean air plans.

This means there is no regulation governing what should happen if the limit values are exceeded despite the existence of a clean air plan. As a result, the legal basis for the introduction of **driving bans** for diesel vehicles along certain roads or in certain areas after the nitrogen dioxide limit value had been exceeded was unclear. In its decision on driving bans in Stuttgart dated 27 February 2018, the German Federal Administrative Court clarified the situation by referring directly to the European Union's directive (8). The short-term air quality management measures mentioned include measures to "suspend activities" which contribute to the risk of limit values being exceeded. In Article 24(2), the directive explicitly points out that this may encompass measures relating to motor vehicle traffic (9).

Driving bans along certain roads or in certain areas for vehicles emitting a lot of pollutants are therefore permissible under EU law, provided that they are proportionate. In its statement of grounds, the Federal Administrative Court underlines the principle of **proportionality** as a fundamental basis of EU law. In particular, the court relates the principle to the creation of prohibited zones and the level of exposure experienced by individuals (10).

German legislators are now taking this up in the Thirteenth Act **Amending the Federal Immission Control Act**, although they relate it to the intervention threshold for the limit value. According to the new Section 40(1a), it should "generally" only be possible to resort to a diesel driving ban if an annual mean limit value of 50 micrograms per cubic metre of air (µg/m³) is exceeded. It is clear that national legislators are not permitted to "correct" the EU's limit values and this has already been commented on by the administrative courts in Cologne and Berlin in their side notes on the German government's plans. They state that if there were a legal dispute, the competent administrative courts would not be permitted to apply a national regulation which modifies the European limit values. The limit value laid down in EU law must therefore be observed.

Against this backdrop, the German government refers to the principle of proportionality and picks up on the time-related aspect specified in the directly applicable EU law. According to this law, the period during which the limit value is not observed must be kept as short as possible. It is therefore tolerable for a limit value to be exceeded in the short term. The German government believes that limits will no longer be exceeded by 10 µg/m^3 within a “reasonable period of time” because their “initiative for clean air in our cities” is taking steps to reduce pollution. It is likely that the matter will also be examined by the European Court of Justice.

References

(1) Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe (Official Journal of the Euopean Union L 152, 11 June 2008, p. 1); cited as "Directive".

(2) See recital 2 of Directive and art. 1, no. 5 of Directive: "maintaining air quality where it is good and improving it in other cases."

(3) "'Pollutant' shall mean any substance present in ambient air and likely to have harmful effects on human health and/or the environment as a whole." (art. 2, no. 2 of Directive).

(4) Case C-723/17 -- Lies Craeynest and Others v Brussels Hoofdstedelijk Gewest and Brussels Instituut voor Milieubeheer, opinion of Advocate General Juliane Kokott; the location of sampling points for the measurement is addressed in art. 7, no. 1 as well as in annex III B no. 1 a), first indent, and b) without provision of scientific methods or the like for the correct positioning of sampling points.

(5) In this way, the decision to refer the matter describes the purpose of the positioning of sampling points.

(6) See marginal number 55 of opinion of case C-737/17.

(7) 39th Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes -- Verordnung über Luftqualitätsstandards und Emissionshöchstmengen of 2 August 2010 (BGBl. I p. 1065).

(8) Cited in no. 6

(9) Art. 23, para. 2 of Directive goes as follows: "The short-term action plans referred to in paragraph 1 may, depending on the individual case, provide for effective measures to control and, where necessary, suspend activities which contribute to the risk of the respective limit values or target values or alert threshold being exceeded."

(10) BVerwG, 27.02.2018 -- BVerwG 7C 30.17 -- marginal note 34.

6. Air pollutants and traffic

Previous chapters discussed how traffic, especially older diesel vehicles, is a major source of nitrogen dioxide emissions which pollute the air along main roads. However, particulate matter – which is generated from many primary and secondary sources – has a much greater impact on health than nitrogen dioxide. Here, too, the focus is on road traffic. This is why the following chapter will predominantly concentrate on traffic-related air pollution. The role played by other sources will only be mentioned here in the context of examples and shall be discussed in more detail in a future statement of the Leopoldina. The more the emissions produced by road traffic are reduced, the more these other sources will come to the fore

Emissions on German roads

Since 1995, there has been an impressive decline in specific emissions of pollutants by road traffic. The emissions per kilometre driven by passenger cars have dropped considerably since this date. In the 22 years between 1995 and 2017, emissions of sulphur dioxide fell by around 98%, non-methane volatile organic compounds (NMVOC) by approximately 87%, direct particulate matter by 79% and nitrogen oxides by 56%. Carbon dioxide emissions were reduced by 15%. Better engines, sophisticated exhaust technology and higher-quality fuel also resulted in a decrease in specific emissions by heavy-duty vehicles. Sulphur dioxide emissions fell by more than 99% and carbon dioxide emissions by around 30%.

Nitrogen dioxide is the only road traffic air pollutant for which exceedances of limit values occur. The main perpetrators are diesel vehicles which do not meet Euro6dtemp/VI emission standards. These vehicles account for 33% of all passenger cars on the road in Germany. Virtually all utility vehicles have a diesel engine (see Box 6.1).

The picture is less positive when it comes to absolute pollutant emissions. Total nitrogen oxide emissions by passenger cars only fell by 48% between 1995 and 2017, while direct particulate matter emissions fell by 76%. Absolute carbon dioxide emissions even rose by 0.5%. Looking at trucks, total CO_2 emissions climbed from 34.2 to 41.0 million tonnes between 1995 and 2017 despite technical improvements, i.e. by about 20%.

Box 6.1: Diesel vehicles on German roads

Of the 46.5 million passenger cars registered in Germany, 15.2 million have a diesel engine. Of these, 37% meet Euro standards 1 to 4, which are currently the focus of discussions surrounding city centre driving bans. The remaining 63% are diesel vehicles meeting the Euro standards 5 to Euro 6d-TEMP (the latest emissions standard). If Euro 5 vehicles were to be included in driving bans, 75% of diesel vehicles would be affected.
Virtually all utility vehicles in the commercial sector have diesel engines. Most passenger cars used in the commercial sector are no more than four years old and are rarely affected by potential driving bans thanks to their modern exhaust technology.

Box 6.2: Traffic volume

The volume of both passenger and freight transportation has been expanding in Germany for years. The volume of traffic is the product of the amount transported and the distance travelled. In 2017, passenger traffic accounted for more than 86% of all traffic on the roads – about 80% private motor vehicles and about 7% public road transport. In addition, freight traffic amounted to 491 billion tonne-kilometres. In terms of distance travelled, 623 billion kilometres were covered by passenger cars and 121 billion kilometres by utility vehicles in the most recent reporting year of 2014.

The discrepancy between the trends in specific emissions and absolute emissions is due to the surge in road traffic intensity (see Box 6.2). The German government predicts that this figure will continue to grow. The number of private motor vehicles is expected to rise by 10% by 2030 compared to 2010, and the number of goods vehicles by 17%. The government also forecasts that greater propulsion efficiency will lower the energy demand of passenger cars by 27% by 2030.

European framework

CO_2 emissions in the transport sector are becoming increasingly problematic. As in other sectors of the economy which are not covered by the EU Emissions Trading System, carbon dioxide emissions must be reduced significantly in this sector by 2030. The EU’s Effort Sharing Regulation has enforced this obligation by giving all member states binding annual targets for reducing their CO_2 emissions between 2021 and 2030. Germany has to lower its emissions by 38% overall by 2030 (compared to 2005 levels) in the transport, buildings and agriculture sectors. The member states are responsible for devising their own national strategies and measures for reducing emissions. One objective of the current draft for a German climate protection act is the establishment of national targets for the individual sectors.

If the annual emission cap is exceeded, emission allowances may be purchased from other member states which have not reached their cap. According to the key information published by the German Federal Ministry of Finance about its financial plan up to 2023, the German government anticipates costs for such national emission allowances from 2020 on. 100 million euros have been budgeted per year for the period between 2020 and 2022. The actual payments will depend on the extent to which the emission cap is exceeded and on the purchase price of emission allowances under the Effort Sharing Regulation. The pressure exerted by the EU’s Effort Sharing Regulation is therefore another urgent reason for a comprehensive restructuring the transport system.

Objectives and conflicting interests, measures and their impact

One of the main challenges facing the transport sector is how to reduce the virtually inevitable negative effects of traffic as much as possible. Meeting the objectives of comfort, speed and affordability contrasts with capacity bottlenecks, greenhouse gas emissions, air pollutants and noise, accidents resulting in personal injury and damage to property;,and land consumption by moving traffic as well as parked vehicles. In addition to **solutions based on vehicle technology,** the situation can be changed by technical **traffic control** measures and the use of pricing and taxation to **influence behaviour.**

1. Propulsion technology

Combustion engines:

Changes in the level of nitrogen oxide emissions in the transport sector will depend on how quickly modern propulsion technologies enters the market. Besides political and legal conditions, this will primarily be decided by the choice of vehicles on offer and by consumer demand. Vehicle manufacturers have been striving to improve both the energy consumption and the nitrogen oxide and particulate matter emissions of combustion engines for years. Progress can be expected from technical advancements such as start-stop systems, 48-volt technology, variable valve timing, turbocharging and engine downsizing. The positioning of exhaust gas treatment systems near engines in diesel cars, the addition of particle filters to petrol engines, better transmissions, improved aerodynamics and lightweight design can all contribute to a reduction in nitrogen oxide and particulate matter emissions.

E-mobility:

The use of electric vehicle engines is likely to lead to a rapid reduction in traffic-related air pollution. Even if the technological, economic and political conditions needed for this only develop at a moderate pace, up to 15% of all new passenger cars purchased in the EU are expected to have a fully electric battery-operated drive and around 40% are expected to be partially electric (mild hybrids, full hybrids, plug-in hybrids) by 2030, while less than 6% will have a conventional diesel engine. And if developments are particularly favourable, it is anticipated that up to 50% of all newly registered vehicles in 2030 will be fully electric and approximately 45% will be hybrid electric. In this scenario, the proportion of cars with diesel engines would decrease even further.

One of the driving forces behind e-mobility is the EU’s carbon dioxide emission standards for new passenger cars. From 2030, these standards will limit the average CO_2 emissions produced by new vehicles to a maximum of 59 grams per kilometre – with electric vehicles being evaluated as completely climate neutral. According to estimates by the European Commission, these standards could lead to electric vehicles accounting for around 12% of all vehicles across Europe and could lower nitrogen oxide emissions on the continent by roughly 42%. Electric vehicles powered by an average European electricity mix already result in lower greenhouse gas emissions over their entire life cycle (including battery production) than conventional vehicles with a combustion engine.

Even electric vehicles generate particulate matter. Nevertheless, e-mobility is expected to lower emissions of particulate matter caused by brake and tyre wear. This is primarily due to regenerative braking systems in hybrid and electric vehicles. With these systems, the conventional brakes are used less frequently and emissions of brake dust produced by abrasion are reduced.

Retrofitting diesel vehicles:

The practice of retrofitting exhaust gas purification systems has been widespread not just in industry but also for vehicles for many years. A distinction is made between the retrofitting of catalytic converters, particulate filters, and the retrofitting of systems to reduce nitrogen oxide emissions (known as selective catalytic reduction or SCR systems).

The retrofitting of catalytic converters to lower emissions in petrol passenger cars was first undertaken in the 1980s/1990s and is regarded as a successful approach. A further

Box 6.3: Retrofitting diesel passenger cars

The first technical challenge when retrofitting diesel passenger cars is posed by the downstream installation of the catalytic converter. This makes it difficult to bring the system to the required operating temperature, especially when driving in urban areas. Complex heating strategies are required and these lead to elevated fuel consumption and CO_2 emissions. A further challenging aspect of lowering nitrogen oxide emissions, in systems using an aqueous urea solution, is the need to supply the solution known as AdBlue for the production of ammonia. All of the systems currently being tested by ADAC use AdBlue as their reducing agent.
Systems using another technology to supply ammonia are also available on the market. In these systems, which were awarded an EU Horizon Prize in 2018, ammonia is stored in cartridges and can be directly added to the exhaust gas. This avoids all the difficulties surrounding the supply of AdBlue, which currently presents something of a challenge in the development of the systems tested by ADAC. This is due to the formation of deposits and/or the need for a certain amount of energy to prepare the aqueous urea solution. At present, the end-of-pipe systems using AdBlue which are being tested by ADAC are not ready for serial production.

These statements were true at the time of publication of the German version (April 2019). In the meantime, several such systems have been approved for the German market. The technical as well as CO_2 *issues do pertain to these systems.*

well-known example, this time from the 2000s, is the technically complex process of retrofitting diesel passenger cars with particle filter systems. Today, this is viewed very critically. Some vehicles were in fact fitted with completely ineffective systems. And through the use of particularly powerful oxidation catalytic converters, the retrofitting of filters led to high nitrogen dioxide emissions.

In buses, the retrofitting of SCR systems has been routine practice for years. In diesel passenger cars, meanwhile, successful retrofitting is extremely challenging from a technical point of view (see Box 6.3).

The retrofitted systems recently tested by the German automobile club ADAC were found to increase fuel consumption significantly and to contribute to a rise in CO_2 emissions of between 0.9 and 28.6 grams per kilometre. In light of the CO_2 reduction targets determined for passenger cars, the use of retrofitted systems to lower NO_2 emissions therefore comes at great cost. In addition, the ability of these systems to reduce emissions drops markedly at temperatures below 10 degrees Celsius, especially when driving in urban areas. In such cases, the same effect could be achieved by software updates alone, which have the added benefit of being far simpler to implement.

2. Traffic control

Zones with restricted access:

Empirical analyses conducted for Germany consistently show that the introduction of green zones has lowered particulate matter by between 4 and 9%. Restrictions for trucks also improve air quality on a local level, as do bypasses. When notice is given of such measures in good time, businesses and the general public can generally adjust to the changes. Following the introduction of green zones, the number of low-emission commercial vehicles in Germany grew by 88%. There has been no drop in the total number of journeys.

Traffic management:

The aim of traffic management is to expand capacity without actually building new capacity. One way of achieving this is to use a green wave to improve traffic flow. However, this only reduces pollutant emissions slightly or within a small area. This is also largely true of traffic control solutions like parking guidance systems. Traffic management has no impact on the number of journeys made, which is a very important parameter when it comes to lowering absolute emissions.

Speed reductions:

Modern cars are designed in such a way that carbon dioxide emissions are at their lowest at speeds of around 60 kilometres per hour. Nitrogen oxide emissions are heavily influenced by the operating status of the catalytic converter and are especially high during a cold start. Generally speaking, the emissions per second in typical urban driving conditions begin to fall from speeds of 30 kilometres per hour. However, speed is just one factor at play here, and acceleration, temperature and engine design also need to be taken into account. The establishment of 30 km/h zones in towns and cities therefore does not necessarily lead to a reduction in pollutant emissions. Along urban motorways, however, air quality has been proven to benefit from speed limits.

3. Pricing and taxation

Expansion of public transport:

Public transport plays a key role in lowering the pollution produced by passenger traffic. According to studies, the construction of new underground railway lines reduces air pollutants by between 4 and 15%. Although free travel offers boost public transport use, they reduce private motor vehicle use by only a relatively small amount. Free travel on public transport is a logical accompaniment to driving bans or toll systems and is a means of compensation which can be implemented at short notice. However, existing public transport systems are likely to be considerably overstretched at peak times with high traffic volumes. To achieve a sustainable transport transition, it is necessary not only to expand public transport but also to connect different modes of transport for both people and goods, and to provide the corresponding infrastructure.

Sophisticated toll systems:

Modern toll systems can be a very efficient way of managing and improving traffic. Effective options include route charges tiered according to the time of day or the observance of Euro standards. This creates incentives for people to use less congested roads, to drive outside of rush hour or to switch to public transport. However, the creation of toll systems like this is expensive and time-consuming for the relevant local authorities or private operators. Examples in Stockholm, Gothenburg and Milan show that such systems are generally accepted by the public, provided that they have clear benefits and that exemptions from paying the toll are properly justified (principle of fairness).

Taxes and tax exemptions:

Here, it is important to distinguish between fuel tax and road tax. Fuel tax is the method of choice for reducing the distances people drive and therefore lowering absolute emissions. As testified by many studies, increases in fuel tax lead to significant changes in behaviour. Fuel tax has a particular impact on frequent drivers and drivers of diesel vehicles. Increasing fuel tax in a socially responsible way may therefore make an appreciable contribution to the achievement of climate and air quality targets.

Studies have shown that adapting road tax to environmental and CO_2 standards makes low-emission vehicles more attractive; here, vehicle registration tax has a greater impact than annual taxes. When considering tax incentives for electric cars, it is important to note that consumers respond better to immediately applicable discounts and VAT exemptions than to income tax incentives.

However, many consumers benefit from tax reductions who would purchase an electric vehicle anyway – especially those in high-income households. Instead of providing benefits to everyone regardless of their income, as is currently the case, authorities might grant subsidies or tax reductions for purchasing electric cars on a sliding scale to make them more socially balanced and cost-effective. For example, as part of its air quality management policy, California has introduced a targeted fleet modernisation programme which provides incentives to people who exchange old cars for electric cars and awards higher rebates to low-to-medium income groups. Programmes like this may be effective in the short term at encouraging people to switch to electric vehicles. Bonus/malus road tax arrangements, which give tax breaks to drivers of electric cars and charge much higher tax rates to drivers of cars with high fuel consumption, are more fiscally sustainable and economically efficient.

Outlook

Mobility is essential for our well-being and prosperity. There is now virtually no doubt about the fundamental necessity of a sustainable transport transition towards clean and integrated mobility. One of the main reasons is that the transport sector is still not contributing to reducing emissions of harmful greenhouse gases in line with the Paris climate goals. Germany is also obliged under EU law to lower its transport emissions. It is impossible to envisage a way of fulfilling these legally binding obligations without developing an entirely new approach to transport.

A long-term approach like this also holds the key to effectively combatting other undesirable consequences of traffic – not just air pollution but also congestion, noise and land consumption. Germany was initially regarded on an international scale as a pioneer of the energy transition. Decisive political action has the potential to turn the country into a trendsetter for a sustainable transport and energy transition.

The transport system transition is not only necessary from an environmental perspective. Instead of focusing solely on individual modes of transport or drive concepts, it is crucial to work towards a health-conscious, environmentally and climate-friendly, affordable mobility system which integrates various means of transport (trains, local public transport services, passenger cars, bicycles etc.). This requires innovations, the right infrastructure for the transportation of both people and goods, and tax reforms. Achieving this calls for cooperation across Germany and internationally.

A transport transition like this also makes sense in terms of industrial policy. There is rapidly growing demand for emission-free cars. At the same time, new competitors from China, Japan and the USA are offering electric vehicles powered by batteries or

Box 6.4: Other sources of particulate matter and how to reduce them

Thanks to the use of exhaust gas treatment systems, the proportion of particulate matter emissions generated by combustion engines in the transport sector and their contribution to direct $PM_{2.5}$ immissions have been continuously declining for years (see Figure 6.1). In contrast, pollution from other sources has been stuck at the same level for many years or is even on the rise. Examples include dust from vehicles (caused by brake and tyre wear) and wood combustion. Both these emission sources, wood burners in particular, make a major contribution to direct particulate matter immissions in towns and cities. An important aspect of emissions from wood combustion and fireworks is that they are often more limited in space and time than other sources.

The number of wood burners has climbed dramatically in recent years, not least due to state subsidies granted under particular conditions. Wood burners (single-chamber fireplaces) often emit substantially more particulate matter during everyday operation than is indicated on the rating plate. Reasons for this include low-grade wood, excessive smoke generation due to fires being lit incorrectly, and poorly controlled incineration processes. Even with new installations restricted to lower-emission wood burners, and with older models being withdrawn from use, wood burners still account for a far greater proportion of direct $PM_{2.5}$ emissions than combustion engines. The contribution made by wood burners to immissions varies widely depending on the region and season. In residential areas with lots of wood burners, very high $PM_{2.5}$ immission values are recorded, especially in the evening. In addition to particulate matter, wood burners also increase levels of polycyclic aromatic hydrocarbons (PAHs).

Effective countermeasures in the transport sector are still largely under development. Examples include systems to reduce brake dust and tyre wear, such as brake dust filters, coated brake discs and modified tyres. Various solutions are currently being tested for wood burners, but these are still not as effective as those developed for vehicles, for example. Particle separation systems for wood boilers are already on the market.

Exhaust gas purification technologies have led to a notable drop in primary $PM_{2.5}$ emissions generated by combustion engines. As a result, increasing attention is being paid to other primary and secondary sources such as wood burners, agriculture, and dust caused by abrasion. This is crucial in the interest of further reducing $PM_{2.5}$ levels.

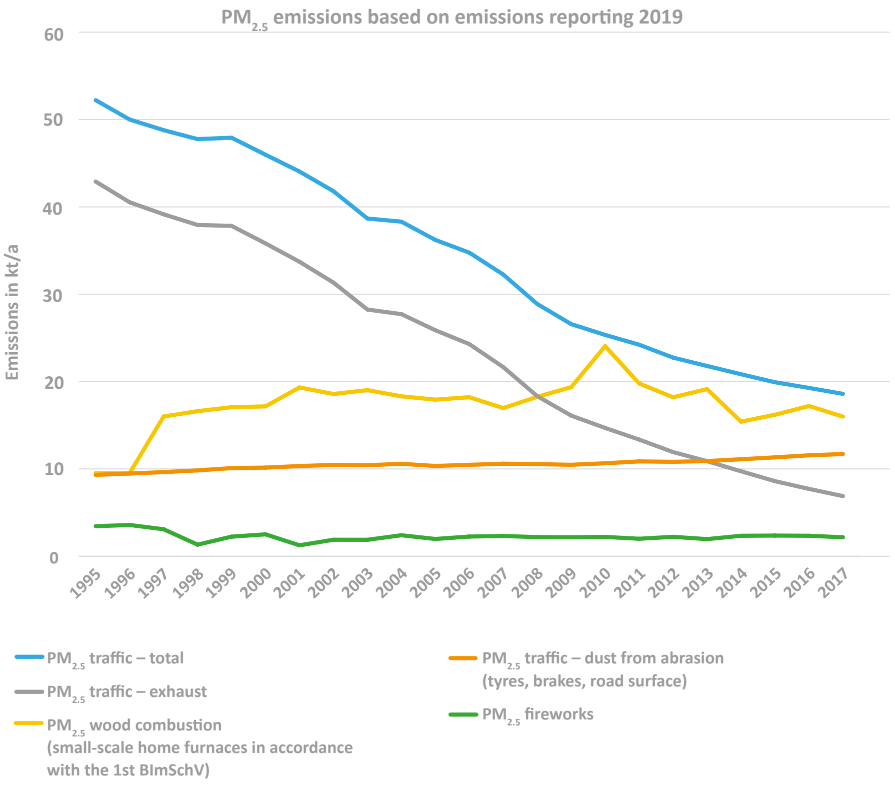

Figure 6.1: Direct emissions from road traffic (exhaust, dust from abrasion, total), wood combustion and fireworks. Please note that secondary organic aerosol formation in the atmosphere, which is responsible for a larger proportion of $PM_{2.5}$ pollution, is not recorded here (Source: Federal Environment Agency, 2019, unpublished).

fuel cells as well as IT services for autonomous driving, and are making ever greater inroads into the traditional line of business pursued by German car manufacturers. Regardless of the political decisions made in Germany, these market trends will not change in the foreseeable future.

There are clearly decisive arguments for policies which actively shape the transport system transition. The conditions which must be created by German and European policymakers will have a considerable influence on how well Germany will be able to keep pace with evolving challenges. Both e-mobility and digitalisation will play important roles here. Adverse effects on domestic production and employment, which are currently difficult to quantify, can be mitigated if political and economic players work to shape the structural change. Besides impairing air quality, a prolonged wait-and-see approach will put the country at risk of losing market shares and jobs.

Germany has the potential to become a pioneer and leading provider of sustainable mobility concepts. However, achieving this objective requires a comprehensive plan. If the right course is set, it will be possible not only to achieve clean air for everyone, but also to protect the climate and pave the way for a development which is both environmentally friendly and economically viable.

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Appendix

This ad hoc statement takes into account and reflects the latest research while observing the rules of good scientific practice. The publication of this statement was financed exclusively by the Leopoldina using the basic institutional funding awarded to it as the National Academy of Sciences by the German government and the federal state of Saxony-Anhalt. The members of the working group who contributed to the statement voluntarily were obliged to reveal any circumstances which could potentially lead to conflicts of interest or bias.

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The working group was established at a meeting in Berlin on 21 February 2019.

On 1 March 2019, the working group organised a consultation on the topic in Berlin; the following German and international experts participated:

Experts who were present at a hearing

Prof. Dr. Michael Bargende	Institute for Internal Combustion Engines and Automotive Engineering (IVK), University of Stuttgart
Prof. Michael Brauer, ScD	School of Population and Public Health, Faculty of Medicine, The University of British Columbia, Vancouver
Prof. Dr. ir. Bert Brunekreef	Institute for Risk Assessment Sciences, University Medical Center Utrecht, Universiteit Utrecht & Julius Center for Health Sciences and Primary Care
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Prof. Roy M. Harrison, PhD	School of Geography, Earth & Environmental Sciences, University of Birmingham
Dr. Michal Krzyzanowski	Science Policy – Environmental Research Group, King’s College London
Prof. Dr. Helmut Küchenhoff	Department of Statistics, Ludwig Maximilian University of Munich
Prof. Dr. med. Nino Künzli, PhD	Deputy Director of the Swiss Tropical and Public Health Institute (Swiss TPH); Dean of the Swiss School of Public Health (SSPH+); Professor of Prevention and Health, University of Basel; President of the Swiss Federal Commission for Air Hygiene (FCAH)
Dr. Ian Mudway	Analytical & Environmental Sciences Division, King’s College London
Prof. Dr. Annette Peters	Institute of Epidemiology, German Research Center for Environmental Health (GmbH), Helmholtz Zentrum München
Prof. Dr. Thomas Weber	Vice President of acatech – National Academy of Science and Engineering; Member of the Steering Committee of the German National Platform for Electric Mobility

The working group also asked the following people to provide written statements on various aspects of the topic:

Experts who prepared written statements

Prof. Dr. med. Dieter Köhler	former Medical Director at the Kloster Grafschaft Hospital
Prof. Dr. Walter Krämer	Faculty of Statistics, Technical University of Dortmund
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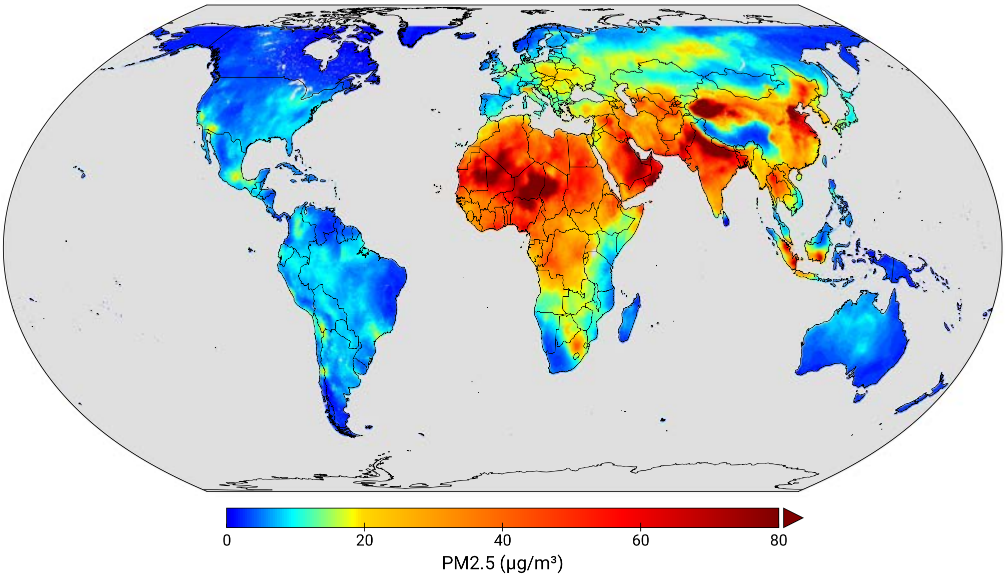

World map of particulate matter pollution: The map is based on satellite observations and shows the average pollution of different continents by particulate matter of size class $PM_{2.5}$ in 2016. With diameters up to around 2.5 millionth of a metre these particles are not visible to the naked eye.

The **world map** depicts the total pollution by particulate matter of size class $PM_{2.5}$ irrespective of its being emitted by natural sources or by human activities (energy industry, manufacturing, agriculture, traffic, households, etc.). The coloured scale includes concentrations up to 80 microgram per cubic metre of respiratory air. In comparison, the limit value in the EU is 25 microgram per cubic metre.

On the **cover** of this statement a detail of the world map is shown to convey an impression of the pollution by particulate matter of size class 2.5 in Europe.

Images: Klaus Klingmüller, MPIC Mainz, derived from satellite observations (Van Donkelaar et al., 2016).

Notes

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