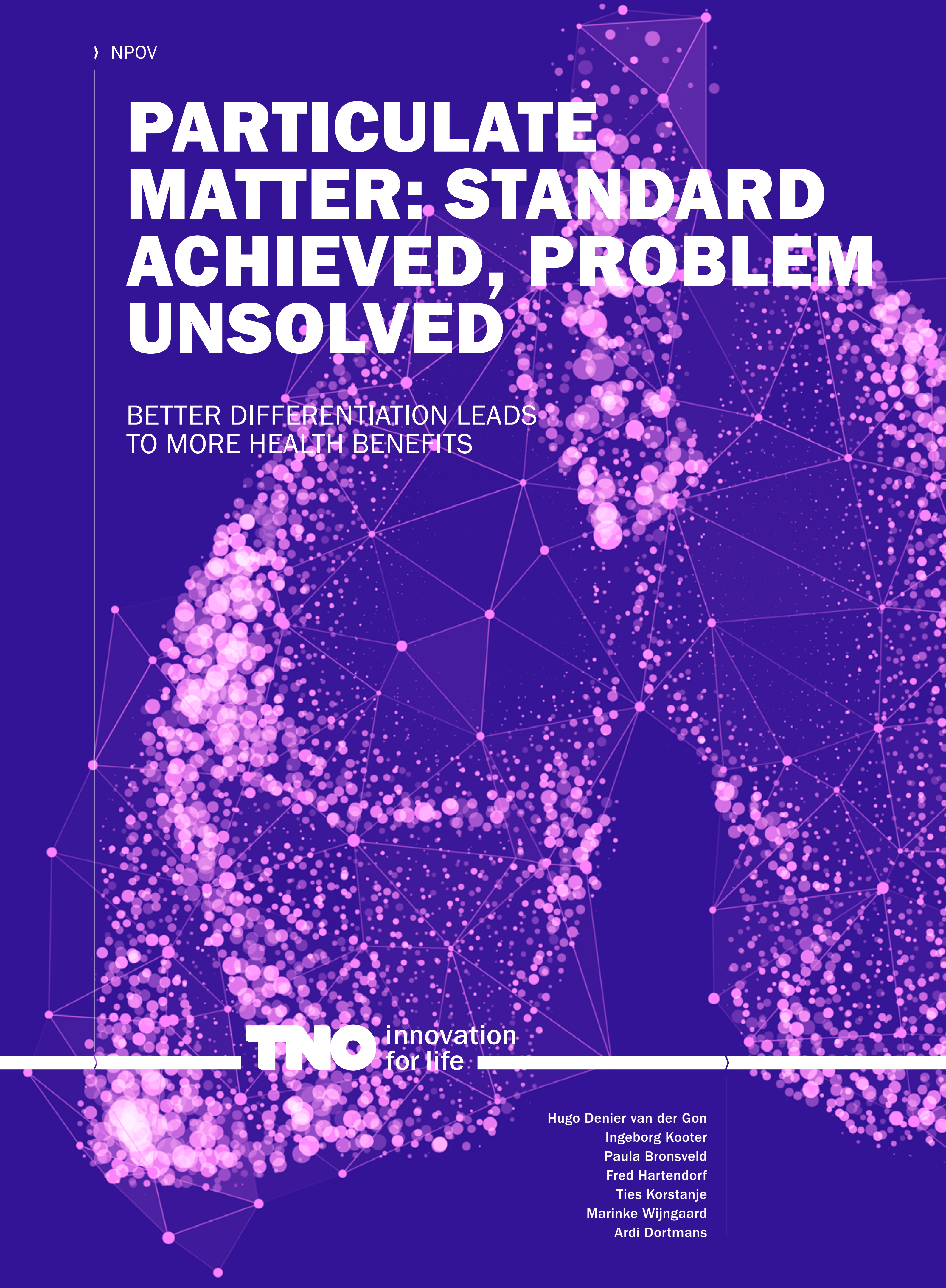

PARTICULATE MATTER: STANDARD ACHIEVED, PROBLEM UNSOLVED

BETTER DIFFERENTIATION LEADS TO MORE HEALTH BENEFITS

TNO innovation for life

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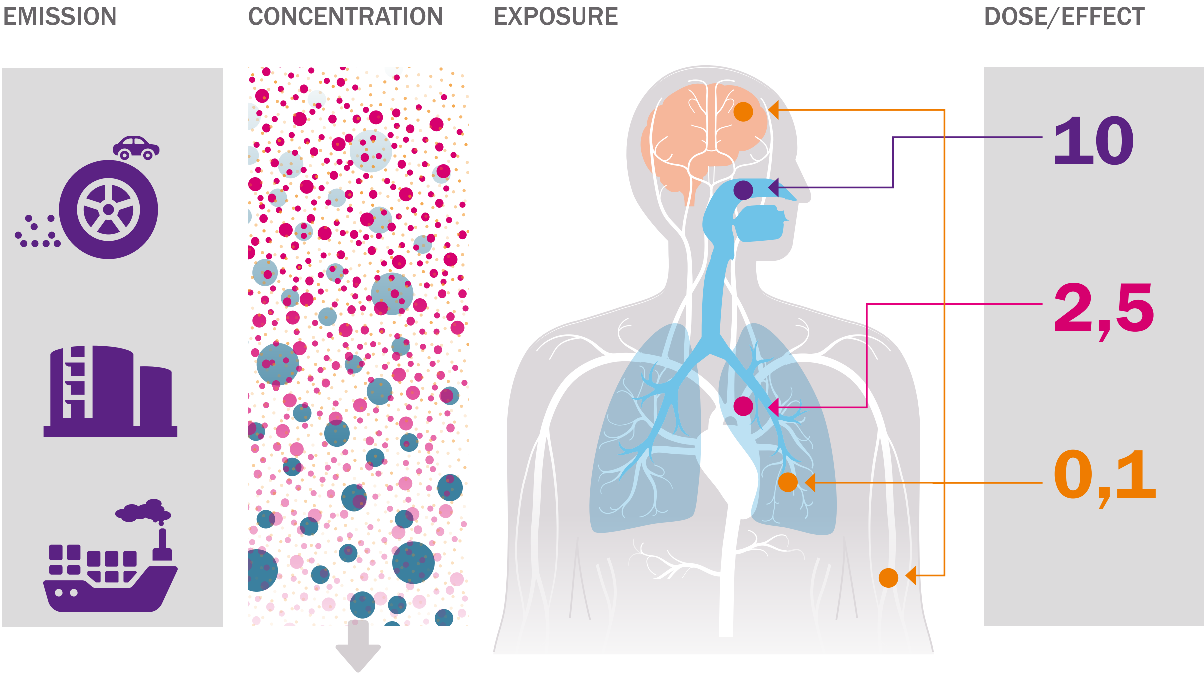
SUMMARY

The air quality limit value for particulate matter currently used in the Netherlands is based on the mass of all particulate matter present in a cubic metre of air. There is a better way to do this. Not all particulate matter has the same impact on health. The health impact is related to the reactivity of the particles in the particulate matter, and this in turn is determined by other properties such as the chemical composition, and size of the particles. For example, the very small particles, which weigh hardly anything, will end up deeper in the lungs.



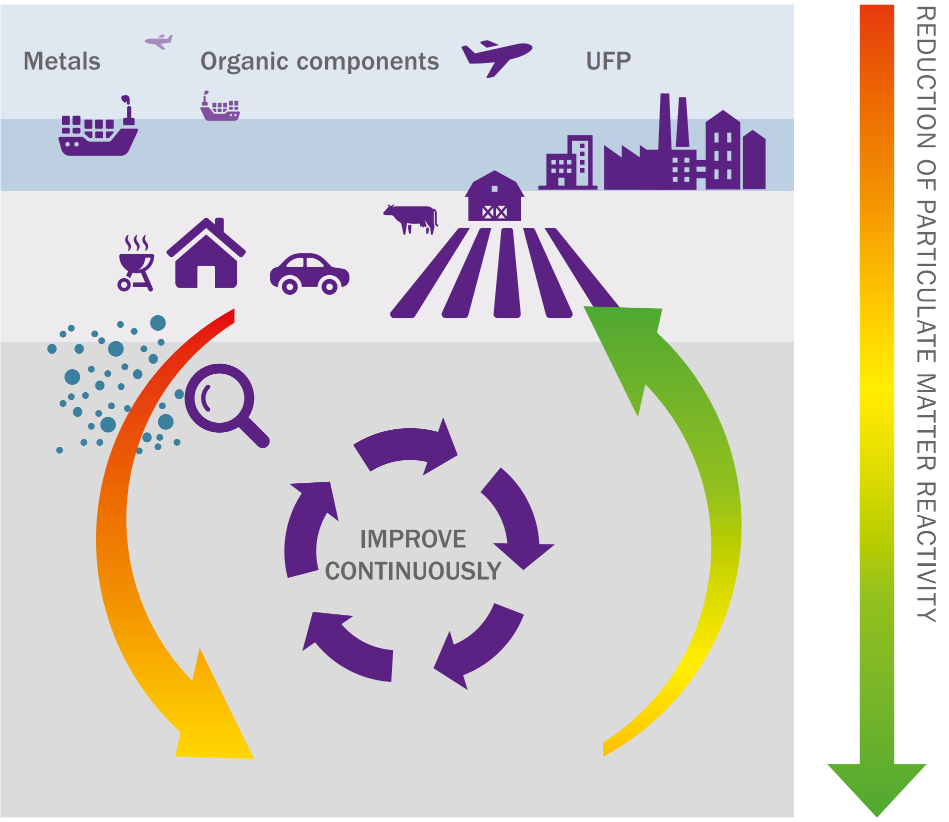
Current regulation
Focus on reduction of particulate matter mass; large particles contribute more.

Differentiation of particulate matter on the basis of reactivity
Focus on lowering total particulate matter reactivity for greater health benefits
(Focus on metrics such as ultrafine particles and composition)

In addition, the composition of particulate matter, and its harmfulness, is not the same in every environment. For example, does harmful particulate matter concentrate in a crowded location in the city where many people live? A situation like that calls for acute action.

These important properties of particulate matter are not taken into account for the current particulate matter standards, nor inlcuded in the measurements taken. As TNO, we believe this to be an alarming situation. Although it is currently possible to properly meet the particulate matter standard, the health risks are not eliminated. This leads to health risks with far-reaching consequences: every year, 9,000 people in the Netherlands still die prematurely due to exposure to particulate matter. Health problems caused by particulate matter lead to direct healthcare costs of about half a billion euros per year. And the social costs? They are many times higher: an estimated 10 to 15 billion euros per year, based on an amount of 1,250 euros per urban resident.

PARTICULATE MIXTURE



Not looking at particulate matter in more detail therefore has consequences. As TNO, we have therefore started to look for possible solutions. What exactly is needed to achieve an approach to particulate matter that better reflects the actual health risks? What measurements should we take in the Netherlands? And above all: to what extent is the required technology already available?

It turns out that there is already a surprising amount that can be done to tackle the particulate matter problem in the Netherlands more decisively. This is the positive news. But to achieve a new particulate matter approach, much remains to be done, both organisationally and in terms of resources. For example, a new approach requires a different way of working and new forms of collaboration – a major challenge. Meanwhile, the clock is ticking. The Clean Air Agreement of the Dutch government sets the goal of achieving a health gain of at least 50% by 2030 (compared to 2016).

If we start now, it will be possible to have the necessary measuring and modelling tools in place in two years' time. And the new insights this provides can be taken into account by the government when tightening particulate matter policy from 2025 onwards. This will allow a more targeted approach to this problem, so that the 2030 target can be met.

A source-specific approach to particulate matter, reactivity-based monitoring, and a link to the local situation. That is what TNO is advocating. We also already have ideas on how to achieve this in the Netherlands through a concrete roadmap:

50%
health gain
2030 compared to 2016

1. **Source-specific, iterative determination of the particulate matter composition.** How much particulate matter is there in a given area? What kind of particulates and corresponding properties are involved? What are the sources? In this exploratory phase, independent (knowledge) institutions will have a particularly important role to play.
2. **Source-specific, targeted monitoring strategy.** Provinces, municipalities, environmental services, and knowledge institutes will be working on long-term monitoring of properties of particulate matter, such as size and reactivity. In doing so, they will use a set of measurement tools to support and develop targeted policies.
3. **Mapping air quality in space and time.** This makes it possible to find out at a local level what the particulate matter map looks like and what the most heavily polluted areas are. And with the necessary support from knowledge institutions, environmental services, and the Municipal Health Service (GGD), municipalities and/or provinces can take appropriate measures to reduce exposure at the most exposed locations.
4. **Targeted determination of the health relevance of local mixtures of particulate matter.** Here we determine the potential impact of local mixtures of particulate matter on public health. In this area in particular, we still have a large information deficit and will therefore have to look for new ways to gain more insight into the health impact of various particulates. Innovative (data) technology could play an important role. On the basis of all the information gathered and analyses carried out, it becomes possible to respond more quickly to a local situation. This will allow knowledge institutions, environmental services, and the Municipal Health Service to indicate what measures are needed locally and what health benefits will be achieved.
5. **A local particulate matter policy with a health-relevant indicator for particulate matter.** On the basis of the above, the (local) government will create particulate matter policy that takes into account the factors that are important in a specific environment. In order to do this in the most targeted way possible, the government will meet with health services and (industrial) stakeholders. This will not only keep the government’s finger on the pulse, but these discussions will also provide information that is useful when implementing improvements. In addition to good monitoring, some form of local enforcement is needed to ensure that all parties keep to the agreements.

This is a brief summary of the 5 steps that we will discuss in more detail in this publication.

The roadmap we propose will not only contribute to cleaner air and, therefore, better public health, but also to the innovative capacity of the Netherlands. Our ambition is to take a new approach to the problem of particulate matter and, in doing so, make the Netherlands a global leader in improving air quality. But as previously stated, we have to start now.

CONTENTS

1. WHAT IS THE PROBLEM? THE EFFECTS OF AIR POLLUTION AND PARTICULATE MATTER IN THE NETHERLANDS

Breathing in polluted air leads to a great deal of health damage worldwide. The World Health Organisation (WHO) estimates that air pollution causes the premature death of 7 million people each year and an even greater loss of healthy years of life.[1] For the Netherlands, this is estimated at 11,000 premature deaths in 2015, of which approximately 9,000 are related to particulate matter. The loss of years of life is comparable to that caused by (severe) obesity or lack of exercise (Figure 1).[2]

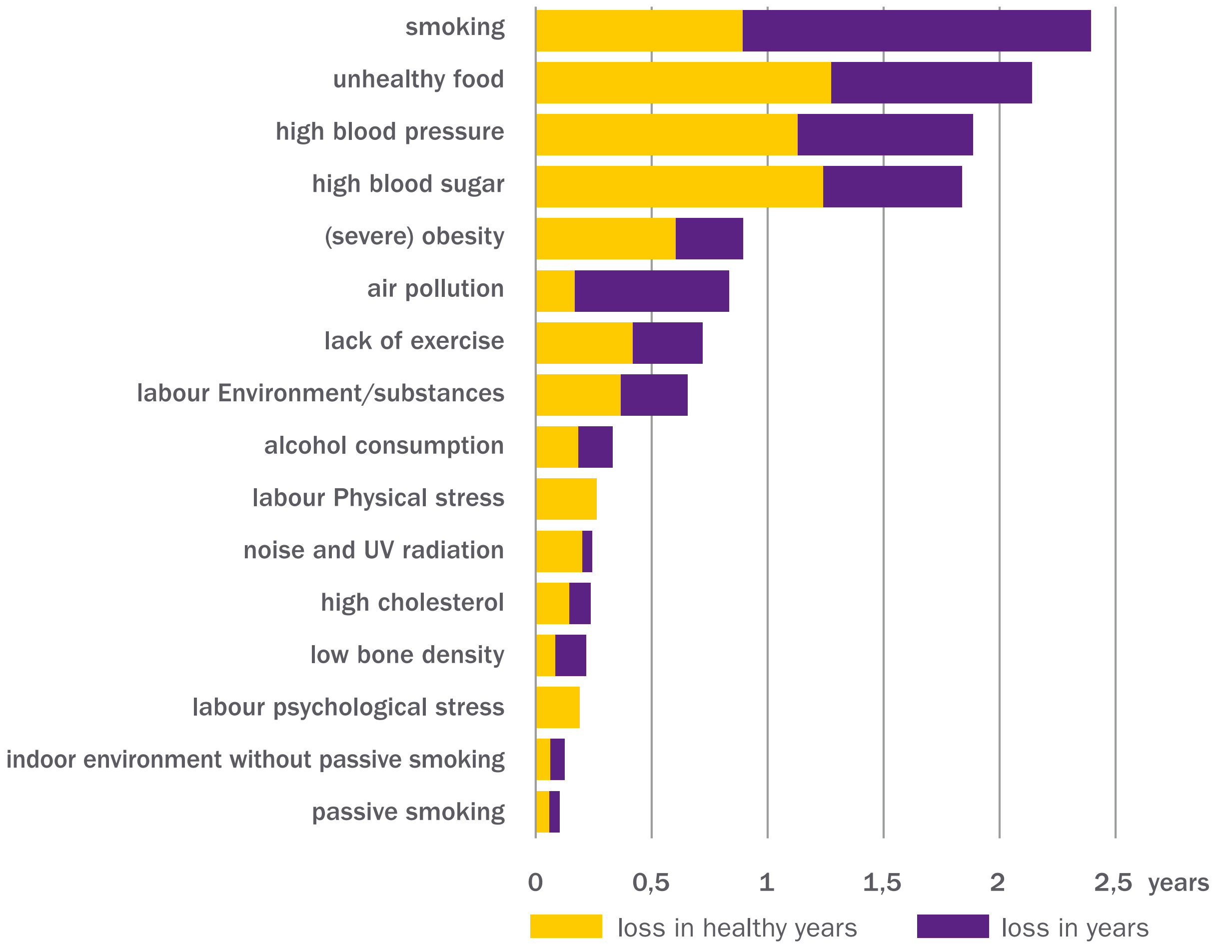
In addition to all the human suffering that air pollution causes, it also leads to costs. In the Netherlands, the direct healthcare costs resulting from air quality are estimated at half a billion euros.[2] There are also social costs resulting from air pollution. For example, a hospitalisation or incurable disease such as Chronic Obstructive Pulmonary Disease (COPD) quickly leads to a loss of prosperity. The associated costs of this loss of prosperity is estimated using the willingness-to-pay principle: healthy days are worth much more to someone than the mere economic loss of a working day (salary). This is, of course, a hypothetical situation, as unfortunately healthy days are not for sale.

All in all, the social costs resulting from air pollution represent a considerable loss. On average, this amounts to 1,250 euros per year per urban resident.[3] For the Netherlands (with more than 17 million residents, of whom approximately 75% live in an urban environment), this is an estimated amount of 10 to 15 billion euros per year.

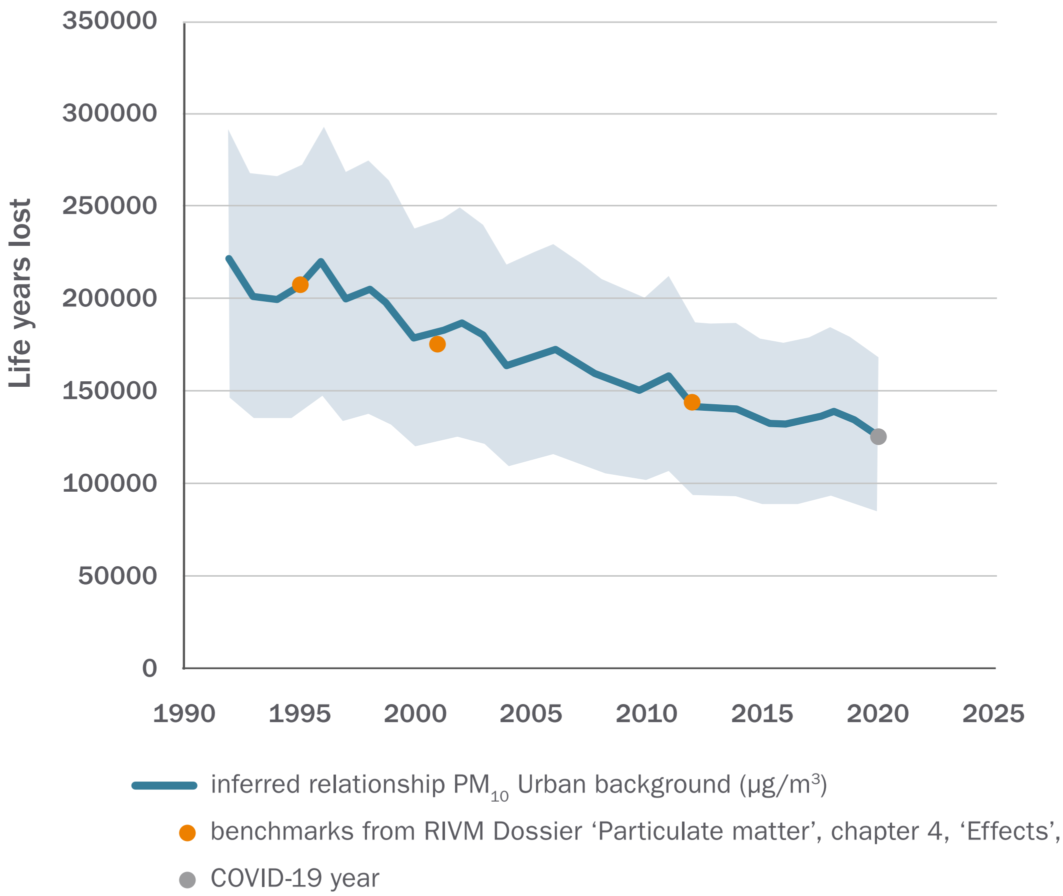
We are, therefore, talking about a major social problem that not only causes a great deal of human suffering, but also comes at an enormous cost. It is worth noting that roughly 80% of the damage to health caused by air pollution in the Netherlands can be attributed to particulate matter. When tackling air pollution, it is therefore a good idea to look more closely at particulate matter, which is an umbrella term for a wide variety of particles, and to zoom in on the different characteristics of the particles and how harmful they are to human health.

Unfortunately, the disturbing news is that even though the standards for particulate matter in the Netherlands have virtually been met, the figures show that there is still considerable damage to health caused by exposure to particulate matter. This means that improving air quality by tackling particulate matter can bring many health benefits. This will also significantly reduce social costs. Action is therefore required.

+/- 80% health damage due to air pollution can be attributed to particulate matter



Figuur 1 *Loss of years due to premature death and healthy years due to illness for various determinants in 2015.*[2]



Figuur 2 *Years of life lost in the Dutch population due to long-term exposure to particulate matter 1992-2020, based on data from the National Institute for Public Health and the Environment (RIVM).*[4] *The particulate matter mass (PM_{10}) concentration has been used as an indicator of health effects. Between 2015 and 2019, there is no further decrease in urban concentration. 2020 is not representative due to covid lockdowns with less road traffic and economic activity.*

1.1 HOW DO WE QUANTIFY HEALTH EFFECTS?

Long-term exposure to particulate matter, as experienced by people who live in areas with high concentrations of particles for many years, has been linked to...
- shortening of the life span
- cardiovascular diseases
- a reduced lung function
- the development of chronic bronchitis
- possibly even premature birth

But how can we best express health effects? In premature death or lost years of life? There has been much discussion about this. In the end, no matter how clean the air is, everyone dies. So it is not possible to talk about ‘deaths by particulate matter’. ‘Premature death’ and ‘shortening life span’ are more correct. In epidemiological studies, researchers also provide information on the average difference in life expectancy between groups exposed to different levels of particulate matter. There are no identifiable deaths, but rather particulate matter causes everyone to become ‘a little bit unhealthier’. This means an estimate of the number of deaths offers a false picture of reality.[5]

Years of life lost is therefore the best benchmark, with an additional distinction between loss in years (death) and loss in healthy years (see also Figure 1). The RIVM provides insight into the number of years of life lost through particulate matter exposure in the Netherlands up to 2011.[4] If we combine the average urban background concentration of particulate matter over the period 1992 to 2020 with the RIVM data, we can see that the downward trend continues until approximately 2015 and then stagnates (see Figure 2).

7 million
people die prematurely every year from breathing polluted air
(WHO 2021)

1.2 WHAT HAS PARTICULATE MATTER POLICY LOOKED LIKE SO FAR AND WHY?

There are two main reasons why the European regulation is based on mass concentration (µg/m^3):

1. The total mass of particulate matter (PM) is relatively easy to measure by catching and weighing all particles on a filter, according to the correct protocol. In establishing the current particulate standard, Europe has not chosen to make a distinction between PM components or fractions. When the standard was set, it was too challenging to measure different particulate fractions and/or components in a proper and reproducible way. Particulate matter can contain many different chemical components and the size of the particles can vary by a factor of a thousand(!). Different measurement methods and strategies may therefore give different results.
   For reasons of practical feasibility, when the European regulations were drawn up, the emphasis was therefore on harmonising the measurement strategy in mandatory monitoring, and not on further specification and determination of the particulate mixtures. Due to the choice of this strategy, little is currently known about the health aspects of specific particulate matter. However, the European approach has ensured that comparable, long-term time series are now available, providing the basis for a reliable and robust assessment of health effects.

2. Epidemiological studies (studying the frequency of diseases in human populations) show a correlation between mass of particulate matter and health damage. This was based on long-term epidemiological cohort studies.[6-8] However, sufficient (epidemiological, toxicological, and health-related) data was and is lacking to be able to classify in greater detail various particulate mixtures in terms of harmfulness. It is true that combustion emissions such as diesel soot[9] or certain fractions, such as ultrafine particles (particles smaller than 0.1 µm), are particularly suspect,[10-12] but there is not enough evidence for a precise differentiation. There are many components and aspects that contribute to the health effects of particulate matter. It is therefore a complex problem.

Due to the need and ambition to meet European standards, the emission of particulate matter in the Netherlands has been reduced considerably over time. Since 1990, emissions of particulate matter have decreased by 65%: from 82 ktons in 1990 and 54.5 ktons in 2000 to 29 ktons in 2020. Thanks to this source policy, the European standards have almost been reached in the Netherlands. And that is an important success. The relative importance of sources has also shifted. For example, Figure 3 shows that the importance of 'road traffic – exhaust' (yellow) has decreased enormously, while the consumer share (grey, mainly the burning of wood) and agriculture (brown) are now much more important than in 1990 or 2000. Since the chemical and physical properties of particulate matter differ from source to source, this also means that the components in the particulate mixture have changed over time. And that affects the risk profile.

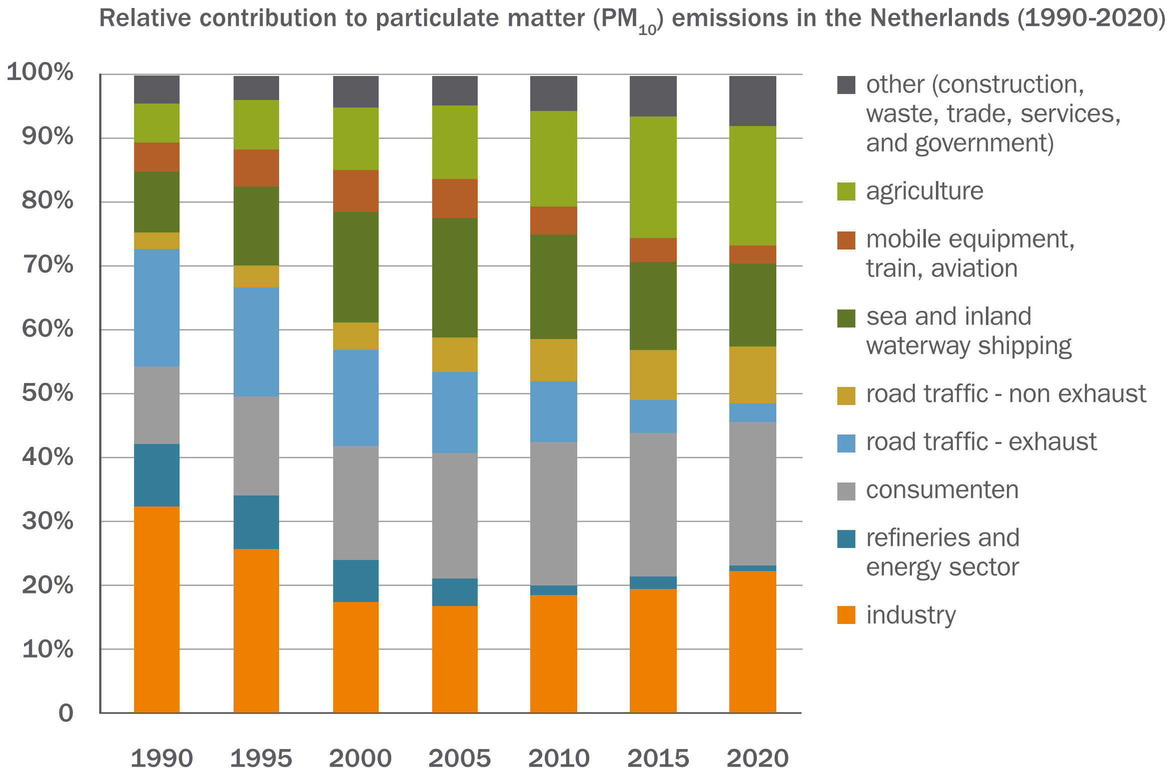


Figure 3 *Relative source contributions to (primary) particulate matter emissions 1990-2020 (based on RIVM/TNO Emission Inventory, provisional figures Dec. 2021). Time increments of 5 years 1990-2015 and last 3 years.*

The Clean Air Agreement (SLA), which the central government concluded with a number of municipalities and provinces in January 2020, aims to halve the damage to health caused by air pollution from Dutch sources by 2030. A fine ambition, but one that we are now giving an important comment on. As explained, the current focus on the total mass concentration of particulate matter is no longer the best way to further reduce its damage to health in an effective manner.

Since 1990, particulate matter emissions have fallen by

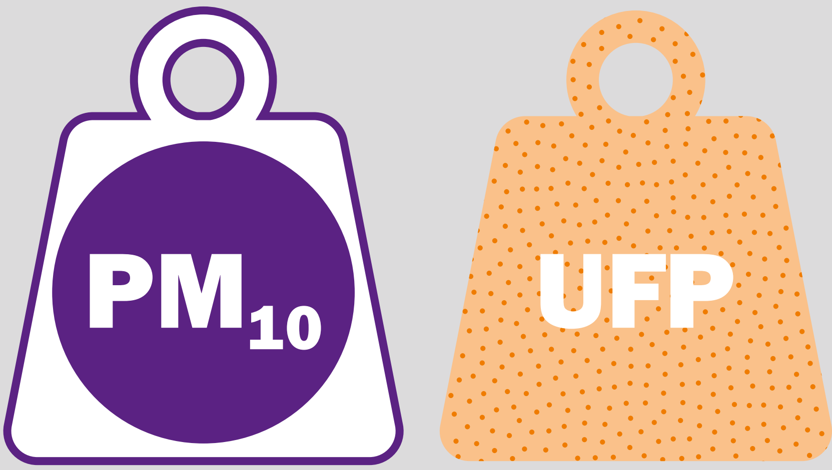
65%

2. WHAT FACTORS INFLUENCE THE HARMFULNESS OF PARTICULATE MATTER TO HEALTH?

That there is a link between exposure to particulate matter and health damage has already been demonstrated very convincingly in long-term studies.[6-8] These studies form the basis for the European and Dutch particulate matter standards. But the exact mechanisms that cause health damage from particulate matter are still partly unknown. What is certain is that oxidative stress, which occurs when too many potentially damaging, tissue-degrading free molecules (‘radicals’) enter your body, and inflammatory reactions play an important role.

There are three main biological pathways that can explain the health effects of inhaling particulate matter:

1. The particles can interact with cells deep in the alveoli, causing oxidative stress and inflammation reactions. The spread of these inflammatory reactions can ultimately lead to the dysfunction of blood vessels or disruption of blood clotting.
2. The particles can react with nerve receptors in the lungs, activating the (autonomous) nervous system. This can lead to increases in blood pressure and changes in heart rhythm.
3. The smallest particles can be absorbed directly into the bloodstream through the membrane of a pulmonary alveoli and travel through the body. There is also evidence that these particles can be transported directly to the brain via the olfactory nerve of the nose.



1 PM_{10} particle can weigh as much as **1 million UFP particles**

After inhalation, the size of the particles determines how deeply they penetrate into the lungs, with ultrafine particles penetrating deepest and being able to be absorbed into the blood (Figure 4).[13] In addition, these smallest particles have a larger reactive surface to which potentially toxic substances can attach (box 2).[14] The biological damage that can be caused by particles is more related to the total surface area of the particles and the number of particles (Particle Number, PN) than to the total mass.[11] In addition, the chemical composition, the reactivity, the shape (e.g. crystalline or rigid fibres), and the solubility of the particles also determine the harmfulness.[15]

As TNO, we advocate a practical and reproducible measurement that, when applied to different particulate mixtures, provides a predictive value for health effects. This predictive value can be expressed, for example, in the form of an index on a scale of 1 to 10. Such an approach with test methods and an index does not yet exist, but there are good candidates. We will come back to this in chapter 5.

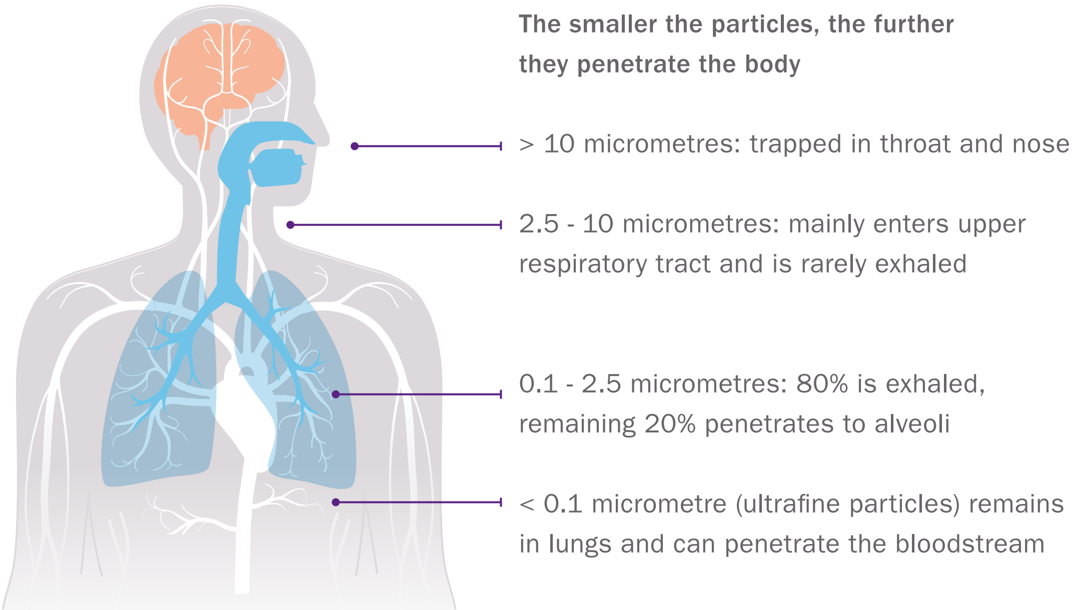


Figure 4 *How deep do different particles penetrate the airways?*[13]

BOX 1 IS AN INDEPENDENT PARTICULATE POLICY STILL NECESSARY IN THE FUTURE?

The energy transition will have a major impact on air quality in the near future. The introduction of renewable energy sources, in combination with electrification and green hydrogen, will drastically reduce current emissions from burning fossil fuels. So, is an independent particulate policy still necessary?

We believe it is. The two main sources of particulate matter in the Netherlands, wood combustion and agriculture (see Figure 3), are hardly affected by the energy transition. The use of biofuels (either as a replacement or as an additional fuel) is not a solution from the point of view of particulate matter problems.[16-18] In addition, for some sectors there are no alternatives yet. For example, electric flight is still a distant future. And the electrification of road transport is not the end of the particulate matter problem in that sector, because with electric driving you still have to deal with particulate matter emissions due to wear and tear of tyres and braking systems.[19] The full electrification of road traffic is also still a long way off: in 2019, 1% of the kilometres driven by passenger cars were done by fully electric vehicles. This is expected to increase to over 10% by 2030. Although this is a significant increase, traffic in 2030 will still be predominantly non-electric.

But what if the transition accelerates in a spectacular way and Dutch road traffic becomes completely emission-free by 2030? What could that mean for air quality in cities? The Municipal Health Service (GGD)[20] recently answered this question. The most important gain would be the complete disappearance of NO_2 emissions. But in terms of reduction of particulate matter (PM_{10} and $PM_{2.5}$), the gains would be very limited. This is most pronounced in the air quality forecasts at street level: the greatest impact is on NO_2 (-20%) and soot concentrations (-9%), while the impact on particulate matter concentrations is very small (-0.7 for PM_{10} and -1.4% for $PM_{2.5}$). Such modest decreases will not be measurable. But that does not mean that, apart from the health gains from the reduction of NO_2, no other health gains will be achieved. This is because the composition, and therefore the reactivity, of the particulate mixture in cities and at street level will change in this situation. **This means that the measurements based on particulate mass (which are currently the standard) say little about the effects on health in this outlined situation.**

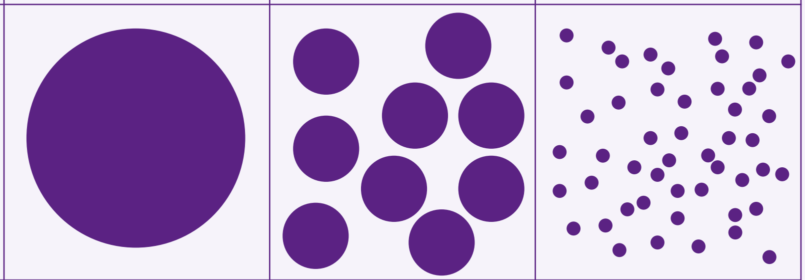
Finally, there is the possibility that new technologies will create new sources of particulate matter and that climate change will strengthen certain sources of particulate matter. In future policy, it is therefore important to take into account a complex and rapidly changing particulate matter problem, in which various developments can affect each other. This means that the policy will have to address multiple problems. To give just one example, which particulate matter emission reductions, important for health, also contribute to reducing CO_2 emissions and/or reducing the nitrogen crisis? For the persistent environmental cases, it would be useful to create a matrix of measures. Such an integrated approach can lead to other, better choices.

3. BUT WHAT IS PARTICULATE MATTER?

By particulate matter we mean all particles in the air smaller than 10 micrometres (PM_{10}) (see box 2). The Netherlands regulates particulate matter via the European air quality standards laid down in the Environmental Management Act. The European air quality standard prescribes 40 micrograms per cubic metre of air ($\mu g/m^3$) as the maximum permissible annual average concentration of PM_{10}. In addition, there is a 24-hour standard of 50 $\mu g/m^3$ that may be exceeded on a maximum of 35 days per year.

BOX 2: PARTICULATE MATTER, PARTICULATE FRACTIONS, PARTICLE NUMBERS, AND PARTICLE SURFACE AREA

Particulate Matter (PM) is defined as all particles in the atmosphere with an aerodynamic diameter ≤ 10 µm (PM_{10}). In addition, there is a distinction between the fine fraction with a diameter ≤ 2.5 µm ($PM_{2.5}$) and ultrafine particles with a diameter ≤ 0.1 µm (UFP). All UFP as well as the $PM_{2.5}$ fraction is therefore part of the PM_{10} fraction. Ultrafine particles have hardly any mass and therefore hardly contribute to the PM_{10} mass. Measurements of PM_{10} are therefore not representative of UFP.[15] UFP is usually expressed as particle number concentration (PN or PNC, Particle Number Concentration) per volume of air, as this is much more representative of UFP than mass.[14]

	10 µm (coarse)	2,5 µm (fine)	0,1 µm (UFP)
			
Mass	1	1	1
Particle number	1	64	1.000.000
Particle surface area	1	4	100

Ratio between mass, particle number, and particle surface area for PM_{10}, $PM_{2.5}$, and UFP.[14]

The annual average EU limit value for PM_{10} ($PM_{2.5}$) is 40 (25) $\mu g/m_3$, there are no legal limit values (yet) for UFP. Below these PM_{10} and $PM_{2.5}$ standards, serious health effects still occur. The WHO recommendation is 15 (5) $\mu g/m^3$ respectively.[1] For particulate matter effects after inhalation, particle surface area is also often proposed as a measure of exposure.[11] Here, too, particulate matter (PM_{10}) is not a representative measure. This is because the total reactive surface area per mass is greater when particles are smaller. With the current PM_{10} measurements (in which important matters such as the surface area are not monitored), it is impossible to arrive at an effective (local) policy and to visualise the extent to which this policy actually contributes to reducing the health damage caused by particulate matter.

3.1 WHAT IS IN PARTICULATE MATTER AND WHERE DOES IT COME FROM?

There are two types of particulate matter:

- Primary particulate matter is created by direct emission of particles into the air. For example, from chimneys and exhausts or construction and demolition dust (Figure 3).
- Secondary particulate matter is created by chemical reactions of gases in the atmosphere, such as ammonia (from agriculture), nitrogen oxides which leads to ammonium nitrate particles. Secondary particulate matter is mainly found in the $PM_{2.5}$ fraction (see Box 2).

Particulate matter can differ enormously in size, reactivity, composition, and behaviour in the body. In order to determine the extent to which exposure to particulate matter leads to a health effect and a loss of (healthy) years of life, it must first be clear what type of particulate matter is involved. Based on this, it will be possible to develop different approaches that actually match the type of particles that are the culprit in a specific situation.

In the current particulate matter policy, only the particulate mass counts and there is no distinction between particles of categories as below:

ULTRAFINE PARTICLES (UFP)

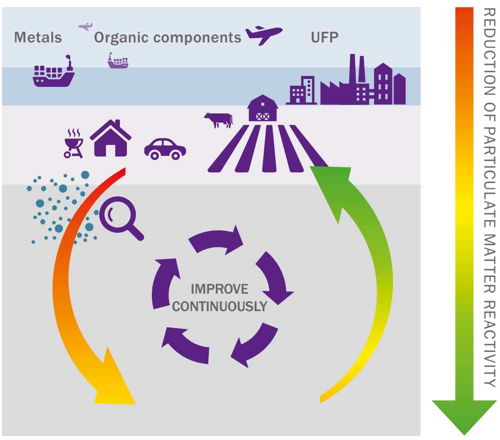
There is increasing evidence that UFP (see Box 2 and Figure 4) play an important role in the health effects of particulate matter.[10,11,14,21] It is not the case that all studies endorse a significant difference between the health effects of UFP and particulate matter (PM_{10}).[22] However, research does show that short-term exposure to UFP around airports has such health effects that research into the potential health effects of long-term exposure to UFP is considered necessary.[23] The National Health Council also recently drew attention to the effect of ultrafine particles on health in a special advisory report.[24]

METALS

The presence of metals in particulate matter is a matter of concern. Their characteristic properties lead to increased reactivity of the particulate matter and therefore to an increased risk of health effects.[25,26] Metals can also occur in the UFP fraction,[15,27] i.e., in the ultrafine particle, and enter the bloodstream when inhaled. The main sources of metals in particulate matter are wear emissions from road traffic[28,29] and industrial emissions.[30]

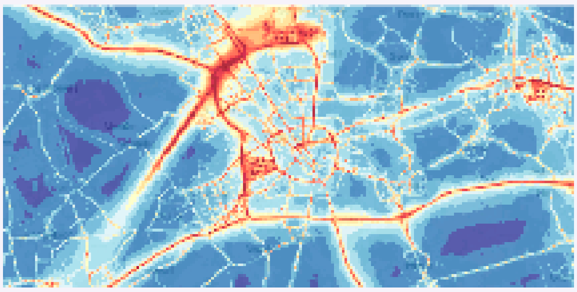
ORGANIC COMPONENTS

Then there is a third category of particulate matter of concern: organic components, such as polycyclic aromatic hydrocarbons (PAH), which are released in particular during incomplete combustion. The main toxicological effect of some PAHs is that they are carcinogenic. Carcinogenic PAHs are found in diesel exhaust[31,32] and are released from cigarette and wood combustion, among others.[33,34] These organic compounds attach themselves to particulate matter and can then enter the body through inhalation.



BOX 3 LOCAL AIR QUALITY AND THE ORIGIN AND SOURCE ALLOCATION OF PARTICULATE MATTER

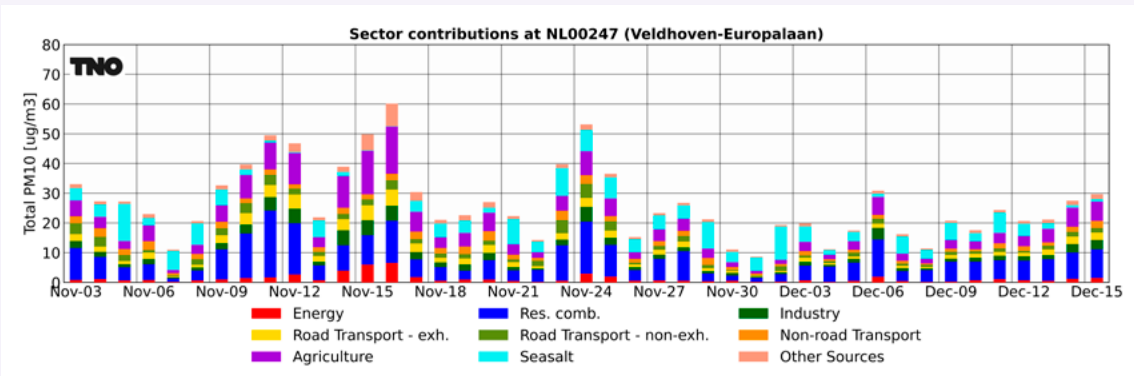
Municipalities are important stakeholders. In the photo (from left to right), Rik Thijs (alderman of the municipality of Eindhoven) and Fred Hartendorf (TNO) are seen discussing the results of the air monitoring network North Brabant at a dashboard showing local air quality. Alderman Thijs: *'With the Regional Monitoring Network, we are laying a unique foundation for research and innovation in our immediate environment, with the aim, of course, of improving our air quality and therefore our health.'*



Location is important because there are sharp gradients in health risk, as shown here.[35] However, composition and therefore relevance to health varies from day to day.

With the **TNO Operational Pollution Apportionment Service** (TOPAS), TNO can provide initial insight into current particulate matter concentrations for various cities and exactly which sources contribute to this. A prototype is currently in operation, collects the measured particulate matter values daily, and then adds source recognition based on TNO knowledge (models and emissions). The graph below, for the Veldhoven site during November/December 2021, shows that there are considerable differences in the origin, and therefore the reactivity, of the particulate mixture. Based on the measured local mix and in combination with data on health-related effects, an indicator can be added that gives an estimate of the (relative) relevance to health of this particulate mixture.

More information: https://topas.tno.nl/



4. WHAT IS NEEDED FOR FURTHER HEALTH GAINS?

Thanks to a targeted policy to achieve the European air quality standards, we have achieved significant health gains in the Netherlands. However, this seems to have plateaued since 2015 (Figure 2), because the (urban) concentration of particulate matter has not decreased any further (Figure 5).[36] And although the Netherlands has met the European standards, the recently tightened WHO standards for particulate matter[1] are not yet within reach.

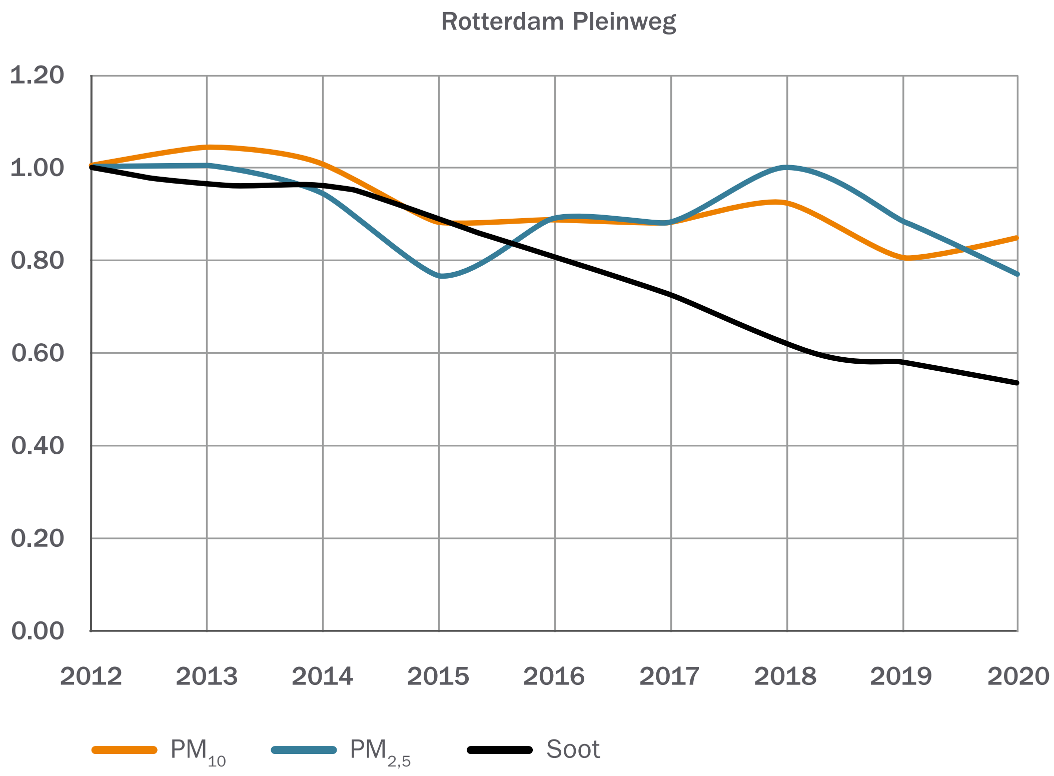


Figure 5 *Index graph (2012 = 1) for particulate matter (PM_{10}), the fine fraction ($PM_{2.5}$), and soot on Pleinweg, Rotterdam.[37] It can be seen that, just like in Figure 2, the concentration of particulate matter (PM_{10} and $PM_{2.5}$) has hardly decreased since 2015, but that there is a continuing decrease in the concentration of soot.*

And here we come to the heart of the problem. What if we in the Netherlands were now to focus entirely on achieving the WHO standards? This would mean that we would continue to steer towards a further and undoubtedly very difficult reduction in the mass of particulate matter, while continuing to assume that all particles are equally harmful. As TNO, we do not believe this is a good idea. Now that we know more and more about how different types of particulate matter lead to different health effects, we can clearly see the shortcomings of the current mass-based approach to particulate matter. We must change course!

Since the most suspect components are often found in smaller particulates or come from a single specific source, which therefore make a relatively small contribution to the total mass, halving the mass concentration of particulate matter does not guarantee that the health effects have or will decrease accordingly. By looking at particulate matter concentrations in a different way, we can come to new insights.

If the mass base is no longer the only indicator, important developments that were previously hidden may come to light.
For example, achieving a significant reduction in soot could be very relevant to health, but would not necessarily lead to a significant reduction in particulate matter concentrations (see Figure 5 for an example of this[37]). The reverse could also happen: a decrease or stabilisation of particulate matter (PM_{10}), but an increase in UFP concentrations. **In short, if we do not monitor the right benchmark, it is not possible to know where we stand and whether we are going in the right direction.**

A SO WHAT THEN SHOULD BE DETERMINED?

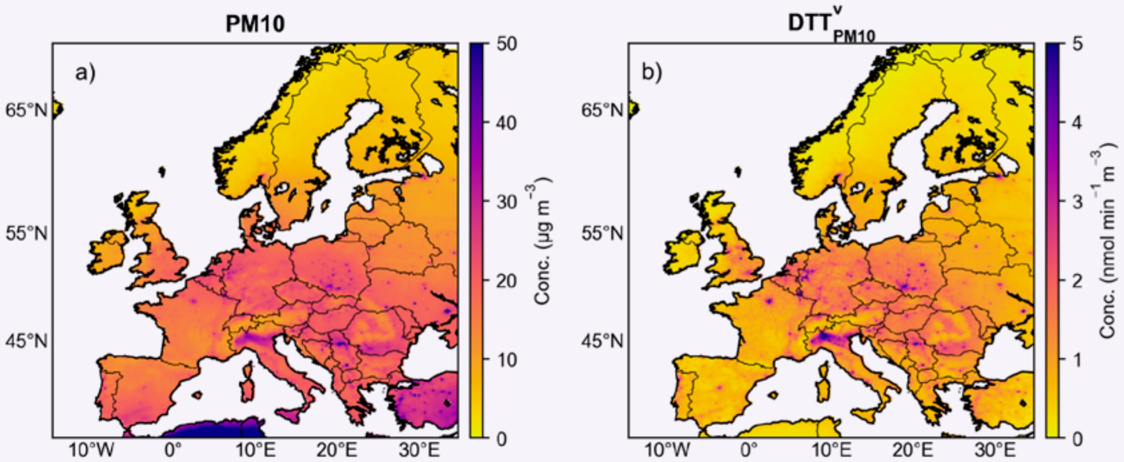
For further health gains, it is necessary to develop a policy that differs from situation to situation and depends on the reactivity of the local particulate matter. To make this possible, we in the Netherlands must first be able to measure the reactivity of particulate matter and check the extent to which there is a correlation with health effects. So, we must unravel the source contributions. Which particles contribute most to the total reactivity of the particulate mixture? Box 4 shows how this can be achieved. And based on these insights, we can then develop targeted measures in the Netherlands to reduce the reactivity of particulate matter, with these measures not necessarily leading to a (signifcant) mass reduction.

An additional point of attention is reducing exposure to ultrafine particles.
Because, as mentioned, the very smallest particulate fraction, ultrafine particles, is able to penetrate deep into the lungs and be absorbed into the body, posing the greatest risk of harmful interaction with the body. Moreover, relatively speaking, these particles have the largest reactive surface.

BOX 4 A BENCHMARK FOR THE REACTIVITY OF PARTICULATE MIXTURES

The adverse health effects of particulate matter are caused, among other things, by its reactivity: when human cells come into contact with particulate matter, so-called reactive oxygen species (ROS) can be formed. This leads to oxidative stress. On the one hand, this may be due to components present in and on the particulate matter itself, such as metals. On the other hand, cells can be induced by the particular matter to form these ROS themselves. The extent to which particulate matter itself can generate ROS can be expressed as the oxidative potential (OP).

There are different OP tests that can demonstrate different ROS. The dithiothreitol (DTT) assay is currently the most widely used test for OP, as it is sensitive to combustion products and is also relatively inexpensive and well reproducible.



Concentrations of particulate matter (left) and oxidative potential (OP) production rate (right) based on DTT assay across Europe for 2011. Clear differences in gradients can be seen with OP more concentrated in busy urban areas.[38] This suggests that sources that dominate particulate matter (PM_{10}) are not or only partly sources that dominate DTT.

B AND WHAT ARE THE MAIN POINTS OF ATTENTION?

Measuring something accurately is one thing. But drawing the right conclusions from it is another story. And when it comes to particulate matter measurements, there are two main points of attention here:

1. PARTICULATE MATTER EMISSIONS DO NOT ALWAYS LEAD TO IMMEDIATE AND ON-SITE EXPOSURE

Where and when does the emission take place? And where are people potentially exposed to these emissions? Local high-resolution modelling is needed to get a good picture of this. This makes it possible both to develop a measurement strategy (where to measure) and to better map out the particulate matter exposure for humans. The tools are there. And by validating the results of the measurements and incorporating the insights that this provides, a continuous correction mechanism is created that ensures that the model gives an increasingly accurate picture of reality. On the basis of this model, it becomes increasingly clear how many people are actually exposed to certain sources. And that, in turn, makes it possible to determine, on the basis of that information, which targeted measures should be taken in a specific location and how much priority that should have.

2. THE MOST IMPORTANT SOURCES OF PARTICULATE MATTER DO NOT (OFTEN) COINCIDE WITH THE HOTSPOTS FOR UFP EMISSIONS

Local UFP emissions vary greatly. It will be very different for an inland city like Eindhoven, for example, compared to the Rotterdam / Rijnmond region. If we map the local differences in the Netherlands, we can identify, verify, and target the expected hotspots.

TNO is working on a first inventory of UFP emissions in the Rijnmond area in 2022. This was commissioned by DCMR Environmental Service Rijnmond and the municipality of Rotterdam. Shipping and mobile machinery play a dominant role in UFP emissions in that environment. Other sources, such as storage and handling of bulk goods, contribute more to particulate matter (Figure 6). Although there are hardly any (long-term) measurements of the quantities of UFP, the picture seems to be broadly in line with the (limited) measurements that DCMR has. And this first inventory can already contribute to local modelling.

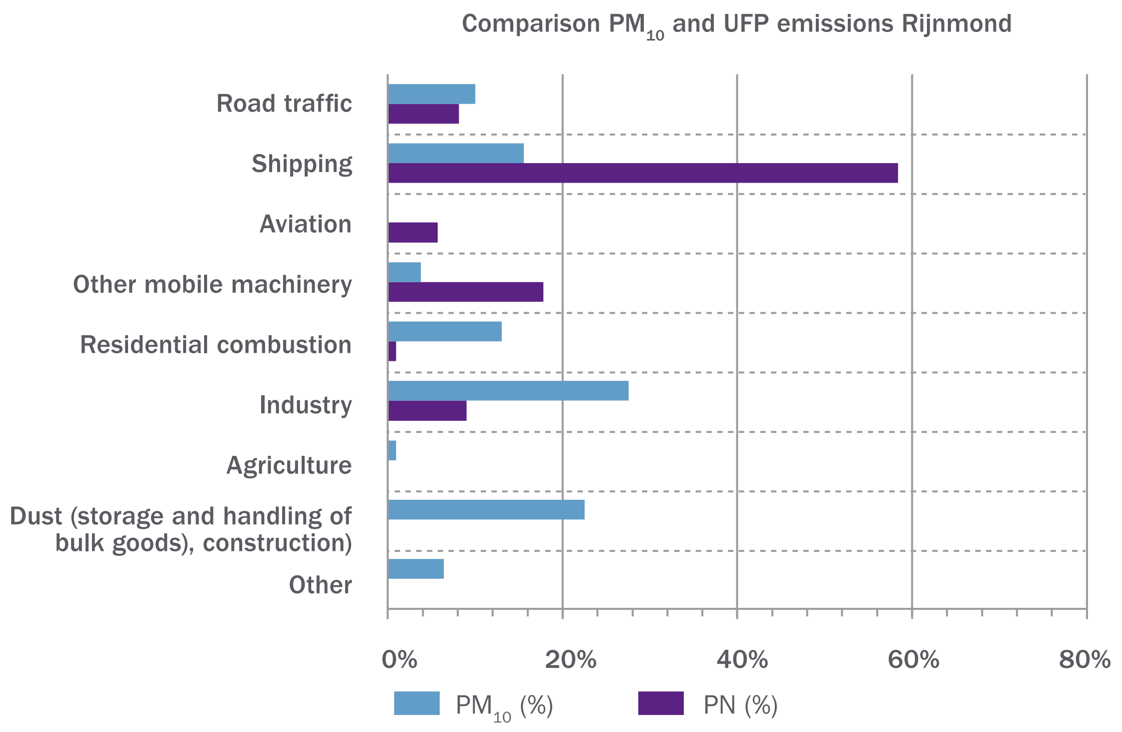


Figure 6 *Relative source contributions in 2019 according to the preliminary TNO inventory of UFP emissions in the Rotterdam/Rijnmond region (purple) compared with fine particulate emissions (PM_{10})[30] for the same domain (blue and purple bars each add up to 100%).[39]*

5. A PARTICULATE MATTER POLICY GEARED TOWARDS HEALTH GAINS (IN FIVE STEPS)

How are we going to do all this? To start with, we must improve the mapping out of the reactivity of particulate matter in the Netherlands. For this, we need to build a measurement infrastructure for measuring UFP and the chemical composition of particulate matter or a direct measurement of reactivity (such as oxidative potential). In doing so, we must look locally at the composition of particulate matter and not blindly rely on locations where a lot of particulate matter has been measured in the past.

Fortunately, much is already possible and known, and resources and techniques are available to monitor particulate matter more locally and more specifically in the future. This offers a perspective for action. By starting to implement this new particulate matter approach quickly and going through the trial-and-error cycle continuously and smoothly, we can make great strides within a few years. An interpretation of this cycle is outlined below on the basis of five steps.

STEP 1: SOURCE-SPECIFIC, ITERATIVE DETERMINATION OF THE PARTICULATE MATTER COMPOSITION

What is the size distribution and chemical composition of the particulate matter? And to what extent is it possible to deduce from this the source of the particulate matter and what effects it may have on health? Based on the current knowledge of particulate matter sources (from literature and inventories), it is possible to make a (first) estimate and to determine which components should be measured and where. This involves fingerprinting: recognising source contributions on the basis of their chemical composition. Measuring everything everywhere is not realistic. This method of working therefore reduces costs.
The following classification can be used for the distribution of measuring instruments:
Physical properties (number and particle size) to be specifically monitored:
– Major sources of ultrafine particles: airports, transport (road and shipping), refineries.
Chemical properties specifically monitored at:
– Major sources of metals: road traffic (brake wear), ports, industry (such as iron and steel).
– Major sources of organic components: wood burning, internal combustion engines, industry.
– Major sources of (organic) secondary particulate matter: agriculture (NH_3); transport and industry (NO_x and SO_2); industry, petrochemicals, and wood combustion.

The next step is to select a number of representative locations and to determine the exact composition of the particulate matter in the air there over a period of several months. Look in particular at the variation in the composition of the source(s). When analysing this data, combine the estimated fingerprints of sources in the vicinity and the measured composition (physical and chemical, including reactivity). This is important information for designing a monitoring set-up that makes it possible to determine the variation in particulate matter composition at representative locations over time.

STEP 2: A SOURCE-SPECIFIC, TARGETED MONITORING STRATEGY

Current particulate matter measurements do not take into account the composition and related health effects. As previously explained, we can no longer base new health-oriented particulate matter measures on mass determinations of PM10 alone. Other properties of particulate matter (such as UFP, reactivity) need to be taken into account. And for this we recommend a source-specific, targeted measurement strategy with appropriate modelling tools. The latter provides insight into the distribution and the contributions of primary and secondary particulate matter and is also suitable for developing targeted policies. With the help of this strategy, we can then provide insight into the impact of the chosen policy and make it measurable.
The new datasets obtained are also important for the international research community and for informing citizens. It is therefore important to open up the data properly and make it available to the public.

The new strategy is based on three key elements:

A. Instruments
If the Dutch authorities and research institutes join forces, within two years, a source-specific measurement infrastructure for the target components can be set up that ties in with existing infrastructure (particulate matter measurements already exist, but this concerns the possibility of further specifying the composition of particulate matter through measurements). However, it is necessary to find out which instruments can best be used where and for which components. An addition to the currently implemented instruments is crucial for a proper quantification of source contributions, including the share of secondary particulate matter from local sources (traffic, wood-burning).

B. Locations
The main objective here Is to characterise particulate matter in a way that directly leads to valuable contributions to health and exposure studies. It is crucial to realise at least one, but preferably two urban top monitoring stations in the Netherlands. The less extensive measurements from other locations can then be linked to the measurements at these stations.

Also essential is the use of sensor networks. They must be located in and around cities and near important sources of particulate matter. Which sensors should they be and where exactly should they be located? An inventory must be drawn up for that. This involves measuring particle numbers and health-relevant parameters with, for example, mid-cost sensors. Especially at the beginning of this development, quality is more important than quantity.

C. Comparable metrics
As in the current policy, it is essential that we maintain similar metrics at the different locations. This ensures that at a later stage we can compare the health impact at different locations, including internationally. We will have to choose standardised measurement standards. The information for this can partly be obtained from foreign literature, but we will also have to look specifically at the Dutch situation.

STEP 3: MAPPING AIR QUALITY IN TIME AND SPACE

In addition to a new measurement infrastructure for the new particulate matter components, the new properties of particulate matter and the dispersion of particulate matter with these properties must be added to the dispersion models. This will ultimately allow us to map the local air quality and link it to the corresponding sources.

We will go into this in a bit more depth: if we apply high-resolution dispersion models for particulate matter (both in space and time), this will provide insight into spatial (where) and temporal (when) exposure (see also Box 3). The models must then be validated for the various components on the basis of the source-specific measurements. Through this validation, the uncertainties in the composition and origin of particulate matter in the models will become smaller and smaller. And so, an ever better picture emerges of the spatial distribution of certain components. Based on this picture, it will also be possible to answer more specific questions about the local origin of particulate matter.

In addition to spatial and temporal variation in air quality, the presence and movement of the population in an area is also important. After all, health impact only occurs when people are actually exposed to particulate matter. By linking population dynamics to air quality data, we can also take this aspect into account. Combining this with the quantification of source contributions provides the next level of detail: an indication of the contribution of a source to the particulate matter exposure of a specific population in a specific area over a specific period of time. We then already have a good enough picture of the situation to be able to come up with an appropriate course of action.

STEP 4: TARGETED DETERMINATION OF THE HEALTH EFFECTS OF LOCAL MIXTURES OF PARTICULATE MATTER

Ideally, we would like to determine the health impact of each specific particulate mixture from each source. But that is not realistic. Moreover, the particulate mixture is constantly changing over time, which would mean that we would constantly be behind the times.

On the basis of the source-specific, local measurements in steps 1 and 2, the introduction of these values into the models, and the knowledge of the health impact of the substances, we can define a parameter: the health-relevant indicator. This indicator assigns a value to the expected local health impact of the particulate mixture in the air, making this health-relevant indicator a concrete tool for making policy.

The oxidative potential is a good metric to start with as a health-relevant indicator. We can measure this value directly (albeit with a rather complex method at present) or model it based on knowledge of the composition. By taking more measurements and modelling them, we can then quickly improve the reliability of the health-relevant indicator.

The potential health impact of locations with the same concentration of particulate matter can vary considerably. This has everything to do with the origin of the particulate matter. Intuitively, we feel this, but of course we want to arrive at a plausible and measurable benchmark for particulate matter toxicity. And this can be done by measuring or modelling the oxidative potential, allowing concentration maps to be converted into health relevance maps. More toxicological research is needed to properly harness the oxidative potential. Meanwhile, there is a step we can take right now. In fact, we can start monitoring oxidative potential at a few well-chosen locations, in order to collect a basic dataset in the Netherlands and to monitor progress. The approach to reduce the local health burden is related to this; the oxidative potential will put much more emphasis on the urban environment (Box 4).[38]

STEP 5: A LOCAL PARTICULATE MATTER POLICY WITH A HEALTH-RELEVANT INDICATOR FOR PARTICULATE MATTER

As a society, as policymaker, and as citizen, we want the right measures to be implemented and at the right location, so that together we can achieve the maximum health benefits. To do this properly, we must know where the health-relevant indicator is alarming. We must be able to determine which sources contribute to this undesirable situation with the help of fingerprinting and modelling tools. The next step is to ensure, through appropriate measures, that the situation improves and becomes manageable.

Dutch research has previously shown that monitoring a specific particulate component (soot) is a better indicator for evaluating health risks related to particulate matter in the inner city than using particulate matter mass.[9] We see that monitoring particulate matter mass does not capture the decrease in a health-relevant component (Figure 5) and is not sensitive enough to measure the impact of an important measure such as zero-emission traffic (Box 2).[20] It will therefore be a challenge to ensure that measurements of alternative benchmarks such as UFP and reactivity become commonplace and reproducible, and then to roll them out widely and integrate them with regular monitoring.

And what can we do to make standard setting, monitoring, and enforcement manageable and feasible? To begin with, we could introduce a phasing of standards. For example, by first setting up UFP determination. Continuously measuring instruments are already available for this and setting a standard is more accessible. The next thing is to focus on reactivity. Parallel to UFP monitoring, monitoring and standardisation for reactivity can be further elaborated and developed, so that in a follow-up phase the standardisation can be directly supplemented with this component.

As soon as the monitoring is in order and the observations are publicly available, it will be possible to target emission reductions (even more) effectively. At least, if the right agreements are made, for example in a covenant or the Environmental & Planning Act. The following elements are very important here:

a) There must be a (local) implementation plan, preferably initiated by the (local) competent authority. Elements of this plan may include:
   - the optimal measurement strategy
   - cost estimation
   - short and long-term goals
   - testing stakeholder support
   - role of citizen participation
   - accessing the information
b) Local authorities need guidance on policy. The development of a good toolbox with options for measures and expected impact on UFP and reactivity is necessary. So too is an exploration of the possibilities for effective enforcement (how and when). Local authorities can make use of the services of existing knowledge holders (e.g., the National Institute for Public Health (RIVM), the Municipal Health Service (GGD), TNO) and play a key role in identifying local pollutants, implementing local measurement solutions, and implementing source-specific measures for sources in their region.
c) Are local sources of particulate matter directly or indirectly owned by companies? If so, they are expected to...
   - cooperate in investigating particulate matter concentrations
   - identify causes of the (relatively) high concentrations of particulate matter and/or certain components therein
   - find possible solutions for specific particulate emissions, with supporting measures where necessary

5.1 A CALL FOR COLLABORATION

In order to successfully implement a new particulate matter policy, the following parties and stakeholders will need to unite:

- Ministries (Infrastructure & Water Management, Economic Affairs & Climate): for a national framework, facilitation, implementation of measurement and modelling instruments, additional incentives, and/or synergy with dossiers such as energy transition and nitrogen policy.
- Municipalities, provinces, and environmental services: for local policies and implementation of national policies, accountability to and involvement of residents, feasibility, and enforcement.
- RIVM and GGD: for monitoring health gains on the road to the 2030 target
- Knowledge institutions (including TNO, RIVM, and universities): for a substantive basis, advice on possible solutions, and implementation.
- Industrial stakeholders (e.g., port authorities, airports, industry, energy sector, stove industry): innovation and implementation together with the aforementioned parties.
- NGOs (e.g., Longfonds, Urgenda, Milieudefensie): agenda-setting and advocacy.

5.2 A CYCLICAL APPROACH

It is possible to implement some of the 5 steps in parallel. In certain cases, this can speed up the process, because sometimes you need information on, for example, particulate matter properties or specific measures for emission sources for one step that are only addressed in a later step. And the insights gained from a later step may also be relevant for an earlier one. A cyclical approach (or iterative process) therefore seems to us to be a good way of arriving more quickly at an appropriate particulate matter policy and proper monitoring, and of being able to implement continuous improvements.

BOX 5: WHAT CONCRETE MEASURES CAN WE TAKE NOW?

The 5-step plan proposed here will not be ready tomorrow. But there are also actions that we can take tomorrow that provide important information and are crucial to the development of this approach:

What we can do tomorrow:

a) Set up at least two monitoring sites in the national monitoring network, which are able to sample particles on filters for further analysis. In addition to detailed physico-chemical composition of the particulate matter at the two monitoring sites, the oxidative potential must also be measured.
b) New standardised toxicity measurements from different sources to identify the effects of particulate matter.
c) Building correlations between physico-chemical characteristics of different source emissions and health effects (toxicology and epidemiology).
d) Development of oxidative potential measurements and identification of health-relevant components such as metals and organic fractions as possible health-relevant indicators.

What we can do after tomorrow:

e) Based on the correlations between physico-chemical and reactivity characteristics of particulate mixtures, and the toxic effects and possible health effects identified, it will be possible in the longer term to make a good choice for a representative health-relevant indicator for particulate mixtures.

6. BENEFITS (AND COSTS) OF A NEW PARTICULATE MATTER POLICY

In this paper, we talk about the structural determination of the complete physico-chemical composition of particulate matter in the air. This is not only complex, but also costly. And that also applies to possible measures. There is no way around it: if we really want to reduce the number of years of life lost due to particulate matter in the Netherlands, we will have to make funding available for this purpose. But on the other hand, a different particulate matter approach leads to a reduction in both direct healthcare costs and social costs. It therefore saves society money, while at the same time significantly improving the quality of life. In addition, the new particulate matter approach that we recommend may contribute to a reduction in (health) inequality in the Netherlands. People in vulnerable neighbourhoods are more exposed to particulate matter, for example because their houses are closer to busy roads or industrial areas.

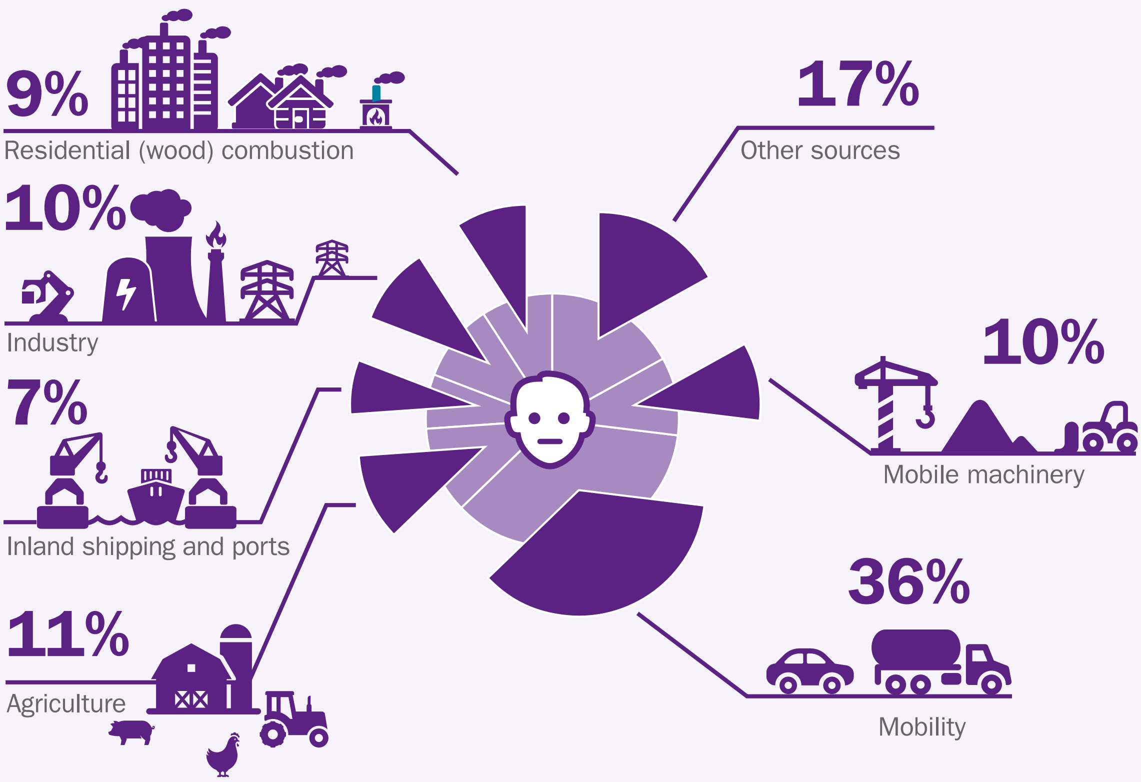
Measured per resident, air pollution costs European city dwellers an average of 1,250 euros in well-being per year. And this is a direct consequence of direct and indirect loss of health due to poor air quality.[40,41] Non-urban residents are also exposed to particulate matter, and the problem is therefore not necessarily very different for rural areas than for cities. However, the source contributions may differ and there are no separate figures for social costs. In the aforementioned European study of 432 cities, Dutch cities are close to the average. As an indication, for a city like Eindhoven the social costs of air pollution are 1,276 euros per resident, with 236,000 residents this amounts to about 300 million euros per year. Exposure to particulate matter is the cause of 80 to 85% of these costs. Based on a population of 17 million Dutch people (75% urban), the indicative figure is 10 to 15 billion euros. These are very high costs and the direct healthcare costs (about 0.5 billion euros for the whole of the Netherlands[2]) are only a limited part of this.

Currently, Dutch policy is focused on generic, national policies for sectors, and cost-effectiveness is based on the effects for the average exposure of the Dutch population over a whole year. But a good cost-benefit analysis should also consider the effect of individual particulate matter measures, the local particulate matter composition, and the spatial distribution of source contributions at specific locations. Addressing it in this way creates a policy that focuses more on the local health benefits of individuals. And that is exactly what we want!

With the environmental zones in cities, steps have been taken in the past towards a more local, targeted policy. In 2020, the national government concluded the Clean Air Agreement (SLA)with a large number of municipalities and provinces (Box 6). Its objective is to further reduce (local) air pollution and, in doing so, achieve a health gain of at least 50% by 2030 (compared to 2016). So, the Netherlands already has the necessary experience to tackle this social problem locally. At TNO, we welcome this and call on all parties involved to extend this local approach even further.

BOX 6: THE CLEAN AIR AGREEMENT

The goal of the Clean Air Agreement is to permanently improve the air quality in the Netherlands. It is an agreement between the national government, provinces, and a large number of municipalities, with the aim of achieving a health gain of at least 50% by 2030 in comparison to 2016. 'This means that people will live longer, healthier, and with more quality,' says State Secretary Stientje van Veldhoven. She was the first to sign the agreement on behalf of the Ministry of Infrastructure and Water Management on 13 January 2020. All 12 provinces and almost 90 municipalities have now signed the agreement. More information is available at www.schoneluchtakkoord.nl.



The infographic shows the health contribution per sector/theme as included in the explanatory notes to the Clean Air Agreement, January 2020.[42]

7. CONCLUSION

Over the past twenty years, the current policy on particulate matter has focused entirely on meeting European standards. This has been successful but has not solved the problem of premature death and years of life lost through exposure to particulate matter. And as long as the focus remains the same, the planned additional policies will not solve the problem either. Considering the important role of air quality in years of life lost in the Netherlands and the high social costs, it is essential to develop a new particulate matter policy, with an additional focus on health gains. The recent Clean Air Agreement (SLA)[42] and the recommendations of the National Health Council[24,43] emphasise this. Support for such policies requires a focus on other parameters than particulate matter mass only.

Achieving health gains is more important than controlling the reduction of a relatively easy-to-monitor parameter, such as the particulate matter mass. We have identified the fraction of UFP in particulate matter and the reactivity of the particulate mixture as the key parameters to monitor, and have shown that the knowledge exists to adopt a new, more health-relevant strategy. The correct parameters must be monitored from the outset. We have also outlined the implementation steps that will enable policy support on other benchmarks besides particulate matter mass to be realised within two years. Key actors and stakeholders must unite to make such a policy successful. And that is fully in line with what the Clean Air Agreement aims to achieve.

For goal-oriented effective control, transparency, support, and insight, we must develop a health-relevant indicator for particulate matter in the Netherlands. In doing so, we are not starting from scratch. There is already much in the Netherlands and beyond that lends itself to this, but it is clear that a concrete leap forward and a long-term vision are needed. Another success factor is the critical monitoring and evaluation of the goals in a cyclical development. Is the health-relevant indicator realistic? Is it understandable for citizens and other stakeholders? And is the indicator unambiguous enough so that we can actually use it in the Netherlands? By constantly asking critical questions and implementing improvements, the policy can be continuously refined.

In addition to implementation of the ideas and tools, this change requires considerable research and development efforts. And we must keep a very close eye on the possibility of a good integration into the policy, especially the SLA.
An ambitious development with so many different facets requires not only broad support and more creativity, but also sufficient financial resources. The government can provide an important impetus, but the goals are only achievable if we also create an economic value chain in the Netherlands with, among other things, opportunities for technology development, sensor developers, service providers, and investors in sustainable developments.

8. LOOKING AHEAD

In the future, air will be even cleaner and healthier. We will walk through our cities and, thanks to the targeted policy on the unhealthy fraction of particulate matter, the air we breathe there will actually be clean. That air will meet the new standards for UFP and reactivity. In the city and the surrounding area, quality of life is paramount. This fits in perfectly with the European Commission's action plan *'Towards a Zero Pollution for Air, Water, and Soil'*, which is one of the main goals of the European Green Deal. We must start now in order to achieve the desired results in three to five years' time and to demonstrate the effectiveness of the new focus of particulate matter policy with practical examples.

ZERO POLLUTION AMBITION

This, therefore, is an urgent appeal to all parties to jointly make a demonstrable difference in terms of the particulate matter approach, so that the Netherlands will be in an even better and healthier position in 2030.

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