National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Knowledge brief

Empirical modelling of UFP

RIVM

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Summary

Assessment of ultrafine particles (UFP) is becoming increasingly important, both from medical and regulatory perspectives. To estimate the levels of ultrafine particles in the Netherlands in the absence of many long-term measurements, an indicative map was created using the combination of almost 100 short-term low-cost measurements of UFP at locations obtained with the help of volunteers, several measurements using professional condensation particle counters (EPCs) and existing NO_X concentration distributions as a proxy. The new map is an evolution of an earlier indicative UFP-map and incorporates recent measurement campaigns, notably those from the CLAIRE project (Hoek, 2025), which used handheld DiSCmini counters. Continuous measurements at a relatively rural background location near Utrecht were used to scale the short-term observations to long-term averages. Most of the short-term UFP measurements were collected during a one-two week period. Since the DiSCminis measure particles with a minimum diameter of 10 nm, whereas the EPCs from the national air quality monitoring network (luchtmeetnet.nl) register particles from 7 nm, a correction was applied to account for the differences between the measurements. UFP concentrations were also modelled on a national scale using NO_X as a proxy. Different NO_X layers, such as highways, provincial roads, shipping and contributions from abroad, were linked to measured UFP concentrations through linear regression. This resulted in sector-specific conversion factors, generally ranging between 100 and 300 particles/cm³ per µg/m³ NOx. The final map was compared to the measurement results of the EPCs. The most substantial differences were observed near traffic sources where the abundance of very small particles is highest. The comparison indicated the need for an overall bias that had to be added to the indicative map of approximately +800 particles/cm³. The result is an UFP map that shows the total estimated contributions from different source sectors in the Netherlands. The new map provides a more complete and more realistic distribution of UFP levels in the Netherlands than the previous version.

Introduction

This knowledge brief presents the results of an empirical modeling approach developed by RIVM to estimate UFP concentrations across the Netherlands. By combining nearly 100 short-term measurements at different locations, continuous reference measurements, and NO_X concentration distributions as a proxy, a new indicative UFP map has been produced. This map builds on earlier work and incorporates recent measurement campaigns, including the CLAIRE project (Hoek, 2025), to provide a more complete and realistic overview of UFP levels from various source sectors.

In this knowledge brief, UFP is used to denote particle number concentration (PNC), and the term UFP is applied consistently throughout.

1.Previous work

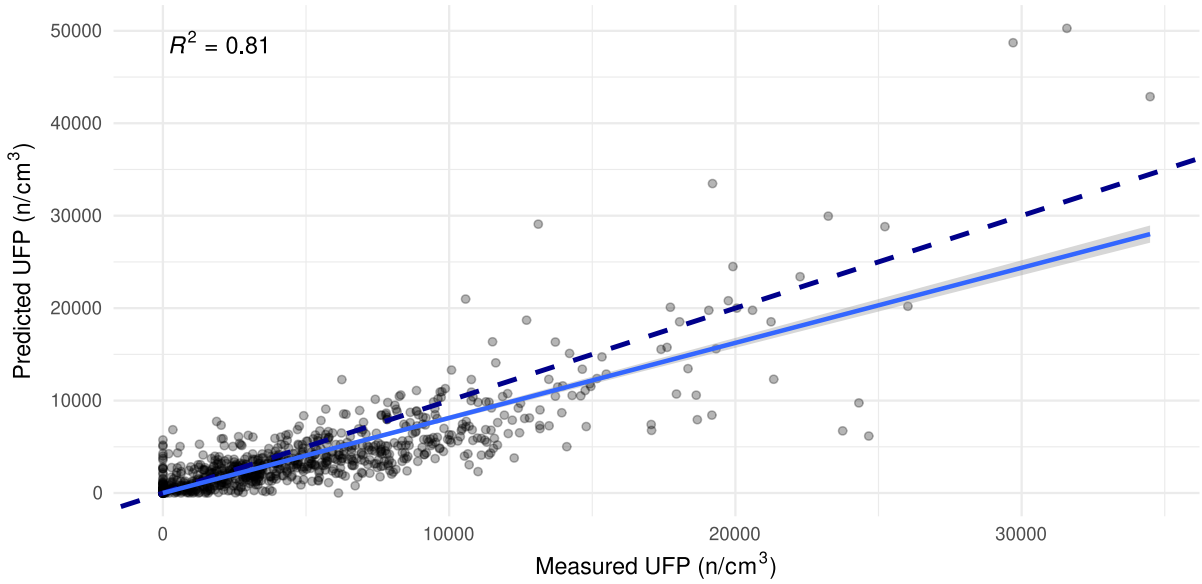
In 2023, RIVM published an indicative map of UFP in the Netherlands. The background layer that was used in the map was based on 20 temporary background locations from the Institute for Risk Assessment Sciences (IRAS), and a small number of background estimates at other UFP measurement locations. Interpolation was done in R, using the spline of minimums method (Shairsingh et al, 2018) for the non-background locations. The map published in 2023 was based on measurements conducted between 2016 and 2021, without accounting for temporal variations in UFP during this period. There were not enough consistent measurement series over this entire period of five years to determine reliable trends in UFP concentrations.

In indicative analyses of UFP-measurements performed by the RIVM, road traffic contributions were split into inner-city (and provincial) road traffic and highway traffic. The UFP contributed to inner-city traffic may well include some residential contributions. Given the limited amount of data, this could not be eliminated in the analysis. The analysis resulted in the fitted UFP-contribution from traffic shown in formula 1. Note that the measurements were performed with a minimum diameter of the particles (D_{50}) of 7 nm.

$$UFP_{urban}\ (n/cm3) = 160 \cdot NO_{Xurban} + 54 \cdot PM10_{urban}. \quad (1)$$

The conversion factors (160 and 54) are in units (n/cm3) / (ug/m^3). The data and the fit are shown in Figure 1.

Figure 1. Estimated UFP concentrations due to traffic contributions and some residential emission contributions from measurements at the C. Erzeijstraat against predicted UFP concentrations using a linear regression model (formula 1).

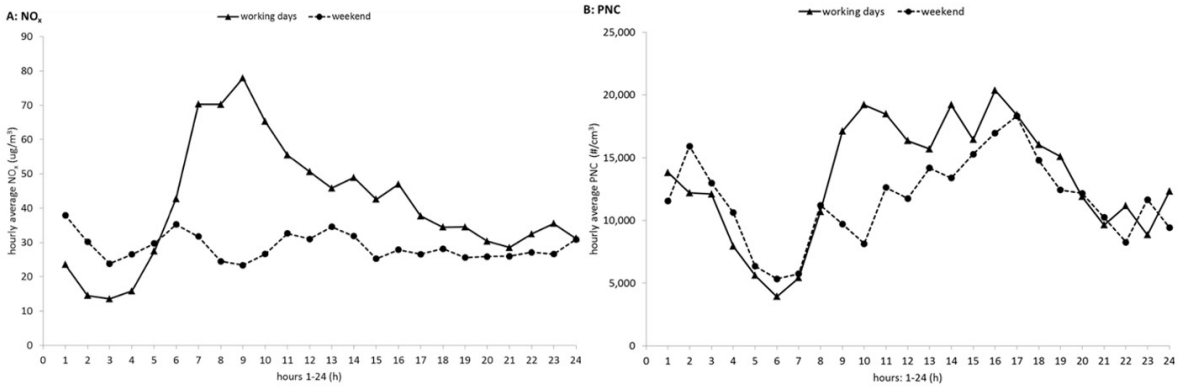


During the period of data collection, the PM_{10} contribution from road traffic was about 7% of that of NO_X. So, a rough approximation to relation (1) was:

$$UFP_{urban}\ (n/cm3) = 164 \cdot NO_{Xurban}. \quad (2)$$

Keuken et al. (2016) performed measurements of NO_X and UFP at an urban background and a traffic location in the city of Amsterdam; "Modelled and measured contributions to NO_X and PNC at the traffic location were used to derive real-world PN emission factors for average urban road traffic." The study found UFP to NO_X ratios in the order of 300-400 for measured difference between an urban traffic and a background location in Amsterdam. The hourly variations of the UFP and NO_X differed, as can be seen in figure 2, taken from Keuken *et al.*. It should be noted that the measurements performed by Keuken *et al*., had a lower limit for the particle diameters of only 4nm.

Figure 2. Diurnal variation in the increments for NO_X (left) and UFP (right) on working days and at the weekend at the traffic location in the study period. Taken from Keuken (2016).



Clearly, the numbers mentioned above (164 (this study) vs 300/400 (Keuken et al., 2016)) differ substantially. Changes in vehicle emissions may cause variations in emissions of UFP over time. The location of the measurements, especially related to the proximity to the exhaust of the vehicles, is also an important factor. In addition, differences in the lower particle diameter detection limits of the measurement devices (4 nm vs. 7 nm) must be considered. So, more, and more extensive, data of UFP emitted by cars is necessary.

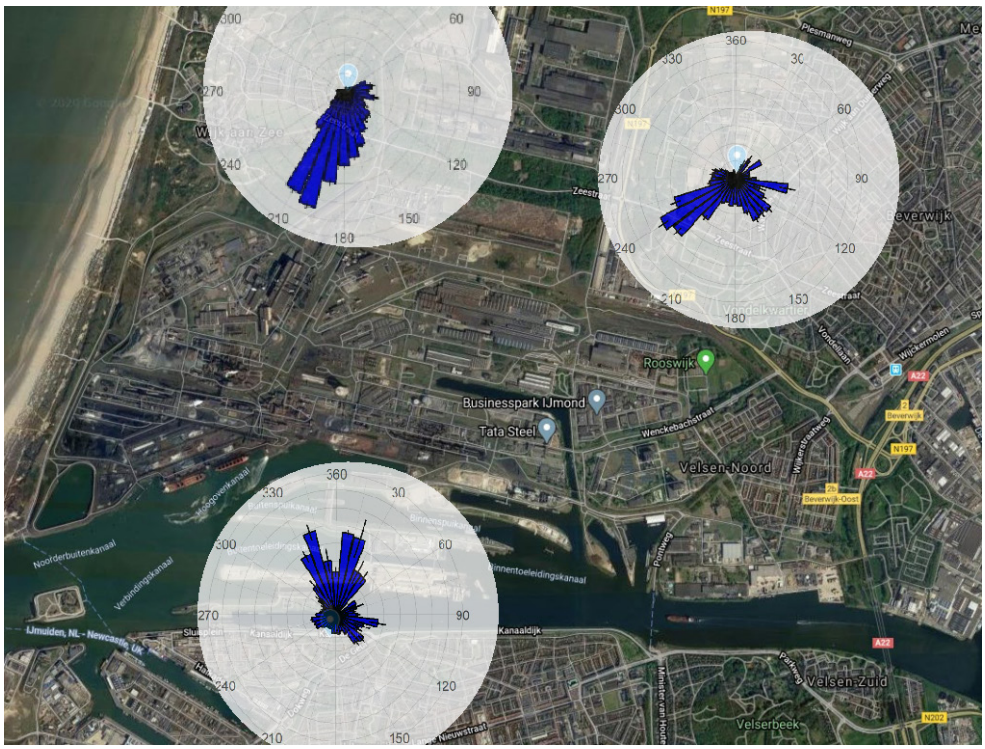
In the previous UFP-map, a general conversion of $UFP_{urban} \sim 200 \cdot NO_{Xurban}$ was assumed for urban contributions, keeping in mind that the uncertainty is substantial. For highways, a conversion factor of 675 was taken from the literature (Voogt et al., 2019), since the available datasets did not allow for a reliable extraction of the highway signal.

Aviation
For aviation, measurements from a single sampling location in Ookmeer were used. This location is situated about 5 km north of the Amsterdam Airport Schiphol. The wind rose in Figure 3 shows that UFP concentrations are clearly higher when the wind is coming from the direction of the airport. Since a representative background location was missing, background concentrations were estimated by selecting data for when the wind was not coming from the airport. Assuming that the measured concentrations are a superposition of background and airport contributions, the aviation contribution could be estimated. This resulted in a conversion factor of $UFP_{aviation} \sim 600 \cdot NO_{Xaviation}$

Industry
In the IJmond area, at the location of a large steel plant, the data at three temporary UFP sampling locations - Beverwijk, IJmuiden and Wijk Aan Zee - was used in an analysis of UFP in the region. The measurement results, in relation to wind direction, are shown in

Figure 3. The measurements in Wijk aan Zee (north location) and Beverwijk (east location) clearly mainly show a large contribution of UFP originating from the industrial complex. At the location IJmuiden (south) two dominant sources of UFP seem to be measured, one of which could be shipping and the other source is industrial.

Figure 3, wind dependent UFP concentrations of three different sampling locations in the IJmond area.



Here an estimate was made of the industry contributions to measured concentrations based on wind weightings, and the optimal model has been examined according to the same criteria as for other sectors. The correlations between UFP and other substances were determined at the three locations with the highest correlations found at Wijk aan Zee. From the correlations it was observed that the sulphur-containing substances SO_2 and H_2S strongly correlate with UFP. Given the specific steel manufacturing processes in the IJmond region, we do not consider the correlations found in the IJmond to be representative for other industrial locations.

Shipping

An indicative UFP map was constructed for shipping, just as for highway traffic, based on methodology outlined by González et al. (2011). In the present study, background concentrations are separated from shipping contributions for NO_X, SO2 and UFP. Here the following tentative model for shipping contributions to UFP has been drawn up:

$$UFP_{shipping} = 640 \cdot SO_{2,shipping} + 90 \cdot NO_{x,\ shipping} \quad (3)$$

Total UFP particle numbers of initial map

Using the different proxies for UFP, a total model was created, as presented on the website of the "Compendium voor de Leefomgeving", see https://www.clo.nl/indicatoren/nl062301-ultrafijnstof-in-de-lucht. This map assumed that

each individual model is drawn up on the basis of data in which one sectoral influence is isolated from all other influences. In practice, many uncertainties are involved when creating this empirical map of UFP. Despite these uncertainties we consider the results a good approximation of nationwide UFP levels.

2. Comparison of measurements with different particle sizes

The fixed measurements, performed by several monitoring networks in the Netherlands, all use equipment counting particles with minimum diameters of 7 nm. Given the abundance of very small particles in the exhaust of combustion engines, measurement results using either a 7 or a 10 nm cut-off diameter (D_{50}) can result in substantial differences. Because different instruments can yield different results, we carried out a campaign at the sampling location 'Breukelen' next to the A2 highway during three periods in the summer of 2023. One of the goals of this campaign was to gain experience with different types of instruments and to obtain an idea of the differences between them (caused not only by a different D_{50} but also, for example, by a different working fluid). To this end, we use measurements that were taken with several different devices. This location is part of the national air quality monitoring network (LML), operated by the RIVM. Measurements were taken with an EPC 3783 (RIVM, 7 nm) a WCPC 3789 (DCMR, this monitor has an adjustable lower limit, for the first 2 periods this is 7 nm and in the last 10 nm), a CPC 3750 (j.j. bos, 7 nm), a CPC 3750-CEN10 (TSI, 10 nm, installed after the first period) and the Nanoscan SMPS 3910 (RIVM, 10 nm), all manufactured by TSI. The tables in Annex A show the different results for the different periods. The rows marked with green are when the measurements are not impacted by the road (NE/SE wind), since the road is on the left side of the sampling location and countryside on the right side. We do not expect the difference in measured numbers of particles to be constant at all types of sampling locations and during all time periods. We do expect different ratios of measured results (by different machines) at different types of locations. For example, next to a busy road, there are more smaller particles, whereas the difference in particle size distribution will be limited at locations that are not close to (combustion) sources. The measurements performed at Breukelen show substantial differences between UFP measured with a 7 or 10 nm cut-off radius when the wind is from the west (highway traffic) and much less differences with winds from the east (roughly rural background).

Given the observed ratios between butanol-based measurements with cut-off diameters of 7 and 10 nm, we assume average ratios of particle numbers of roughly 110-120% (NE/SE, background) and 150% (SW/NW, highway).

3. A new indicative map for UFP in the Netherlands

Building upon previous work and new measurements, a new indicative map for UPF was created.

Measurements
In recent years, extensive measurements of UFP have been performed by the RIVM and IRAS, as part of the CLAIRE project (Hoek, 2025). Most of these measurements have been carried out at locations of volunteers from the citizen science community "SamenMeten". The measurements lasted up to two weeks at most locations, sometimes a bit longer, and were performed using DiSCmini handheld UFP-counters (see www.testo.com). The DiSCmini 's counted particles with diameters larger than 10 nm. For a large part of the project, continuous measurements were performed as a reference to calibrate the other measurements. These calibration measurements were performed at

the location of IRAS, near Utrecht. All hourly measurements were converted into long-term averages (over the whole length of the campaign) by RIVM. The procedure was as follows:

- For every week with measurements, the average value at the reference site was calculated and divided by the campaign average at the reference site, yielding a weekly scale factor:

  $$\text{scale factor}_{\text{period}} = \frac{\overline{C}_{\text{ref, period}}}{\overline{C}_{\text{ref, campaign}}} \qquad (4)$$

  The weekly factor was used to scale the measurements at the volunteer's site (during that week) to an estimated long-term average value at that location. For several weeks there was no calibration at the reference site. In those cases, an average calibration factor was applied.
- All hourly measurements at locations of volunteers in a specific week were scaled using the calibration factor derived for that specific week:

  $$C_{\text{hourly, calibrated}} = \frac{C_{\text{hourly}}}{\text{scale factor}_{\text{period}}} = C_{\text{hourly}} \cdot \frac{\overline{C}_{\text{ref, campaign}}}{\overline{C}_{\text{ref, period}}} \qquad (5)$$

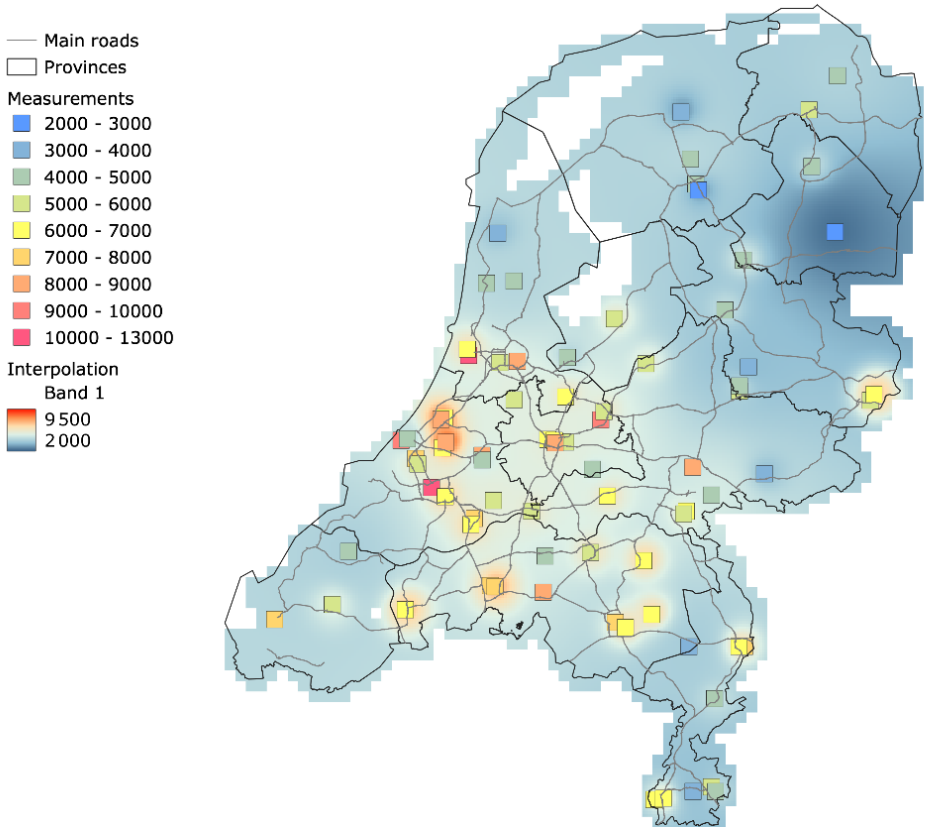
- For all measurement locations, the average values of the scaled hourly concentrations were calculated, resulting in estimated long-term UFP numbers for every location. Evidently, the uncertainty in the resulting long-term particle numbers is substantial.

Interpolated map

The long-term values were interpolated using Inverse Distance Weighting (IDW) employing the modified Shepard's method[1]. The spatial representativeness of measurements at rural background locations is assumed to be relatively large, at urban backgrounds the spatial representativity is smaller and measurements at traffic locations are assumed to be only representative for their direct surroundings. The data points and the results of the IDW interpolation are shown in Figure 4.

[1] https://en.wikipedia.org/wiki/Inverse_distance_weighting (Accessed on 22 September 2025)

Figure 4. Results of CLAIRE measurements (scaled to long-term values) and the IDW interpolation of these values. All results in n/cm3.



Using NO_X contributions as proxies for UFP

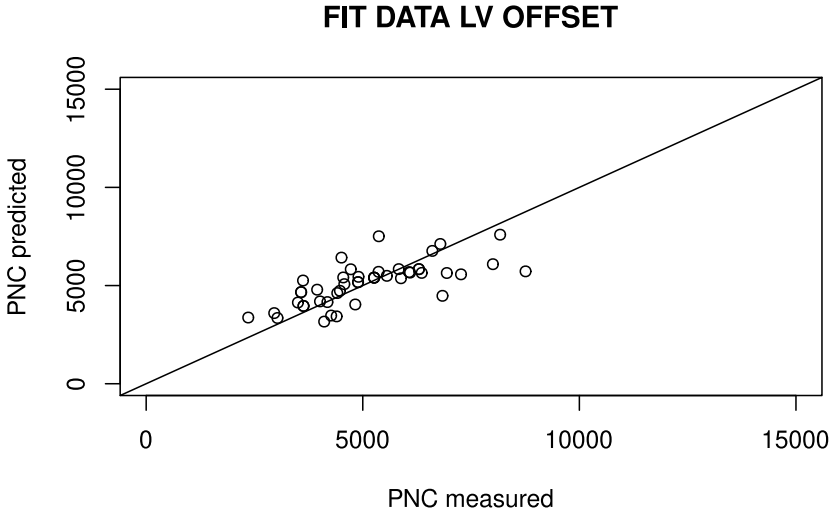
The interpolated UFP field, although giving an impression of the particle number in a large part of the country, is based on too few measurements to show the general structure of dominant sources of UFP, like the main roads. A next step is to use the generally assumed reasonably good relation between UFP and NO_X to estimate UFP over the whole country (see Voogt, 2023, for some remarks on this assumption). The Dutch background calculations (GCN) are performed separately for many substances and for many types of sources, see Mijnen-Visser, 2025. With these, it is possible to estimate separate relations between UFP and NO_X due to sources like main/secondary roads, sources abroad, shipping, aviation etcetera.

The measured UFP were used as input for a multi-linear fit of a combination of national NO_X concentration layers. I.e. for a number sources, (sufficiently) linear relations are assumed between the NO_X concentrations due to these sources and UFP particle numbers due to these sources. The values of various NO_X layers from the GCN of 2023 for the year 2022 were obtained from GCN at the locations of the UFP measurement points. This is done on the native resolution of GCN, 1x1 km2. So, a measuring location that lies in a particular gridcel of GCN is associated with the NO_X concentrations in that cell. Initial testing suggests that the layers "highways" (NOXHWN), "provincial roads" (NOXPROV), "abroad" (NOXBTL), "inland shipping" (NOXBV) and "sea shipping" (NOXZEE) are the most important. It should be kept in mind that a fit of the UFP with NO_X is only sensible if there are measurements at locations where the different layers have significant contributions.

The NO_X layers that will be fitted separately are first subtracted from the total NO_X, creating a "remainder" layer of the NO_X, indicated as "remainder". We then fit the measured particle numbers to the weighted sum of the remainer-layer and the separate layers, each with their own scaling factor of NO_X to UFP. For aviation, there are not enough measurements in the vicinity of Schiphol to make a sensible fit to the data. A visual inspection of the available NO_X contributions from aviation and the UFP measurements performed in 2017 (Voogt, 2023) suggests a conversion factor of roughly 800 n/cm3 per ug/m3 NO_X. Over the past few years, there was somewhat less aviation traffic than the years before that. Keeping in mind that the older UFP measurements were performed with EPCs counting particles with diameters larger than 7 nm and we are creating a map of particles with diameters larger than 10 nm, we assume a fixed conversion factor of 400 n/cm3 per ug/m3 NO_X. Furthermore, using a conversion factor of 400 also results in a slightly better fit of the scaled NO_X fields to the measured UFP. A conversion factor of 400 was applied to all industrial contributions, except the steel industry, for which a conversion factor of 1000 was used in order to be more consistent with the measurements performed by Weijers (2020). These numbers are highly indicative, as they rely on assumptions regarding the representativeness of measurements lasting only a few months. Furthermore, the conversion factors from NOx to particle numbers are very industry-specific.

A comparison of the original UFP and the fitted weighted sum of the converted NO_X layers is shown in Figure 5. There is a quite reasonable agreement between the measured and fitted numbers of particles.

Figure 5. Comparison of the measured UFP (X-axis) and the fitted weighted sum of the converted NO_X layers (Y-axis). All results in n/cm3.



The results of the fits are presented in Table 1, below.

Table 1. results of the fits of the different contribution layers

Coefficients:				
	Estimate	**Std.Error**	**p value**	**Layer**
(Intercept)	1068	825	0.20	Offset
remainer	118	88	0.19	Remainder of layers
NOXHWN	157	158	0.33	Highways
NOXPROV	311	291	0.29	Large other roads
NOXBTL	292	99	0.01	Contributions from abroad
NOXBV	271	217	0.22	Inland shipping
NOXZEE	153	264	0.56	Sea shipping

The fit, based on the data from the DiSCmini's and the NO_X from GCN, suggests a constant layer (Intercept) of roughly 1100 #/cm3 over the whole country, on top of the converted NO_X layers. Furthermore, the results indicate that the conversion of ug/m3 NO_X to UFP varies between the different layers. For the highway layer, the conversion factor of roughly 160 n/cm3 per ug/m3 NO_X is substantially lower than that found in earlier measurements of road contributions around the airport of Schiphol. This may be due to changes in the emissions of cars since 2017 and the fact that the older measurements used 7 nm as a lower particle diameter, versus 10 nm in the later measurements. The different layers of fitted UFP are shown in Figure 6 and Figure 7. As expected, the spatial structure of the major sources is quite clear to see. Note that all scales in the plots of the individual layers differ.

Figure 6. Maps of UFP fitted to different groups of sources. Shown are highways (top, left), provincial roads (top, right), sources abroad (bottom, left) and the layer with contributions from aviation (bottom, right). All results in n/cm3, note that the scales of the figures differ.

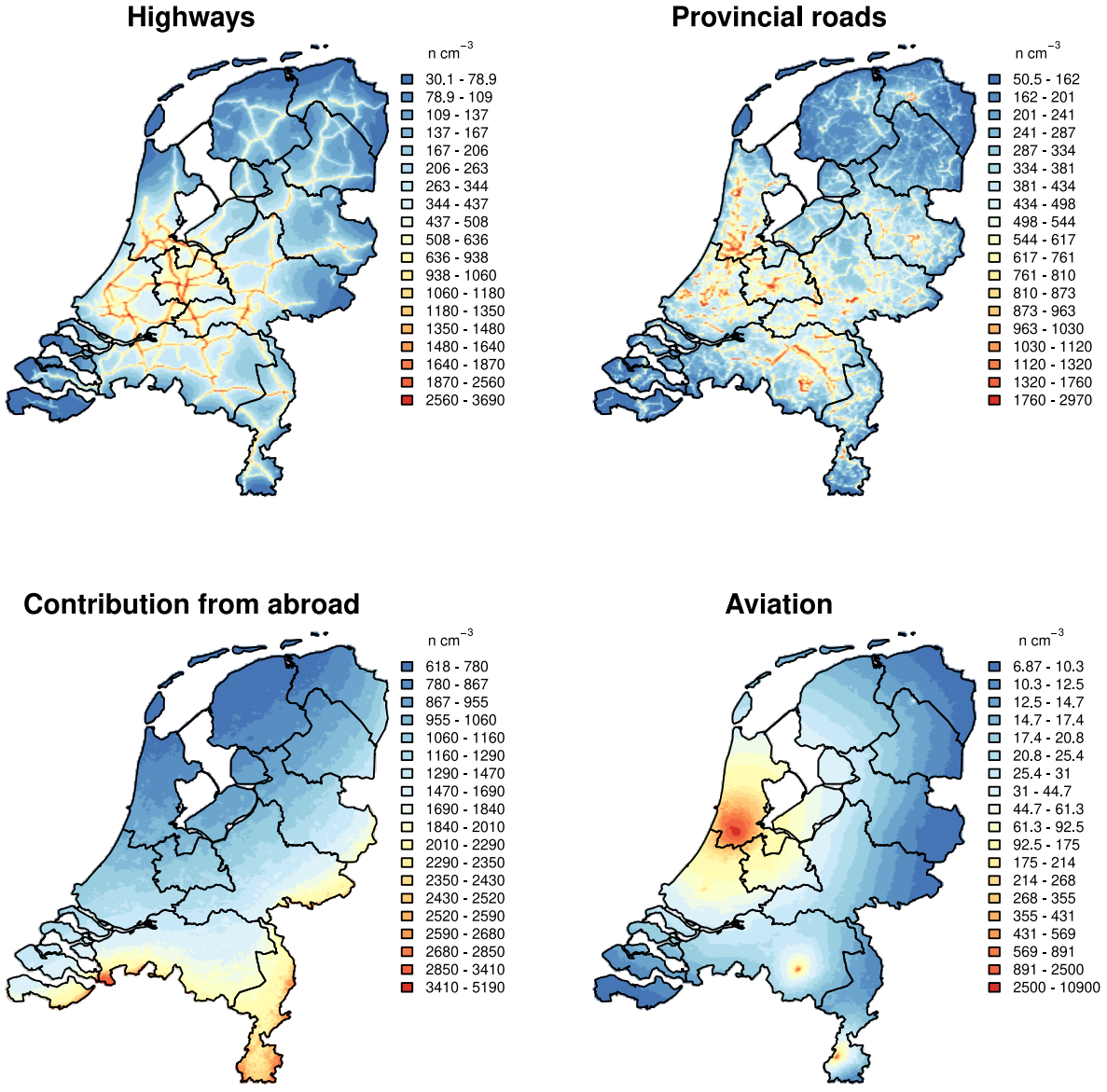
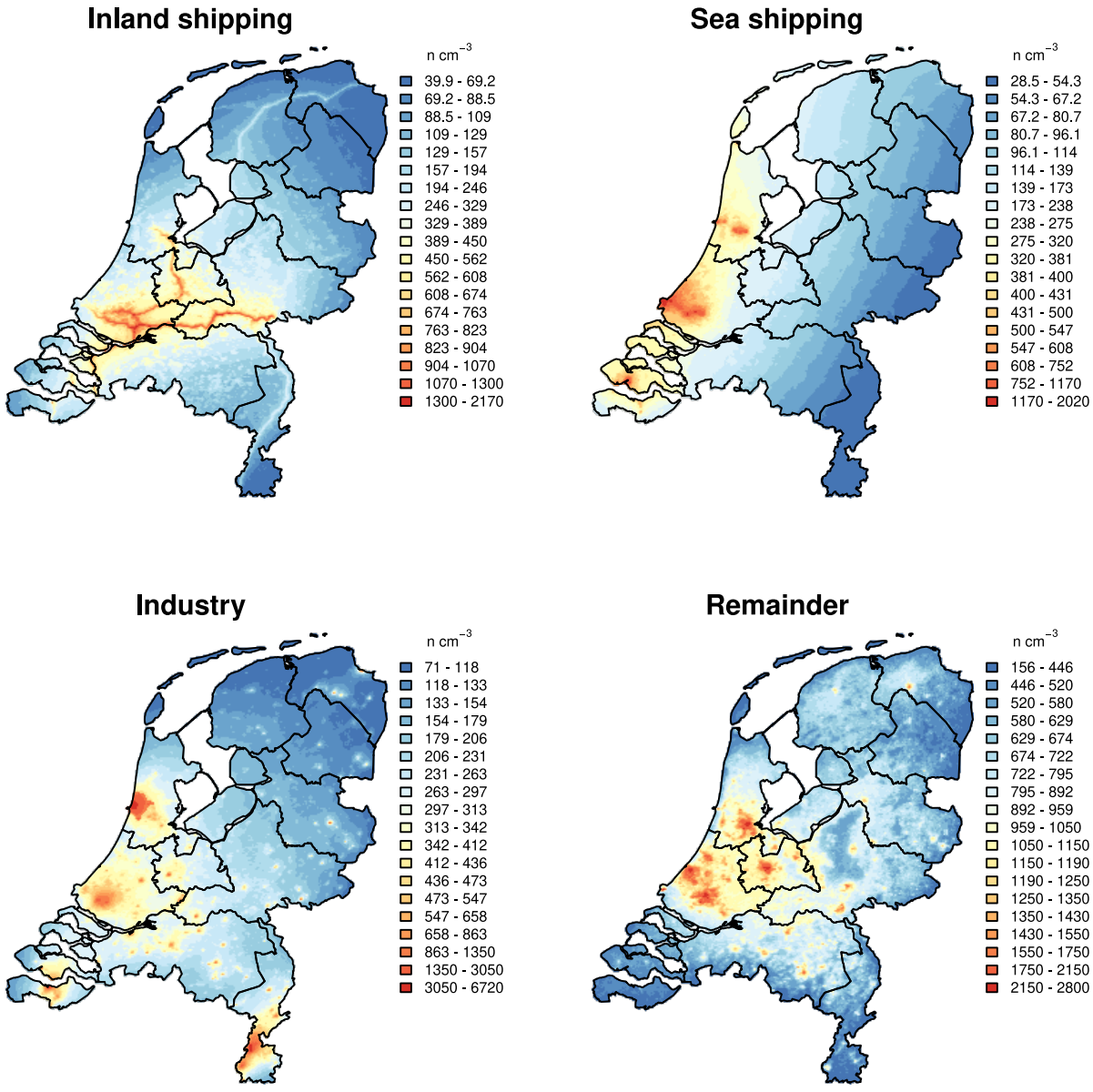


Figure 7. Maps of UFP fitted to different groups of sources. Shown are inland shipping (top, left), sea shipping (top, right), industry (middle row, left) remaining sources (middle row, right). All results in n/cm3, note that the scales of the individual figures differ



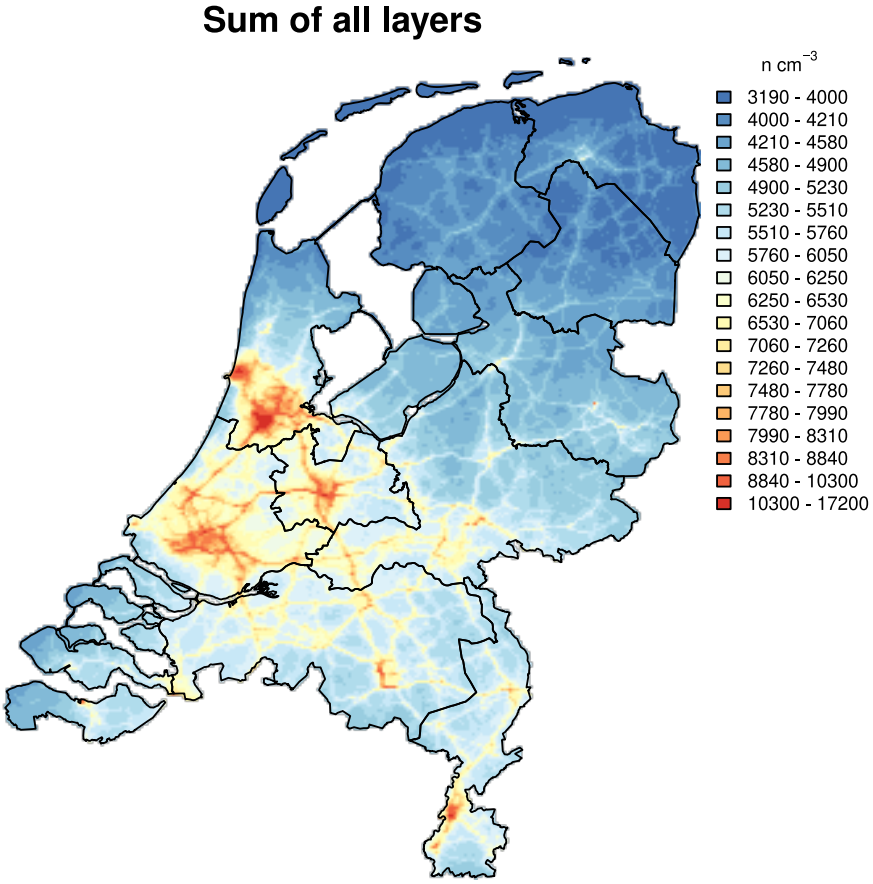
So far, the results of the measurements and the calibration measurements have not been compared to the results of long-term measurements using more professional equipment, the EPCs at the LML locations of Cabauw, Utrecht Griftpark and Utrecht Constant Erzeijstraat. The long-term average particle numbers (taken over the same period as the DISCmini measurements) measured at the rural and urban background locations of Cabauw and Utrecht Griftpark have been converted to estimated values for particles with a minimum radius of 10 nm by applying a factor of 1/1.10 (see section 2). These values have been compared to values in the map constructed from the measurements using the DiSCminis, see table 2 below.

Table 2. Comparison of EPC measurements and DISCmini-based map values at Utrecht-Griftpark and Cabauw.

	Utrecht-Griftpark	Cabauw-Wielsekade	
Measured UFP (7 nm)	7986	7998	
Measured UFP (10 nm) estimated	7260	7271	
Value of fitted map	6970	5934	
Measured-Interpolation	290	1337	
Average difference			814

The comparison suggests that the UFP based on the fit of the DiSCminis to the NO_X are roughly 800 below those derived from the EPCs. We therefore added 800 to the interpolated map, resulting in the final map shown in figure 8, below.

Figure 8. Combined map of UFP, fitted to different groups of sources, including an additional offset based on the comparison to the EPC's. All results in n/cm3.



Discussion and conclusion

In this note, we present a new empirical map of UFP concentrations in the Netherlands. Important differences with respect to the previous map are

- integration of nearly 100 short-term measurements,
- use of continuous reference data and
- use of several NO_X-based proxies.

Another noteworthy difference is that the previous map also used proxies such as SO_2, whereas the new map relies solely on NO_X as a proxy. This can result in differences in outcomes, for example in the industry layer.

The new map incorporates the estimated contributions from various source sectors such as road traffic, shipping, aviation, and industry. Sector-specific conversion factors were applied, generally ranging between 100 and 300 particles/cm³ per µg/m³ NO_X, with higher factors for aviation and the steel industry. To align the estimated particle number concentrations with long-term monitoring data, based on EPC measurements, an overall correction of 800 particles/cm³ was applied.

Despite these improvements, several substantial uncertainties remain in the current approach. These include the stability and accuracy of the DiSCmini measurements used at volunteer locations, the representativeness of the selected calibration sites, and the assumptions underlying the use of NO_X as a proxy for UFP.

The combination of data from instruments with different particle size cut-offs (D_{50}, 7 nm and 10 nm) introduces additional variability, particularly in traffic-influenced areas where the abundance of smaller particles is high. The 'remainer' layer in the model, representing sources not explicitly accounted for, could benefit from more representative measurements to further improve the fit. While the absolute calibration has a relatively limited effect on the spatial pattern of the map, expanding long-term monitoring at more locations in the national air quality network, currently ongoing, will be essential to improve the robustness and precision of future UFP maps. However, despite all the assumptions and caveats, the newly developed map provides an improved and, we expect, more realistic estimate of UFP levels across the Netherlands.

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Annex A Comparison of measurements in different periods

Measurements were carried out next to the highway in Breukelen using different equipment, across multiple periods. The columns "Nhour CPC's" and "Nhour Nanoscan" indicate the total number of hours measured with each device for a given wind direction during that period.

Period 1: 12th of July – 4th of August

wind sector	Nhour CPCs	Mean RIVM 3783-7nm [n/cm3]	Mean DCMR 3789-7nm [n/cm3]	Mean JJBos 3750-7nm [n/cm3]	Mean TSI 3750-10nm [n/cm3]	Mean 3910 Nanoscan 10 nm [n/cm3]	Nhour Nanoscan
NE	6	47,732	40,298	31,157	24,162	12,859	3
SE	54	25,044	20,813	18,938	14,148	10,805	31
SW	372	32,261	25,076	20,866	14,261	10,282	252
NW	100	41,691	33,408	27,193	19,007	11,099	24

Period 2: 4th of August- 16th of August

wind sector	Nhour CPCs	Mean of RIVM 3783-7nm [n/cm3]	Mean DCMR 3789-RaisedCutoff [n/cm3]	Mean JJBos 3750-7nm [n/cm3]	Mean TSI 3750-10nm [n/cm3]	Mean 3910 Nanoscan 10 nm [n/cm3]	Nhour Nanoscan
NE	11	8,904	10,233	10,157	8,866	8,712	15
SE	41	11,492	10,873	11,919	10,116	9,396	33
SW	100	30,739	22,399	22,429	16,123	13,091	81
NW	58	30,613	18,495	21,112	15,265	10,016	64

The following observations were made:

- Equipment with the same lower limit for the particle size sometimes differs substantially in the measured numbers of particles.
- The difference between equipment located in Breukelen with different lower limits is greater with a westerly wind. This is to be expected as there are more particles with diameters below 10 nm when the emissions on the highway next to the sampling location are transported to this location

The TSI 3750 provided by j.j. bos (7 nm) and the TSI 3750 provided by TSI (10 nm) have both measured in periods 1 and 2.

	Period 1				**Period 2**			
	Mean JJBos 3750-7nm [n/cm3]	Mean TSI 3750-10nm [n/cm3]	Diff	Ratio	Mean JJBos 3750-7nm [n/cm3]	Mean TSI 3750-10nm [n/cm3]	Diff	Ratio
NE	31,157	24,162	6,995	129%	10,157	8,866	1,291	115%
SE	18,938	14,148	4,790	134%	11,919	10,116	1,803	118%
SW	20,866	14,261	6,605	146%	22,429	16,123	6,306	139%
NW	27,193	19,007	8,186	143%	21,112	15,265	5,847	138%