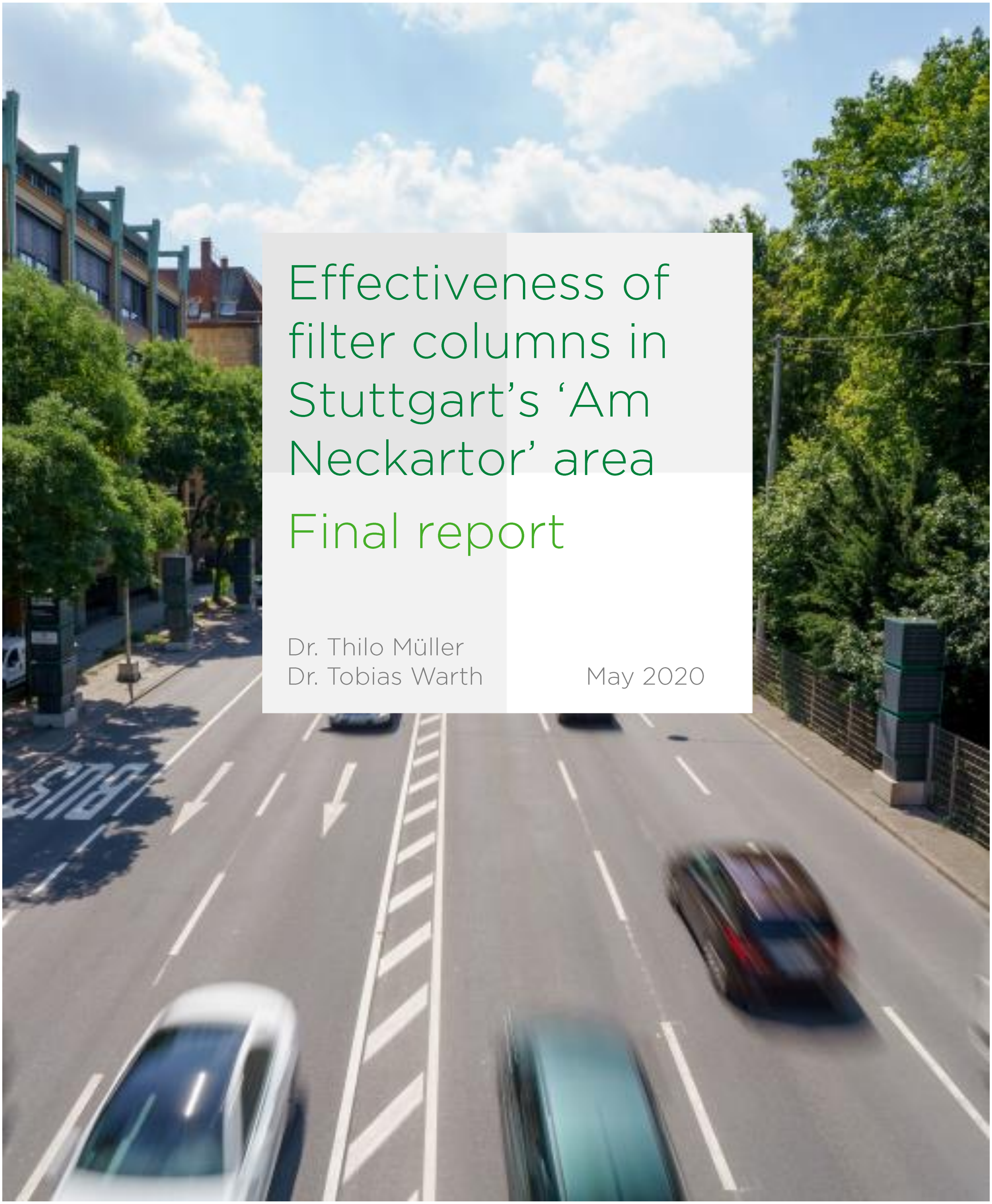

Effectiveness of filter columns in Stuttgart's 'Am Neckartor' area

Final report

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May 2020

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This final report was produced as part of a pilot project by the company MANN+HUMMEL.

Project period: May 2018–June 2020

The project was sponsored by the Baden-Württemberg Ministry of Transport and supported by the state capital Stuttgart.

Contents

1 Introduction

1.1 Starting point

In recent years there have been continuous improvements in air quality, but many cities still do not comply with the limit values. Currently, most exceedances are due to NO2 values being too high. At the start of the project in early 2018, however, the number of exceedance days for particulate matter (daily average PM10 > 50 µg/m^3) was above the limit of 35 per year at Stuttgart's Neckartor in particular.
A significant part of the level of pollution present in the local area is made up of regional background pollution. The reasons for this are environmental influences such as weather conditions, emissions from the energy sector and also agriculture. In addition, there is the urban background pollution due to municipal sources such as building sites, households and small consumers. Alongside the background pollution, there is also additional local pollution. This is frequently due to high volumes of traffic. In combination with a poor air exchange in particular, this can result in 'hotspots' with particularly polluted air (in relation to this see Figure 1.1). Stuttgart's 'Am Neckartor' area is one of these hotspots.

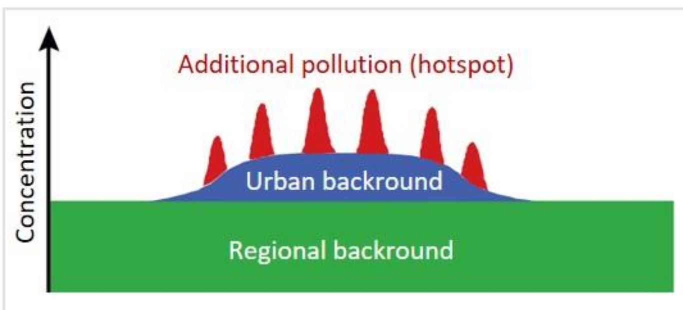


Figure 1.1 – Schematic representation of the background and additional pollution (Lenschow et al., 2001; LUBW 2015).

Comparing the measuring point at the Neckartor with the Bad Cannstatt urban background measuring point illustrates the significance of the share of emissions caused by traffic. Figure 1.2 shows the local increase at the hotspot in comparison with the urban background for PM_{10} and NO_2. In this diagram, the green area shows the share of pollutants caused by traffic.

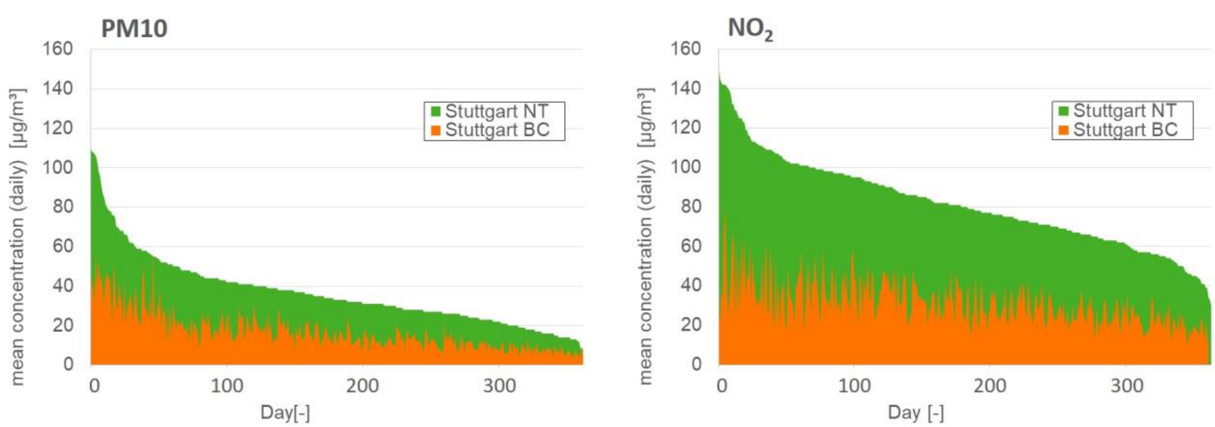


Figure 1.2 – Illustration of the share of emissions caused by traffic via a comparison of the 'Am Neckartor' (NT) and 'Bad Cannstatt' (BC) measurement points; daily averages sorted according to the level of the measurement (left: PM10, measurements 2016; right: NO2, measurements 2017). Data source: LUBW.

A more detailed breakdown of the causes of the pollution load at the Neckartor is provided by the diagrams in Figure 1.3 from the clean air plans for Stuttgart (LRP Stuttgart, 2018 and 2019).

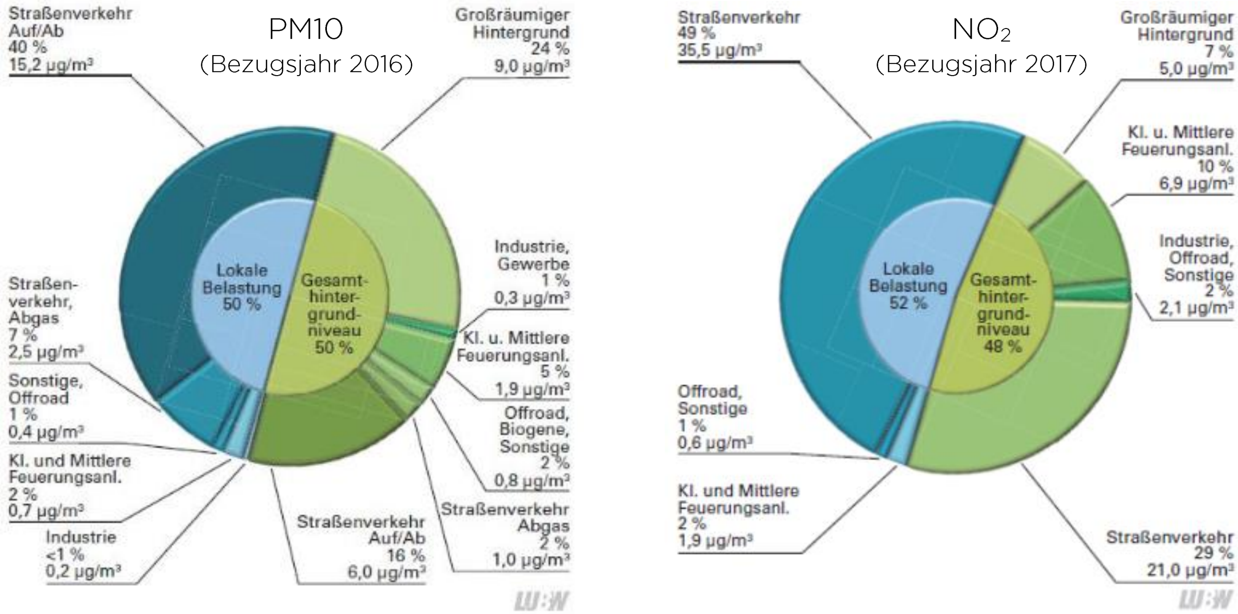


Figure 1.3 – Contributions from the various sources, which contribute to the total pollution at the Neckartor from the clean air plan for the city of Stuttgart (LRP Stuttgart, 2018 and 2019). Left: PM10 for the reference year 2016, right NO2 for the reference year 2017.

Based on the general problem of excessive pollutant concentrations at main inner-city transport axes with unfavourable air exchange conditions, MANN+HUMMEL has developed technologies and products for the filtration of particulates as well as a second stage involving the reduction of the nitrogen dioxide concentrations.

2 Project phases and aims of the filter system operation

As part of a pilot project by MANN+HUMMEL, sponsored by the Baden-Württemberg Ministry of Transport and supported by the state capital Stuttgart, the intention was to set up filter columns to reduce particulates and NO2 at Stuttgart’s Neckartor. The aim was to reduce the local increase in pollutant concentration at this hotspot and to provide general evidence of the effectiveness of the measure.

The course of the project can be broken down into three phases, each with different objectives. The temporal progression of the construction and testing work for the individual phases are summarised in Figures 2.1 and 2.2. During the planning of the project in early 2018, the focus was initially on reducing the particulate pollution at Stuttgart’s Neckartor. The subsequently developed filter columns were installed and put into operation from November 2018 (phase I). The full system capacity was available from 18/12/2018. During the New Year period and into January, extremely rainy weather conditions caused the particulate pollution to be so low that no impact evaluations were possible. Suitable conditions were only present from mid-January, meaning that it was possible to start measurements.

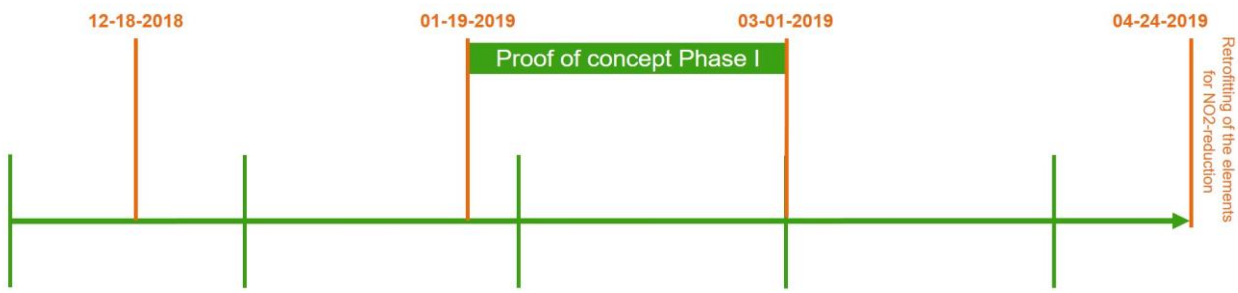


Figure 2.1 – Process for project phase I.

As a result of the ban on Euro IV diesel vehicles driving in the Stuttgart city area coming into force (01/01/2019), the public focus shifted onto the NO2 concentration at Stuttgart’s Neckartor. As sufficient proof of the effectiveness of the purely particulate filter systems had already been provided in the first quarter of 2019 (in relation to this see section 6.1.1), the decision was made to convert the filter systems to specially developed activated carbon combi filter elements.

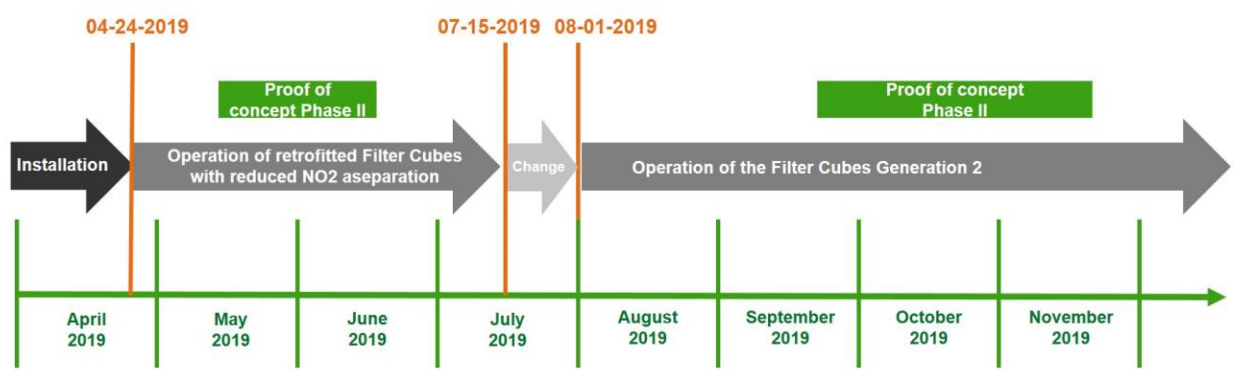


Figure 2.2 – Process for project phases II and III.

Model calculations carried out in the run up to the conversion demonstrated the need to increase the capacity of the systems and to make the filter elements bigger in order to achieve the desired reduction in NO2 (see section 4.1.2). As a result, the filter systems themselves and their locations needed to be completely revised in order to optimise the NO2 reduction. However, before this extensive structural work was carried out, in April 2019 as an initial transitional measure the existing filter systems were converted to the new combi filter medium (phase II) in order to examine the fundamental feasibility of NO2 reduction experimentally with this technology that had never before been used in the open air. In parallel, MANN+HUMMEL started further development of appropriate higher-performance filter columns. Following the positive completion of these testing activities (see section 6.1.2), the second generation of the filter columns with increased filtration performance was installed in August 2019 (phase III) and impact evaluations were carried out (section 6.1.3).

Sections 2.1 to 2.3 below describe the three project phases, as well as the focus and objective of the impact evaluations. The technical data for generations 1 and 2 are examined in section 3.

2.1 Phase I: Reduction in particulate pollution (PM_{10})

Before the structural implementation, the potential for reduction was investigated by an independent simulation agency (Ingenieurbüro Rau, Heilbronn) and a productive system arrangement to optimise the performance level was identified. This considered the city topography, meteorology, background pollution, local sources (traffic in particular) as well as the installed filter capacity. Section 4.3 shows the reduction potentials for particulate matter (PM10) forecast in these simulations under meteorological conditions typical for the location. The aim of the first project phase was to provide measured evidence of the reduction effect of 10–15% forecast in advance by the simulations in relation to particulate matter of size PM10 at the ‘Am Neckartor’ measuring station (see section 4.3.3). In addition to the percentage reduction effect, confirmation also needed to be provided that the installation of the particulate filter systems would contribute to reducing the number of exceedance days for particulates (days with average PM10 concentrations >50 $\mu g/m^3$) to below the legally permitted number of 35 days per year. Evidence of this effect was provided on the basis of a developed test method, which is described in detail in section 5.1.

2.1.1 Structural implementation

The structural implementation was carried out in close cooperation with the city of Stuttgart, the Baden-Württemberg Ministry of Transport and the civil engineering department of the city of Stuttgart. In addition to the findings from the simulations, the location selection for the Filter Cubes also considered the necessary structural and (traffic) safety guidelines.

A supporting foundation must be built before a Filter Cube can be set up in a publicly accessible space. The foundation was dimensioned and designed in advance by a structural engineer. Both installation foundations and countersunk foundations are used. Figure 2.3 shows the different boundary conditions and implementation for the safe installation of the foundations.

Figure 2.3 – Boundary conditions when laying the foundations.

Figure 2.4 – Installation of the foundations.

Figure 2.5 – View of the western section of the pilot project following installation of the Filter Cubes (generation 1).

2.1.2 System arrangement at the Neckartor

According to the layout supported by the simulation results, in November 2018 a total of 17 Filter Cube III were installed in the relevant section of road. Figure 2.5 shows the area in front of Stuttgart District Court looking towards the city after installation. Figure 2.6 provides an overview of the locations of the 17 Filter Cubes implemented in phase I of the pilot project.

Figure 2.6 – Arrangement of the generation 1 Filter Cubes as part of project phase I and II.

2.2 Phase II: Functional expansion of the systems (NO_2 reduction)

The functionality of the Filter Cubes was developed further in two stages. In project phase II, it was possible to use initial prototypes of specially developed combi filter media in order to additionally reduce the NO2 concentration at Stuttgart's Neckartor. The replacement of the filter elements and the associated functional expansion was carried out in April 2019. In order to maximise the reduction effect in phase II, the capacity reserves of the generation 1 Filter Cubes were utilised in full. This meant that the volumetric flow rate could be increased by 26%. The final capacity expansion was carried out later with the use of generation 2 in phase III. The aim of the impact evaluation in phase II was to present an initial effectiveness confirmed by measurements and not based on theoretical considerations for NO2 reduction in the field (section 6.1.2).

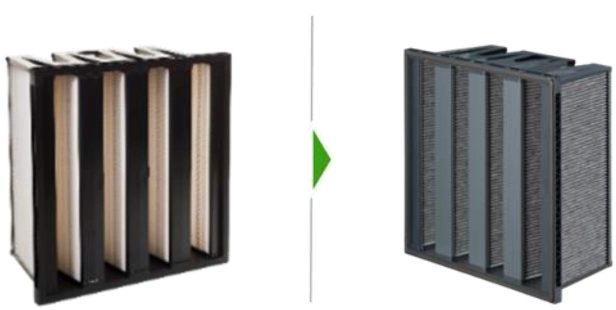


Figure 2.7 – Conversion of the Filter Cubes with combi filter elements (left).

2.3 Phase III: Final system capacity expansion stage with focus on NO_2

In the last phase of the pilot project, the existing generation 1 Filter Cubes were replaced with higher-performance generation 2 models. In addition, six more Filter Cubes were installed. These are highlighted in colour in Figure 2.8.

Figure 2.8 – Arrangement of the generation 2 Filter Cubes as part of project phase III (green: new locations).

Figure 2.9 – View of the eastern section of the pilot project following installation of the Filter Cubes (generation 2).

The final expansion stage of the installation therefore included 22 Filter Cube III and one Filter Cube II. The increased air flow rate was necessary in order to achieve the required pollutant reduction according to the design. The aim of this phase was to provide evidence of the reduction effect of 8.5% identified in the simulation-based forecast (see section 4.4) in the area of the LUBW measuring station and >10% in the area near the building.

The structural expansion in comparison with phase I was again carried out in close cooperation with the city of Stuttgart, the Baden-Württemberg Ministry of Transport and the civil engineering department of the city of Stuttgart. In addition to the findings from the simulations, the location selection for the six additional Filter Cubes again considered the necessary structural and (traffic) safety guidelines. The locations from phases I and II were retained and the existing foundations were reused. Appropriate new foundations were created for the six additional Filter Cubes and the entire electrical infrastructure was adjusted to the higher-performance Filter Cubes (400 VAC instead of 230 VAC in phase I, in relation to this see also the performance data in section 3).

3 Technical description of the systems

Figure 3.1 shows the modular structure of the Filter Cube systems. Each cube-shaped 'Cube' unit has the same function, meaning that the different variants can be used according to the performance required and also depending on the space available. The polluted outside air is sucked in through a filter unit with the help of a fan, and during this process the particulates and, depending on the design of the filter element, gaseous pollutants are removed from the air. The outlet side is opposite the intake side. The column should preferably be positioned so that the intake side faces the polluted environment (the road).

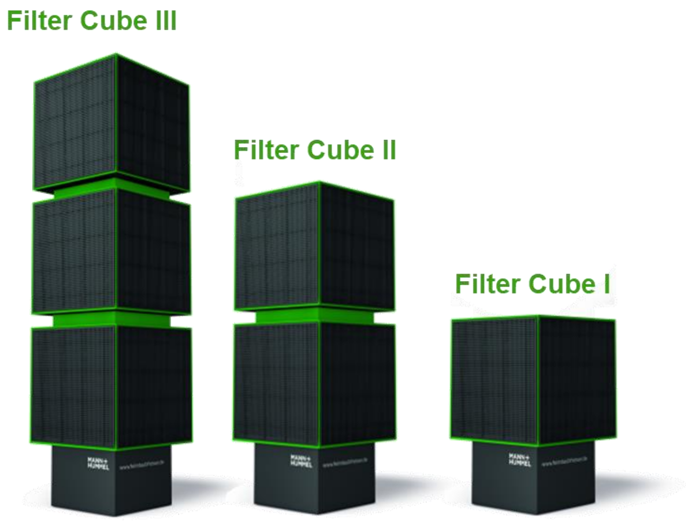


Figure 3.1 – Modular design of the Filter Cubes.

3.1 Filter Cube – generation 1 (focus: particulate reduction)

As previously described in detail in section 2, 17 Filter Cube III were used in phase I of the pilot project. The locations in the project are shown in Figure 2.6.

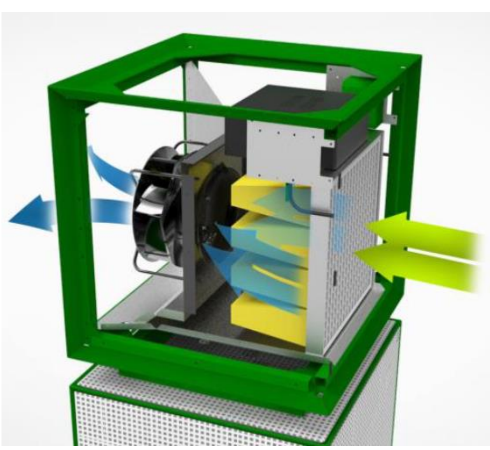


Figure 3.2 – Structure and function of a generation 1 Cube.

The base houses the electronics required to operate the system. The control unit is located in the central one of the three Cubes. The system has a cloud connection, meaning that it can be operated via internal and external sensors and control factors as needed. This allows operation to be as energy-efficient as possible. The data for all systems is logged, processed and analysed via the cloud connection.

MANN+HUMMEL has the technical expertise to develop filter media and elements for maximum efficiency based on simulations, and then to use them for the specific application. The filter elements are designed so that optimum dust separation and dust capacity is achieved with the lowest possible pressure differential, and therefore a very low energy use throughout the entire service period. The filter elements usually have to be replaced twice per year. The interval should be reduced in the event of particularly high average particulate pollution (»100 µg/m³). In phase II of the pilot project, the pure particulate filter medium in the filter element used was replaced with an activated carbon combi filter medium (see Figure 2.7).

The performance data for the generation 1 Filter Cube is shown in Table 3.1, and other technical data can be found in Table 3.2.

Table 3.1 – Generation 1 Filter Cube performance data.

Volumetric air flow (operating point)	3,400 m³/h
Rated voltage, fan	230 VAC
Electrical power (operating point/max.)	approx. 300/500 W
Cube weight	approx. 300 kg
Weight of a column (Filter Cube III)	approx. 1,000 kg

Table 3.2 – Additional technical data for the particulate filter element.

Usage limits	
Continuous operating temperature	<75°C
Recommended/maximum final differential pressure	450 Pa/800 Pa
Permitted relative humidity	<100%
Filter material	
Glass fibres	
Separation efficiency as per ISO 16890	
ePM_{10}	>87%
$ePM_{2.5}$	>62%

3.2 Filter Cube – generation 2 (particulate and NO_2 reduction)

Through the further development of the systems, the generation 2 Filter Cubes can be used to separate both particulate matter and NO2 from the surroundings. This generation was used from phase III of the project. Further design developments within the Cubes allow for the operating volumetric flow of a Cube to be increased from 3,400 m³/h to 4,833 m³/h. At the same time, the changes ensure a sufficient service life of the combi filter elements. In addition, thanks to the lack of use of a plastic frame (due to an integrated incorporation of the filter panel directly in the Cube), valuable resources are preserved (Figure 3.3). The modular structure of the Filter Cubes is still retained. In addition to the electronics, however, the base now also houses the control unit, because all of the space within a Cube is used for filtration.

Figure 3.3 – Use of several filter panels per Cube without plastic frame (left) to preserve resources (from generation 2); service access (right).

Figure 3.5 – Structure and function of the Filter Cubes (generation 2).

In the filter medium developed especially for this purpose and produced in Germany, the NO2 separation function is carried out by an activated carbon layer. The selection of the ideal activated carbon, the design of the layer thickness as well as the filtration layer for the separation of particulate matter are core competences of MANN+HUMMEL. The 'combi' filter medium is able to decisively reduce both the particulate and the NO2 concentration in outdoor air conditions and, when doing so, allow for the maximum service life. Figure 3.6 provides a schematic representation of the structure of this kind of filter medium.

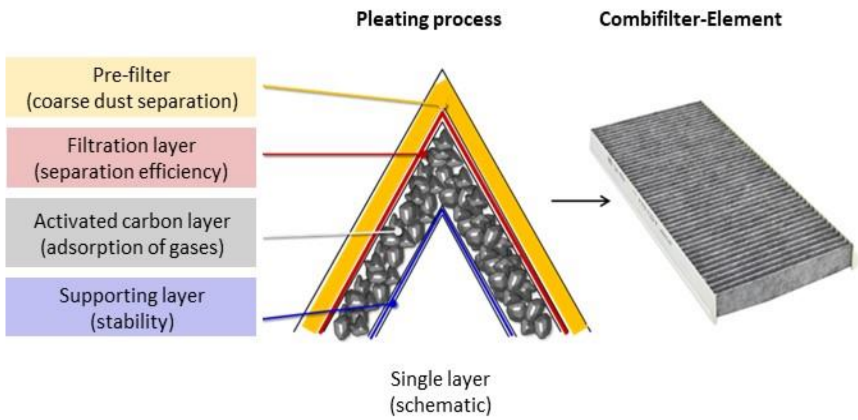


Figure 3.6 – Filter media structure of activated carbon media.

The performance data for the generation 2 Filter Cube is shown in Table 3.3, and other technical data can be found in Table 3.4.

Table 3 3 – Generation 1 Filter Cube performance data.

Volumetric air flow (operating point)	4833 m^3/h
Rated voltage, fan	400 VAC
Electrical power (operating point/max.)	approx. 500/950 W
Cube weight	approx. 300 kg
Weight of a column (Filter Cube III)	approx. 1,000 kg

Table 3.4 – Additional technical data for the combi filter element.

Usage limits	
Continuous operating temperature	-40°C to +80°C
Recommended/maximum final differential pressure	+50 Pa/+200 Pa
Permitted relative humidity	Recommended 65% RH; max. 95% RH

Separation efficiency	
NO_2	80% (average separation according to design)
PM_{10}	80%
$PM_{2.5}$	50%

It is assumed that the combi filter elements need to be replaced roughly every 30 days during the pilot project in order to achieve an average NO2 separation efficiency of 80%. When new, the value is >90% and this decreases as they become more contaminated. The design and the simulations were based on an 80% average separation efficiency.

Meteorological data as well as data on air quality can be used, among other things, for regulation and needs-based control of the system. This can minimise the energy required. In relation to this, see also Section 6.4. The data for all columns is processed, saved and analysed via a Cloud connection.

4 Forecast pollutant reduction

In a first step, initially there was basic consideration of the potential efficiency of filter systems on public roads. The aim here was to estimate an initial scale for the potential reduction and a basic design for the project (section 4.1). Further simulations were intended to be carried out to refine this prediction. The simulated predictions then needed to be confirmed with measurements (section 6).

MANN+HUMMEL has extensive expertise in the area of computer-supported flow and particle simulation. The experience was also used in the area of developing the Filter Cubes and the layout for the pilot project. The product and layout data obtained via this process was given to an independent consultant (Ingenieurbüro Rau, Heilbronn) with the aim of determining the potential of the Filter Cubes to reduce pollution at the Neckartor. In its roughly 30 years working as a consultant, Ingenieurbüro Rau has helped authorities, courts and companies in matters relating to air purification and the urban climate. It has particular experience in numerical and physical micro-scale modelling. During the numerical modelling, among other things it uses the 'MISKAM' (forecast micro-scale flow and diffusion model).

The basis for the emissions calculation is the "Handbuch für Emissionsfaktoren des Straßenverkehrs – HBEFA" [Manual of emissions factors for road traffic] in version 3.3 (HBEFA, 2017). The emissions factors provided there indicate what quantity of pollutants are emitted per vehicle and for the distance travelled. In the present case, the emissions factors for the vehicle categories car, light goods vehicle and heavy goods vehicle were used. When determining the emissions, the specifications of VDI [Association of German Engineers] guideline 3782, sheet 7 (determining car emissions) were also considered. The emissions factors for NOX and NO2 are exclusively 'engine-related'.

4.1 Consideration of the reduction effect via mass balance calculations

A comparatively quick option for estimating the effectiveness of the Filter Cubes is to consider the results for the pollution situation by looking at the sources and reduction in the balance area, i.e. in this case the area of the 'Am Neckartor' road section in the area of the LUBW measuring point. Below is a consideration firstly of the result for phase I (PM10 reduction) and then for phase III (NO2 reduction).

4.1.1 PM_{10} reduction for phase I

To estimate the PM10 reduction effect, first the source, i.e. the traffic-related proportion of the PM10 concentration is determined. The traffic data and the emissions factors for the individual vehicle types (HBEFA, 2017) result in a value of 104 g/(km h) for the road section in the pilot project. This is contrasted with the filter columns as a PM10 sink. In order to determine the mass separated by the Filter Cubes, in this consideration the permitted limit value for PM10 of 50 µg/m³ (daily average at the position of the measuring station) is used. Due to the proximity of the Filter Cubes to the source (road), a value increased by a factor of 1.5 is used for the PM10 raw gas concentration. The simulation results (see section 4.3) confirm this assumption. If there are 60 Filter Cubes per kilometre (roughly corresponds to the use of 17 filter columns in phase I of the project) with a separation efficiency of 80% and a flow rate of 10,000 m³/h for each Filter Cube III, this results in a reduction of traffic-related particulate matter emission of approx. 35%. If the particulate matter quantity is transferred to purely car emissions, the reduction is 49% for cars.

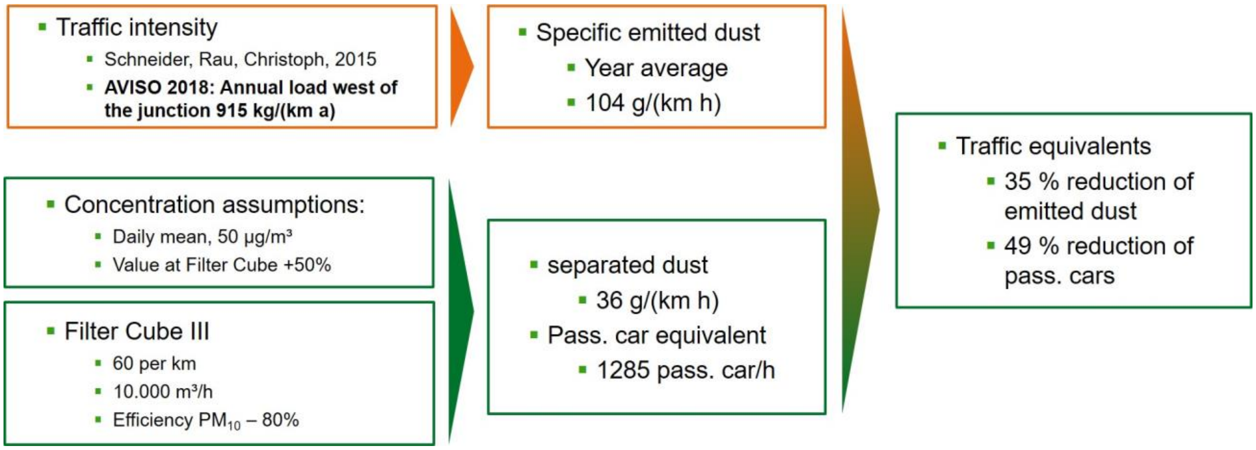


Figure 4.1 – Schematic representation of the balance calculation for PM10 at the Neckartor.

4.1.2 NO_2 reduction for phase III

In a similar way to the balance calculation for the PM10 reduction, an estimate can also be carried out for the NO2 reduction. Due to the complex chemical processes in the atmospheric chemistry, in particular due to the equilibrium reaction of nitrogen monoxide (NO) with ozone (O3) to form NO2, however, the considerations are more complicated in this case. It is therefore necessary to differentiate between direct vehicle emissions, i.e. the NO2 mass emitted directly from the exhaust, and the traffic-related additional pollution in the area of the road due to conversion processes (NO2 total). Based on assumptions regarding the traffic data for 2019, the emission factors for NOx, NO2 and NO (HBEFA, 2017) can be used to determine the source value for the balance calculation. This is contrasted with the NO2 sink provided by the Filter Cubes. An increase in the number of columns at the Neckartor from 17 to 23 (corresponds to roughly 92 columns per kilometre), an increase in the volumetric flow to 14,500 m^3/h and a separation efficiency of 80% results in a reduction in the NO2 pollution in relation to traffic of 35% (direct) or 21% (total).

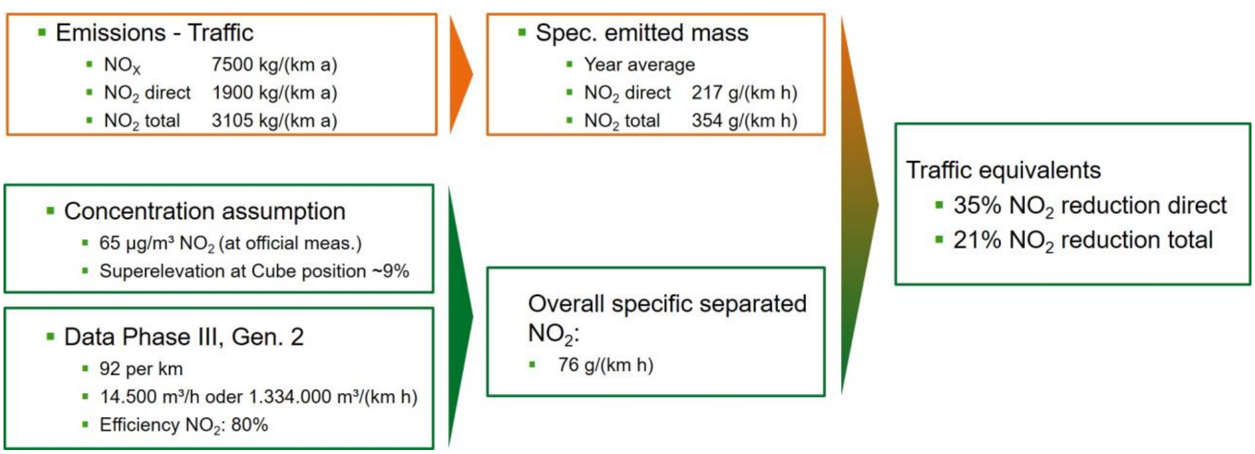


Figure 4.2 – Schematic representation of the balance calculation for NO2.

This balancing process uses the average concentration at the columns as determined in the simulation. This differs considerably less from the concentration at the measuring point (+9%) than was the case for the PM10 concentration. This is caused by the different diffusion processes as well as the additional column locations. The greater the concentration at the columns and therefore the closer the filter columns can be positioned to the additional source 'traffic', the higher the traffic equivalent reduction.

4.2 The MISKAM model system

MISKAM was developed at the University of Mainz and is used both for research purposes and as part of surveying work (Eichhorn J., 1989, 2011). MISKAM is based on the basic fundamental equations of fluid mechanics. The wind speed field is calculated via the numerical solution of the conservation equations for momentum, mass and energy. A standard-k,ε model is used as a turbulence model. Individual buildings and obstacles can therefore be explicitly solved in terms of their shape. The MISKAM model system includes a wind field model for small-scale forecasting of the wind dispersion, as well as an Euler dispersion model for calculating pollutant concentrations in the area of individual buildings as well as in roads and right through to districts of a city. MISKAM is an episode model. It calculates stationary three-dimensional flow and dispersion fields, as they occur in the dynamic equilibrium in the structural (roughness and development structure) and meteorological (inflow profile) boundary conditions. Transient calculations in consideration of time-dependent boundary conditions, such as e.g. energy flows at the ground or on building shells, and therefore the simulation of thermal wind systems without any dynamic drive are therefore not possible.

Comparisons with measurement results from wind tunnels show that flows around and over buildings and building complexes, the formation of return flow zones and the front vortex area can all be realistically depicted using MISKAM (Rau (2000), Röckle et al. (1995)). The use of the modelling system has therefore been standard for surveying purposes for many years.

4.3 MISKAM simulations to determine the PM_{10} reduction

In order to be able to calculate the reduction effect of the Filter Cubes, it is first necessary to depict the pollution present in the study area realistically in the model. The result of the calculations with MISKAM are the additional emission loads caused by emissions on the roads in the test area. The total emissions load is determined by overlaying the calculated additional pollution with the background pollution. The background pollution is caused by the other local (municipal) and regional emissions sources and transport of pollutants over a wide area.

This total pollution in the area without influence from the Filter Cubes forms what is known as the zero case. The boundary conditions and model assumptions presented below were used in order to determine this zero case.

4.3.1 Model boundary conditions

The inflow parallel to the road (222°, south westerly wind direction; 1 m/s 10 m above ground) was selected for a simulative consideration as a representative, frequently occurring wind situation (weak, low exchange) that is critical for high PM10 pollution. The basis used for the traffic-induced PM10 source was the average daily traffic figures for 2018 (DTV, according to traffic lane). The background pollution was selected so that the limit value for the daily average pollution (50 $\mu g/m^3$) is reached at the measuring station and was therefore 39.5 $\mu g/m^3$.

4.3.2 Model implementation and limits

Some simplifying assumptions need to be made in order to implement the model. This modelling is therefore an approximation. In terms of meteorology and pollutant load, the wind direction and wind speed vary throughout the day. Both the background pollution and the additional pollution due to traffic also vary throughout the day. Model assumptions also need to be made on the technical side. For example, MISKAM cannot precisely reflect the one-sided intake of the filter systems and the targeted blowing of the purified air flow into the road area in terms of dynamics, which would be possible when using a traditional CFD simulation. It is therefore not possible to depict the dynamics and an appropriate 'throwing distance' for the purified road air. As a substitute, a source with purified air is therefore used in the computational cell on the outlet side in the model The amount of the source and the resulting intervention of purified air corresponds to the designed volumetric flow of the Filter Cube in the relevant generation. The further dispersion of the clean air is also purely related to the meteorological situation. The wind-related inflow of the Filter Cubes is a traditional (square) cylinder circulation. Depending on the wind direction and strength, high and low pressure zones form, which may mainly have effects on the volumetric flow brought forward and therefore the effectiveness. However, in real terms the influence is assessed as being low and the volumetric flow is assumed to be constant. In addition, the vehicles in the road area have an effect on wind pressure and turbulence (and therefore on the dispersion of the purified air), but this cannot be presented in detail using the model.

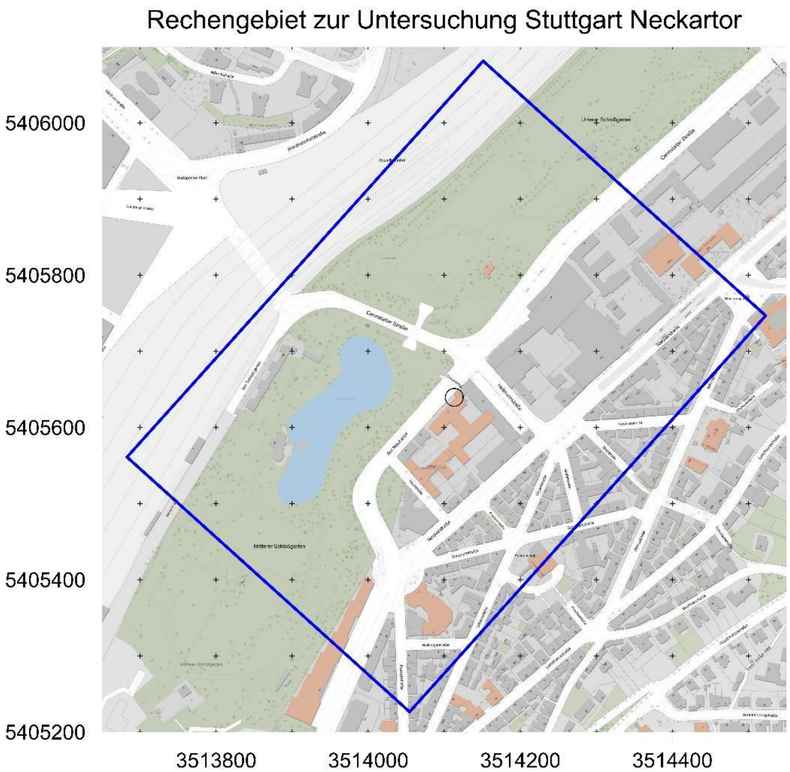


Figure 4.3 – Representation of the model area for the simulation.

Figure 4.3 shows the size (630 x 530 m^2) of the simulation area. This is based on cadastral maps and 3D building models. These are three-dimensional digital models of buildings, which are used in combination with a digital terrain model to describe the earth's surface. Various levels of detail (LoD) are used in the presentation. LoD1 was used for the simulations. In the relevant core area, a resolution of 1x1 m^2 in the surface and 0.4 to 3.2 m in the vertical is used for the flow computational grid.

4.3.3 Simulation-based reduction effect for PM_{10}

The 17 Filter Cubes in project phase I each had an extraction capacity of 10,000 m^3/h at a height of 3.6 m. At 1.0 x 1.0 m^2, the base corresponds precisely to the resolution of a computational cell. In the simulation, the extraction efficiency was assumed to be 100% for simplified PM10. In accordance with ISO 16890, the filter elements have an extraction efficiency of >87%, whereby this value increases further due to the pollution. In principle, in accordance with the arrangement and capacity implemented in phase I of the pilot project, the Filter Cubes can reduce the PM10 pollution in the vicinity of the columns. Greater reductions in pollution in front of buildings are achieved using an appropriately increased column density. If they are not suitably positioned, the effect of the individual columns may be less than in this estimate as they may influence each other.

The percentage reduction during operation of the Filter Cubes in comparison with the zero case is shown in Figure 4.4. The reduction effect of the Filter Cubes on the total PM10 pollution is determined to be around 10–15% in the area of the local measuring point, and as much as 30% in the vicinity of the Filter Cubes and in the building area. These values relate to the stated wind situation and are an approximation due to the model assumptions made. The simulative forecast therefore required experimental investigation for this first pilot project.

In the event of stable weather situations with high particulate matter pollution in the range of the PM10 daily limit value, therefore, a significant reduction in the area close to the building relevant for the assessment should be expected. It can therefore be expected that there will be a decrease in exceedance days at the LUBW measuring station.

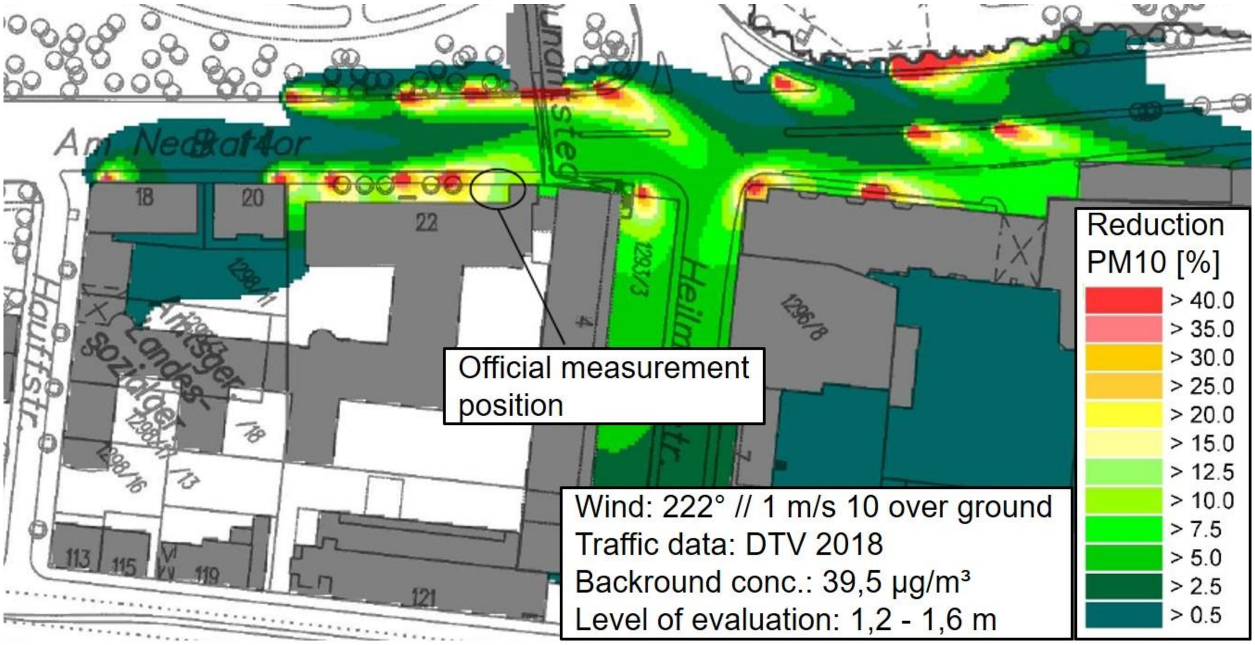


Figure 4.4 – MISKAM simulation of the reduction effect of the Filter Cubes (phase I, PM10).

With an average emission rate of 104 g PM10/(km h) due to traffic in the 300 m long section observed, as well as a considered background pollution of 40 µg/m³ PM10, the separation efficiency of all 17 Filter Cubes together is below the boundary conditions used as a basis here at 9.6 g/h or 32 g/(km h) and therefore is a similar magnitude to the reduction previously already estimated from the mass balance calculation (36 g/km h). In addition, it is possible to deduce from the results that the efficiency when reducing the additional 'traffic' pollution is greater the nearer the columns are to the source (in this case the road).

4.4 MISKAM simulations to determine the NO_2 reduction

The model for predicting the reduction effect of the Filter Cubes in relation to nitrogen dioxide has a similar structure in principle to the one for PM10. However, the modelling here is more extensive because on the one hand the focus is not on complying with the exceedance of daily limit values, and instead for NO2 the target figure is the annual average of the concentrations. Therefore, in this case it is not possible to consider a representative individual situation, and instead it must be based on yearly average meteorology and pollution levels. In addition, the atmospheric chemistry must be considered for a realistic observation of the NO2 concentrations.

4.4.1 Meteorology

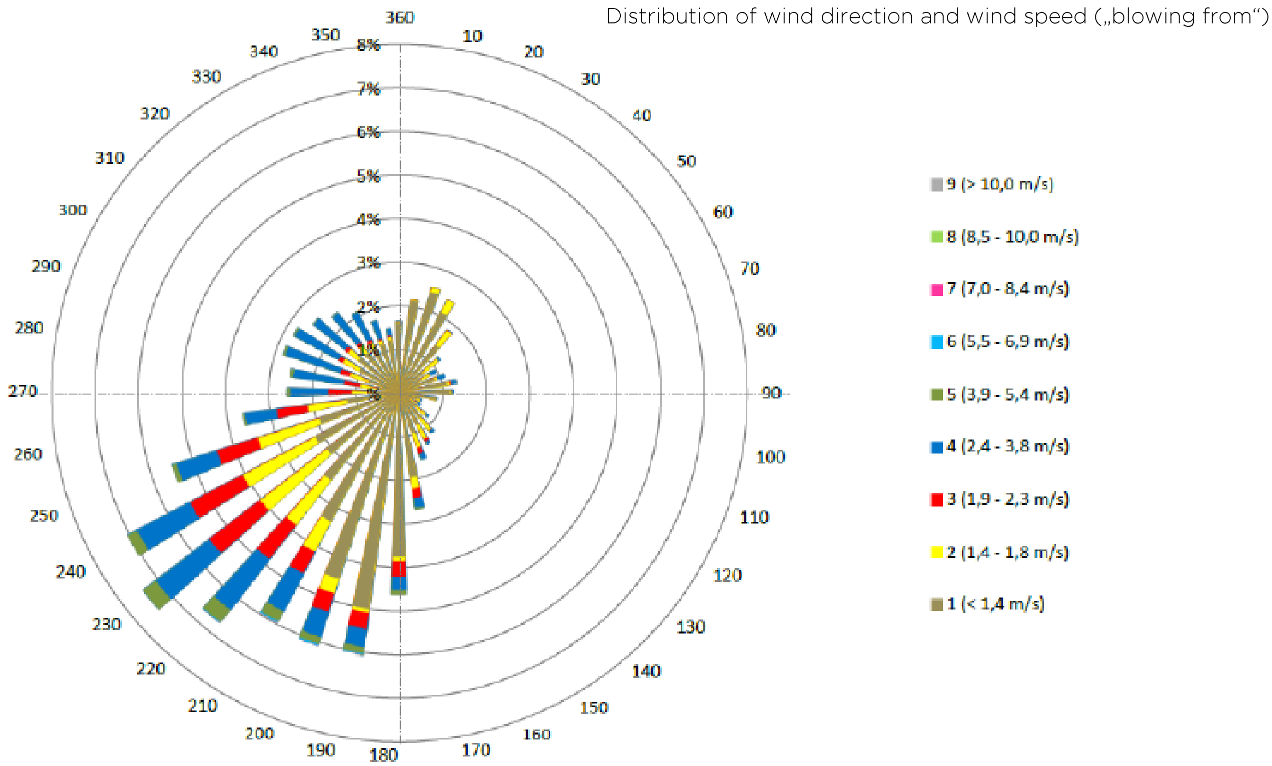
For the determination of statistical values for the air pollutants to be studied, NOX and NO2, representative meteorology data is required for the study area, which is available either in the form of dispersion category statistics or a dispersion category time series. When carrying out studies within inner-city development, it is standard to work with a 2-dimensional wind dispersion (wind direction and wind speed incidence) and neutral layering, because the building turbulence dominates small-scale thermal effects.

The annual average values are determined via weighting of the emission concentration fields determined for each flow direction and wind speed class in accordance with the percentage frequency of the corresponding dispersion situation. The latter are included in the wind statistics by specifying the wind direction and the wind speed.

The synthetic wind data from metSoft were classified as representative for the study area. The synthetic wind data are calculated dispersion category statistics, which are available in a grid of 500 x 500 m² for the whole of Germany and were produced by the IB Rau/METCON joint venture. Figure 4.5 shows the wind rose for the reference years 2001–2010. The wind rose distribution shows the incidence of wind directions in 10° increments as well as the wind speed classes according to TA Luft [Technical Instructions on Air Quality Control]. The maximum wind direction is for winds from the west-southwest. The annual average wind speed is around 1.0 m/s at 10 m above ground.

4.4.2 Determination of the total pollution for NO_2

The forecast for the year 2019 available at the time of the investigation (Schneider et al. 2018) was used for the background pollution. In the area of the Neckartor, this was 31.7 µg/m³ for NO2, and 15.9 µg/m³ for NO with an ozone value of 42 µg/m³. The additional pollution due to traffic in the 300 m long section observed was estimated with an average emission rate of 258 g/h for NOX and 66 g/h direct NO2 emission (Schneider et al. 2018). These values result in a concentration of 65 µg/m³ at the LUBW measuring station in the simulation.



Version: SYNTHETISCH_2.05bc0 Year (Reference: 01.01.2001 – 31.12.2010)

Coordinates: 3_GK DHDN/PD RW 3514504 HW 5405494

Figure 4.5 – Wind statistics, above roof level (source: SynAKS from MetSoft for the Neckartor location).

4.4.3 Annual averages

The characteristic values for the background pollution were used to calculate the statistical values (annual averages for NO2) via overlaying them with the calculated additional pollution values. When overlaying the background pollution values with the additional pollution values, the NO–NO2 conversion must be considered for nitrogen oxides. The chemical conversion of NOX to NO2 is extremely complex and depends on a series of parameters such as e.g. UV radiation, ozone value and temperature. For the present study, according to state of the art, the empirical model approach according to Düring (Düring et al., 2011) is used for the conversion, and this describes the NO–NO2 conversion level as a function of the total NOX emission and the background O3 concentration. The background values for NO2, NO and O3 mentioned above were used for this purpose.

4.4.4 Implementation of the filter columns in the model

The MISKAM microscale forecasting model cannot correctly reflect the complex mechanism of the one-sided intake of polluted air and the blowing out of purified air from the opposite side of the filter column in terms of its dynamics. Likewise, the separation of NO2 in the filter column cannot be modelled. For this reason, a replacement system was defined, which is described below.

At the specified flow rate, the filter columns suck in the NO2 pollutant concentration, which is present in the area of the intake opening for a certain meteorological situation at the height of the respective Filter Cube. The NO2 concentration results from the NO2 emission released directly by the traffic as well as the NO2 background concentration, which as an initial approximation is defined as a constant value in the road area at a particular time. This NO2 mass flow is purified to a level of 80% and released again on the outlet side. This sink is integrated into the model as a pseudo source and overlain with the local varying concentration field present in the road area via differentiation. As a result, a spatially modified NO2 field is obtained in comparison with the initial situation. Then the spatial total NO2 pollution for the annual average is determined in consideration of Düring's empirical approach. In this case, annual average values are used for the ozone concentration and background pollution.

4.4.5 Simulation-based reduction effect for NO_2

With stationary NO2 columns, it is possible to reduce the emissions level in the vicinity (see Figure 4.6). For the case investigated, on the basis of the meteorological data of a representative year and for average emissions conditions and an annual average NO2 background pollution/O3 concentration, the emission concentration (total NO2 pollution) in the area of the measuring point can be reduced by up to 8.5% in the area of the measuring point at 1.5 m above ground. Spatially extended reductions in the area near the building are achieved via an appropriate column density. Therefore the reduction values in the western area and area particularly in need of protection near the building are around 10–15% and up to 30% in the vicinity of the columns.

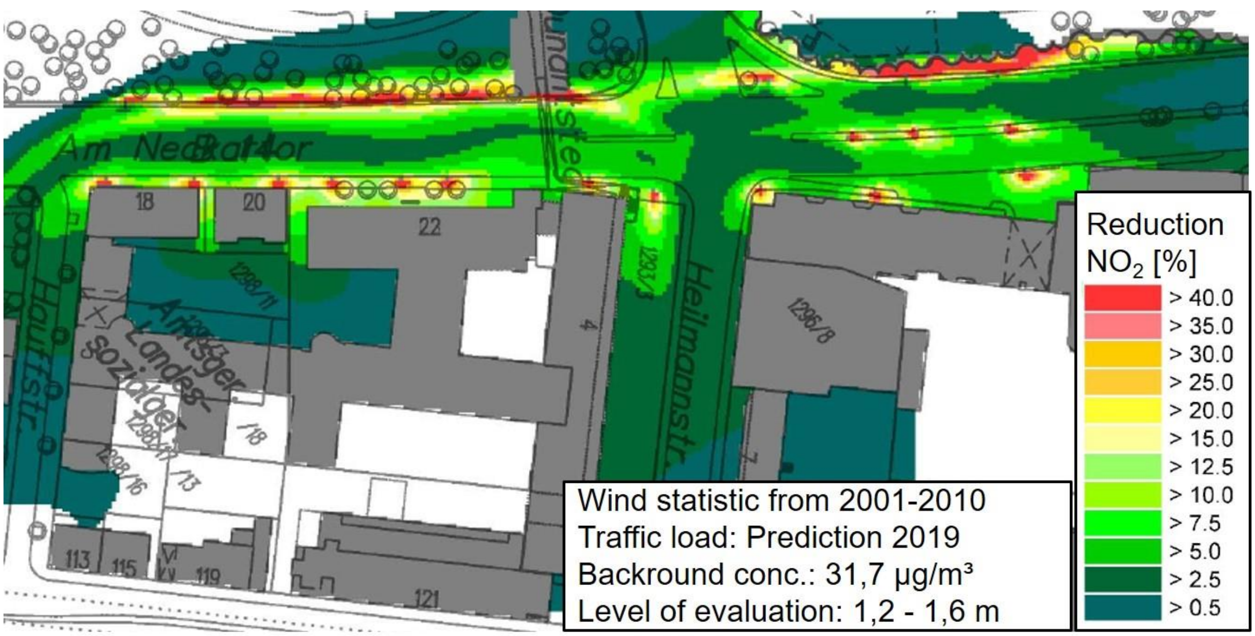


Figure 4.6 – Reduction effect for an arrangement of 23 Filter Cubes with a volumetric flow of 14,500 m³/h per Filter Cube III. The actual locations of the columns have been optimised again in the eastern area of the crossing, see Figure 2.9.

The average NO2 separation efficiency of all 23 Filter Cubes combined is around 18.8 g/h in the simulation. The average emission rate due to the traffic in the around 300 m long section in question is 258 g/h for NOX and approx. 66 g/h for the direct NO2 emission. Accordingly, the filter systems should compensate for 28.5% of direct emissions. Due to the model assumptions previously described, the results are an approximation. The simulative forecast therefore required experimental investigation for this first pilot project.

5 Test method and measuring devices

The shared aim of all measures described below is to describe the change in the ambient concentration for PM10 and NO2 due to the use of the filter columns at the Neckartor. In this case, particular attention is paid to the statistical validity of the results achieved. The usual approach when assessing the effectiveness of air purification measures is to collect measurements for pollutant concentration for as long as possible after the measure has started and then to compare this data either with reference periods at the same site or with data collected at the same time in reference sites. In the case of the filter systems at Stuttgart's Neckartor, the historical comparisons are only of little significance because numerous measures to improve air quality have been implemented or tested both during the test period and in previous years (Table 5.1). As shown in section 6.2, it is indeed possible to identify a significant reduction of the pollutant concentration in calendar year 2019. However, it is not possible to record the quantitative share for the filter systems using a simple cross comparison. Therefore a measurement program was developed as part of a master's thesis (Yildiz, 2019) together with the Institute for Mechanical Process Engineering and Mechanics at Karlsruhe Institute of Technology in order to be able to provide reliable evidence of the purification effect of the filter columns. The test approaches developed during this process in particular use the digital networking of the filter columns, which allows for central, remote-controlled activation or deactivation at short notice.

5.1 Switching tests

The filter columns installed at the Neckartor have a remote maintenance function, which can be used to switch the columns on and off centrally. This was originally used for the maintenance or control of the systems in special situations. It can easily be used to verify the function. By periodically switching the operating status while simultaneously carrying out permanent measurement of the pollutant concentrations, it is possible to aggregate average values for the 'ON' and 'OFF' operating statuses. In order to obtain quantitatively valid and meaningful data for the ON and OFF status via switching tests of this kind, some quality-relevant criteria must be fulfilled and consideration must be given to disruptive influences. The following sections are dedicated to these aspects. In summary it can be stated that due to the one-sided negative disruptive influences, the pollutant concentration reductions in the switching test always represent a worst-case scenario in comparison with hypothetical continuous operation.

Table 5.1 – Chronological progression of the measures to improve air quality at the Neckartor with relevance for the current study.

Project	**Period**
Moss wall (Uni Stuttgart, Züblin)	03/2017–04/2018
Particulate reduction using road sweepers	
(Dekra, on behalf of the city of Stuttgart)	since 10/2017
Speed reduction to 40 km/h (Bosch)	since 06/09/2018
Introduction of bus route X1	since 15/10/2018
Euro4 diesel entry ban for Stuttgart	since 01/01/2019
Euro4 diesel driving ban for city residents	since 01/04/2019
Introduction of bus lanes for route X1 in the Neckartor area	since 07/2019
Change in the road surface at the Neckartor to 'CleanAir' asphalt	since CW16/2019

Route-specific driving ban for Euro5 diesel vehicles (since 01/01/2020)	since 01/01/2020

5.1.1 Overall scope

In accordance with the objectives from section 4, the task of the filter systems is to reduce pollutant concentrations of PM_{10} by 10%–15% (phase I) and of NO_2 by 8.5% (phase III) at the LUBW measuring point. In relation to the later annual averages from 2019, this is 2.8 µg/m³–4.2 µg/m³ PM_{10}, or 5.3 µg/m³ NO_2 (phase III). Providing evidence of these comparably low changes in total concentration during the test is a challenge. This is mainly due to the fact that the pollutant concentrations are subject to considerable fluctuations due to the influence of numerous factors (including traffic flow, wind direction and strength, precipitation, road condition, solar radiation), which is expressed in very high standard deviations (Table 5.2). The longer the test period, the lower the measurement uncertainty and therefore the correspondence between the average value of the measurements and the actual average concentrations in the ON and OFF status. The relationship between the achievable accuracy of the results and the test period can be estimated using a t-test according to Welch (Welch, 1947) for the difference Δc between the average values $\overline{c_{An}}$ and $\overline{c_{Aus}}$ in the ON and OFF status. The following applies for the standard error SE for Δc subject to the assumption that the averages have a normal distribution:

$$\Delta c = \overline{c_{Aus}} - \overline{c_{An}}$$

$$SE_{\Delta c} = \sqrt{\frac{s_{AN}^2}{n_{AN}} + \frac{s_{AN}^2}{n_{AUS}}}$$

Darin sind s_{AN} und s_{AUS} die Standardabweichungen sowie n_{AN} und n_{AUS} die Anzahl der Messintervalle im AN- und AUS-Zustand. Das 95%-Konfidenzintervall für die Konzentrationsänderung Δc entspricht bei den vorliegenden Werten von n und Halbstundenmittelwerten meist$\Delta c \pm 1.96\, SE$. Unter den Annahmen einer näherungsweisen Gleichverteilung der Stunden und einer Reduzierung der Standardabweichung um 10% im AN-Zustand folgen die in Tabelle 5.2 gelisteten Konfidenzintervalle. Bei PM10 kann nach knapp vier Monaten eine Genauigkeit von ± 1 µg/m³ des erhaltenen Mittelwerts erreicht werden, bei NO_2 ist dies erst nach mehr als einem halben Jahr der Fall.

Die Werte aus Tabelle 5.2 können zudem zum grundsätzlichen Nachweis der Wirkung der Säulen auf die Umgebungskonzentration herangezogen werden. Das (zweiseitige) Konfidenzintervall für 95% entspricht jenem für ein einseitiges Konfidenzintervall bei einem Signifikanzniveau von 97.5%. Liegt nach 30 Tagen beispielsweise eine PM10-Reduzierung von mehr als 2 µg/m³ vor, ist dies mit einer Signifikanz von 97,5% der Nachweis dafür, dass der PM10-Wert durch die Filtersäulen gesenkt wird. Beim häufig genutzten Signifikanzniveau von 95% sind die Konfidenzintervalle etwa 16% kleiner. Im Beispiel des PM10-Messwerts nach 30 Tagen wären das 95%-Konfidenzintervall ±1.68 µg/m³.

Table 5.2 – Statistical values of the 30 min average values of the 'Am Neckartor' measuring station of LUBW throughout calendar year 2019. Confidence intervals calculated subject to an assumption of a normal distribution of average values.

			95% confidence intervals for Δc (both sides)			
Pollutant	Annual average [µg/m³]	Standard deviation [µg/m³]	10 days [µg/m³]	30 days [µg/m³]	100 days [µg/m³]	1 year [µg/m³]
PM_{10}	24.5	20.4	±3.5	±2.0	±1.1	±0.6
$PM_{2.5}$	11.4	16.6	±1.8	±1.0	±0.6	±0.3
NO_2	53.0	26.0	±4.4	±2.6	±1.4	±0.7

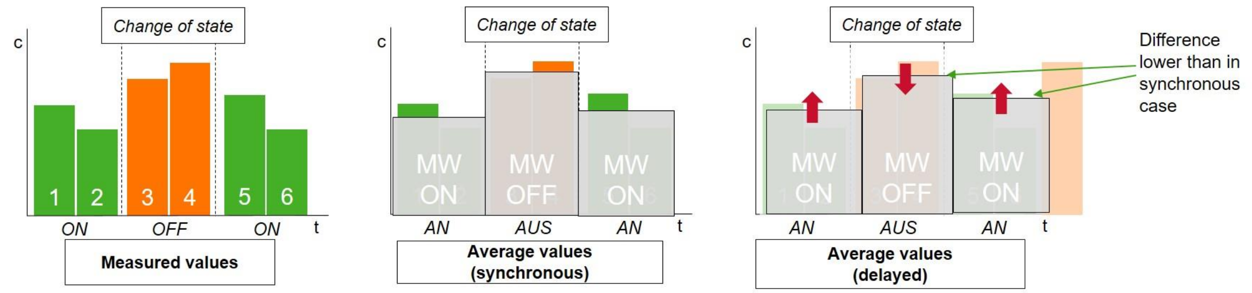


Figure 5.1 – Effect of a time offset between switching points and measurement data using the example of half-hourly measurement data with a one-hour switching interval.

In the first project phase, the switching of the systems was still carried out manually, which is why the majority of the test data was recorded between 6:00 am and 10:00 pm. In the second phase, the functionality of the filter columns was expanded via a firmware update which allowed for schedule-controlled test operation 24 hours per day. This functionality was also retained for the second-generation filter columns (phase III). While the test periods in phase I and II each lasted around 30 days, the duration of testing in phase III was considerably increased. Therefore with each phase the significance of the switching tests increased.

5.1.2 Synchronicity between test data and switching data

Another factor that has a negative effect on the test result for the pollutant reduction are time differences between the switching points and the collected data. These may occur to a low extent due to time offset between the various data collection systems and the system control. Delays in implementing the switching commands via the mobile network are more significant. In phase I in particular, in which the switching was carried out manually, delays of up to three minutes were possible. The effect of the time delay is shown in Figure 5.1. If the (higher) values from the OFF status are recorded in the ON status, and vice versa, there is a decrease in the difference between the average values for the two datasets and therefore in the calculated concentration reduction. If it is assumed that the systems have a basic effect (OFF concentration on average higher than ON concentration), this problem has a negative effect on the test result.

5.1.3 Suitable duration of the switching intervals

When selecting the switching interval, a compromise must be found between arguments in favour of long and short intervals. On the one hand, short intervals mean that both datasets for the ON and OFF status are collected in comparable boundary conditions and therefore the concentration progressions typical at the location do not have too much influence on the measurement result. If the measurement intervals are very long, the ambient conditions may change so much between neighbouring intervals that this change exceeds the effect of the filter columns. This will result in a distortion of the recorded measurement results. A lot of measurement days will need to be completed before these individual events average each other out in the overall results. Figure 5.2 shows that significant concentration fluctuations throughout the day are normal at the Neckartor due to the pronounced influence of traffic. Short switching intervals are important for short test durations in particular, because in this case it cannot be guaranteed that very distorting individual events will occur with comparable frequency in both datasets. In the case of on-site tests, the distortion can only be counteracted by always using a reference measurement point outside of the filter systems' range of action. By relating the measured data to the reference concentrations, it is possible to compensate for short-term changes in the ambient concentration (see section 6.3.2).

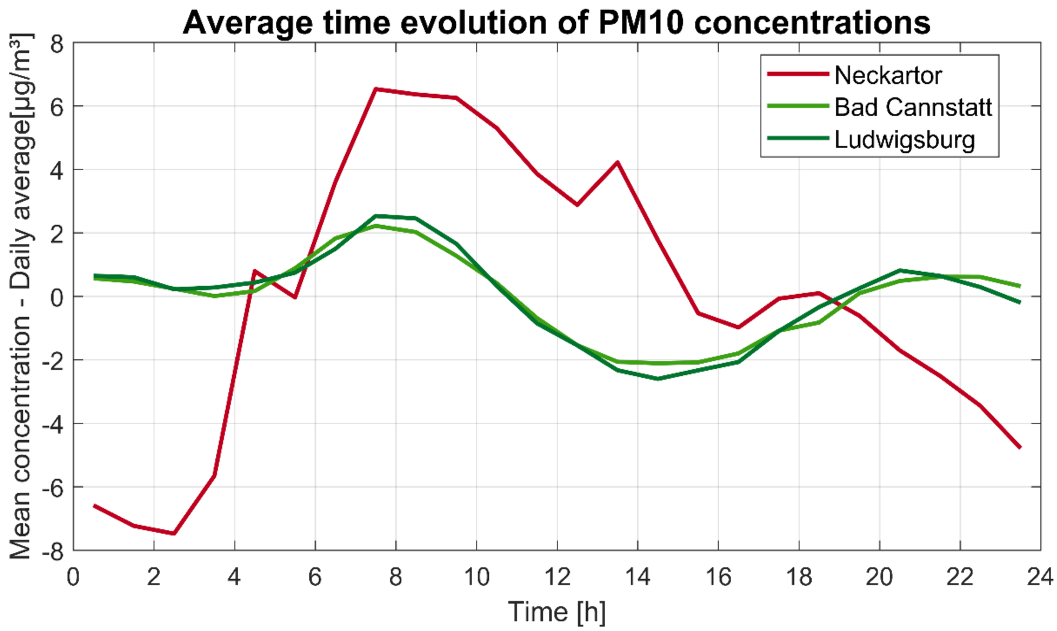


Figure 5.2 – Daily variation of the PM10 concentration at the Neckartor, Bad Cannstatt and Ludwigsburg, determined from the average difference between the measured data and the respective daily average value.

On the other hand, long switching intervals allow for more precise measurement results. Firstly, short-term effects, such as the traffic light phases of the B14/Heilmannstrasse/Cannstatter Straße crossing, become less significant. This results in less variance in the measurement results. Secondly, the measured values recorded are more precise, particularly for PM10. The diffused light measuring devices used determine the PM output values on the basis of particle size distributions. In the case of low particulate concentrations, the number of high-mass particles of coarse dust fractions is so low that a reliable particle size distribution, and therefore a precise measurement for PM10, will only be available after a long measurement duration. For this reason, the Palas Fidas 200 measurement devices used by MANN+HUMMEL and LUBW are preconfigured for 15-minute averages in the certified operating mode. Distributions for the PM2.5 determination tend to be reliable quicker, because the size classes considered for this purpose are present in higher numbers of particles in typical European conditions. This also applies for the number concentration of particles. As a result, short on-site tests are mainly used due to the particle number argument (see sections 5.3.2 and 6.3.2).

A further argument in favour of long switching intervals is based on the attempt to represent later performance in continuous operation as closely as possible with the switching test. The requirement for this is that during the switching test in the ON status there are comparable concentrations as in continuous operation and there are conditions as in long-term system downtime in the OFF status. This requirement cannot be fulfilled due to the sluggish reaction of the ambient concentrations. After switching on, the clean air produced by the filter columns mixes with the ambient air and gradually reduces its pollutant concentration. After switching off, the initially clean air mixes with heavily polluted air, in particular that coming from the road. This process partially takes place passively via diffusion, but is considerably accelerated if the wind or turbulence from road traffic amplify the mixing process. At the measuring points placed at the greatest possible distance from the columns, the changes in concentration can only be observed with a delay after switching. The delay is particularly extreme when switching off, because the flow from the columns itself as support for air exchange is lost. When there is little wind and a low traffic volume, the concentration only increases very slowly due to a lack of local pollutant sources. The results of the switching test in phase III presented later provide impressive proof of this behaviour, particularly for the LUBW measuring station which has slight wind protection (see section 6.1.3). Mathematically, the switching on and decay behaviour has a selective negative effect on the result of the switching test, because the measured data is higher in the ON status and lower in the OFF status than in the case of assumed continuous operation. The calculated concentration difference between on and off is therefore lower in the switching test than in continuous operation. In low-exchange situations, it must even be assumed that the absence of a concentration increase in the OFF status means that the total pollutant level is always decreasing further during the switching test, in a similar way to the case during continuous operation. This behaviour cannot be quantified using the data available.

In consideration of these arguments, a switching interval of one hour was selected for the endurance switching tests. This means that there are two measuring points for the data of the LUBW measuring station, which is recorded every half hour, for each interval. In the event of a long test length (phase III), this means that the first half hour after switching can be disregarded in order to better hide the switching on and decay effects of the ambient concentration. Shorter time intervals of 20–30 minutes were selected for on-site tests. Due to the broad distribution of the PM10 values obtained, the more quickly determined particulate matter concentration was then used as the main indicator.

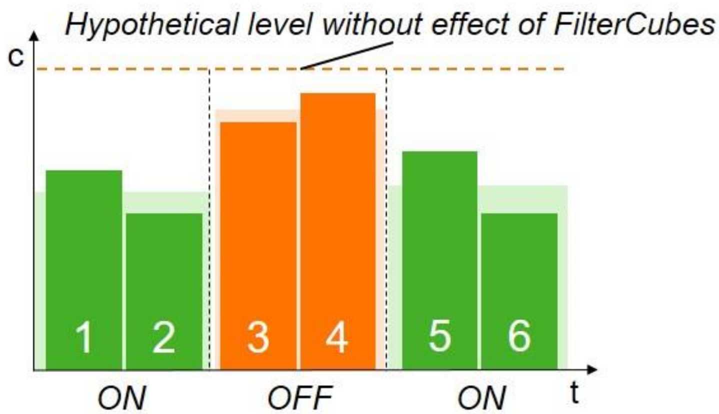


Figure 5.3 – Simplified representation of the effect of switching on and decay effects during the switching test using the example of half-hourly measurement data with one-hour switching interval.

5.1.4 Comparability of the samples – suitable switching time schedule

The strong dependence of the pollutant concentration on the traffic flow at the Neckartor results in recurring patterns in the progression of the pollutant concentrations. This includes the daily variation (Figure 5.1) and the reduction of the level at the weekend as well as on public holidays and days between a weekend and a public holiday. In order to avoid distortions in the datasets for the ON and OFF status, the switching schedule was shifted on a daily basis.

5.1.5 Handling of operational interruptions and precipitation

There may be brief interruptions during the operation of the filter systems. Most of these are due to the sensor-supported rain protection control of the systems. This has the task of protecting the individual systems against the ingress of water or snow in the event of heavy precipitation. There are also breaks due to system maintenance and filter replacement. Operational interruptions in ON phases result in a fall in the filtered air volume and therefore impair the result of the switching test. As appropriately heavy precipitation also results in partial washing away of the particulate matter, heavy rain phases are problematic for short tests at least. The resulting jumps in concentration are individual events, which can distort the results of the switching tests in both directions if they do not occur with even distribution in both datasets. In the most extensive test in phase III, the discarding of rain intervals did not have a significant effect on the test result. In the analysis of phase I and II, on the other hand, 30-minute time windows affected by switching off due to rain were discarded. This affected 14% of the test period. In addition, in phase I data blocks after rain interruptions were only used if they contained both ON and OFF intervals. In the case of the 24-hour tests in phase II and III this was not necessary because isolated hourly blocks were much rarer.

5.2 Measurement devices and data sources

For the present investigations, the measurement data from the public measuring point at the Neckartor for PM10, PM2.5 and NO2 was the most important reference. This data was provided in the form of preliminary 30-minute average values throughout the entire test period by the Landesanstalt für Umwelt Baden-Württemberg (Baden-Württemberg Regional Environment Office, LUBW). In addition, the weather data from the Bad Cannstatt and Bernhausen stations as well as data recorded on a quarterly basis from LUBW NO2 passive samplers were also used. In addition to this public measurement data, in phase III MANN+HUMMEL set up a measurement network consisting of emissions measurement devices at the Neckartor. This was used to expand the monitoring area during the switching tests and therefore provide evidence of the effect of the systems in the area. Figure 5.3 shows the locations where the sensors were installed on the western side. A further measurement point was installed on the eastern side in front of the Schwabengarage building. In addition to the Palas Fidas 200s certified as per EN 16450, the measurement network consisted of sensors from Dr Födisch Umweltmesstechnik AG, which are also suitable for continuous outdoor use. The type GSA19 NO2 sensors used are prototypes, which have a cross-sensitivity to ozone due to the measurement principle. The ozone is also very efficiently separated by the activated carbon filters that are used. In order to avoid measurement errors resulting from the cross-sensitivity, data from time windows in which the ratio of ozone concentration to NO2 concentration is very low should preferably be used when determining the NO2 reduction.

In the on-site tests, top-quality mobile particle counting devices of the type Palas Fidas Frog were used, however they do not have heated measurement sections. In order to reduce the risk of counting errors due to condensed water droplets, all measurements with these measurement devices were carried out at temperatures considerably above the dew point.

Table 5.3 – Measurement devices used for measurement activities and continuous monitoring.

Gerät	**Hersteller**	**Messgrößen**	**Mess-prinzip**	**Phase**	**Einsatz**
Fidas 200s with WS600 weather station	Palas	PM10, PM2.5, PN Wind, Niederschlag	OPC	I & III	Mobil (I) Dauer (III)
Fidas Frog	Palas	PM10, PM2.5, PN	OPC	I	Mobil
ICAD Analyzer	Airyx	NO_2, NO	ICAD	II & III	Speziell
FDS15	Dr. Födisch	PM10	OPC	III	Dauer
FDS18	Dr. Födisch	PM2.5	OPC	III	Dauer
GSA19	Dr. Födisch	NO_2	EC	III	Dauer

Figure 5.4 – Measuring points of the measurement network set up by MANN+HUMMEL on the western side.

5.3 Supplementary on-site tests

5.3.1 Direct measurement of the NO_2 adsorption of the individual systems

In phases II and III, in each case an NO2 measurement device was installed in a Filter Cube at the south-western corner of the Heilmannstraße/B14 crossing (Figure 5.3). For four (phase II) or six (phase III) weeks, the Airyx ICAD Analyzer was alternately used to measure the NO2 concentration of the dirty and clean air side and to use this to calculate the adsorption efficiency. The sampling was carried out using hoses from the flow channel directly upstream and downstream of the filter element.

A comparable measurement of the level of particulate matter separation within the columns was deemed not to be productive. The crucial factor in this decision was in particular the requirement for sampling in the form of isokinetic suction at a high flow speed. Due to the expected low clean air concentrations (in the area of the lower measurement limit of the measurement devices) it was also expected that a low accuracy would be able to be achieved. Therefore reference is made to the PM measurement campaigns listed in the section below for fundamental evidence of functionality for the individual columns.

Figure 5.5 – In-situ measurement of the NO2 adsorption efficiency. Airyx ICAD measurement device installed in a filter column (phase III).

5.3.2 Measurement campaigns for particulate matter filtration (phase I)

At the start of phase I (particulate matter filtration), there were no permanent spot measurement data available at the Neckartor apart from the LUBW measurement station. Therefore supplementary on-site tests were carried out as part of a master’s thesis, which helped to answer fundamental questions. A detailed description of these tests can be found in Yildiz (2019). As these comparatively short tests do indeed provide a clear picture of the effect of the systems, but at the same time do not provide any reliable quantitative results for the PM10 reduction (see 5.1.1), the results section 6.3.2 only presents one test by way of example.

Another group of preliminary tests were used to investigate the surroundings and included measurements of the spatial distribution of the particulate matter concentration as well its temporal progression. The aims were to characterise the local aerosol, determine suitable measurement intervals for the switching test and to identify typical local influence and disruption factors. A second group of tests consisted of switching tests on site, which were intended to be used to show the location-dependent effect of the filter columns on the ambient concentration, in particular in the area of the building development on the western and eastern side. Each switching test was started with comparative measurements between the measurement devices used at a central measurement point. Then the measurement devices were taken to the intended locations and switching tests were carried out with intervals of 20 to 30 minutes. Then the devices were compared again.

6 Results and assessment

6.1 Endurance switching tests

For each project phase switching tests were carried out, which were intended to provide evidence of a reduction in the pollutant concentrations due to the filter systems. In accordance with the methodical discussion in section 5, the relative pollutant reductions later achieved in continuous operation are higher than the results of the endurance switching tests.

6.1.1 Phase I – Purely particulate matter filtration

Between 19/01/2019 and 28/02/2019, daily switching tests were carried out with the purely particulate matter filters. In this case the systems were manually switched on and off at hourly intervals. Table 6.1 shows the integral result of the switching test. The sole continuous measurement point available in the investigation period for phase I was the LUBW measurement station. In accordance with the target specifications from section 4.3.3, the particulate matter filters were intended to reduce the PM10 concentration by 10–15% on potential exceedance days (daily average value ≥ 50 µg/m³). However, the restriction to exceedance days reduces the test duration and therefore the accuracy that can be achieved in the test. Analogously to the analyses in phase II and III, all measurement points recorded in precipitation-free test periods are therefore included in the result.

The average value for the PM10 concentration measured with the filter systems switched on was

6.3 µg/m³ lower than when they were switched off. This corresponds to a reduction of 10.4%[1], which correlates well with the simulated forecast. As expected, the reduction for the PM2.5 fraction is lower because the separation efficiency of the filters is lower for this fine fraction (see 3.1). Statistically, the results can be assessed using a Welch test (Welch, 1947) for the difference between the average values for the ON and OFF status. The fundamental evidence of the PM10 reduction due to the filter systems is provided using a one-sided t-test based on the hypothesis 'average ON < average OFF'. The confidence level for the acceptance of this hypothesis is 99.5%. On the other hand, the measure in phase I has no effect on the NO2 concentration.

Table 6.1 – Results from the switching test for phase I. Integral result for all 30 min. average values.

Phase I – Overall result	**Pollutant**		
	PM10	**PM2.5**	**NO_2**
Average value ON [µg/m³]	**54.4**	21.7	82.2
Average value OFF [µg/m³]	**60.7**	22.8	82.3
Difference [µg/m³]	**6.3**	1.2	0.1
Percentage reduction	**10.4%**	5.1%	0.1%
Number of intervals ON	482	482	447
Number of intervals OFF	450	451	422
Standard deviation ON [µg/m³]	32.2	10.2	26.7
Standard deviation OFF [µg/m³]	38.0	10.8	27.8
Standard error [µg/m³]	2.3	0.7	1.9
Confidence interval 95% [µg/m³]	±4.5	±1.4	±3.6
Confidence level for evidence (one-sided)	99.5%	96%	-

[1] An initial interim report talked of a PM_{10} reduction of 10.9% for phase I. The difference results from the filling of data gaps, in particular for 25/01/2019, as well as uniform data assessment for all test phases.

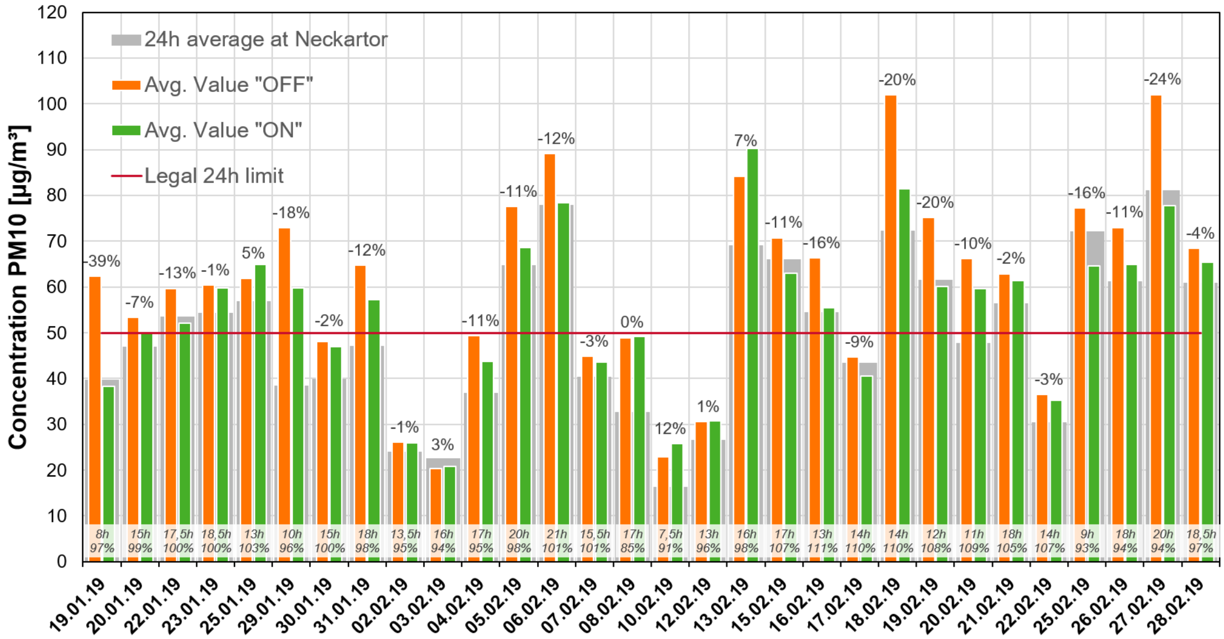


Figure 6.1 – Daily average values for the PM10 concentration (continuous measurement) with the filter systems ON and OFF.

Figure 6.1 shows the daily average values of the PM10 concentration on the test days. The results presented show how difficult it is to extrapolate meaningful measurements from short experiments. An improvement in air quality is visible on an overwhelming majority of the days. However, on individual days the concentration in the OFF status is higher than in the ON status. The level of the reduction also varies. This is due to the typical local variance in the PM10 concentration, which is mainly caused by the traffic and the weather. The wind in particular plays a major role. High reductions can be achieved in low-exchange situations. With high wind speeds, on the other hand, there is an increased removal of the purified air and therefore there tends to be a reduction in the differences between the ON and OFF status (see e.g. 03/02 and 10/02, the windiest days in the test period).

6.1.2 Phase II – feasibility of NO2 reduction

The endurance switching test for phase II aimed to investigate the fundamental effect of activated carbon combi filter elements in the open air. The investigation was used in particular as a basis for making a decision on the technical upgrading measures in phase III (see 2.3). For this purpose, activated carbon combi filter elements with the same design as in phase I were used and the volumetric flow of the systems was increased. The endurance switching test for phase II took place from 18/05 to 17/06/2019. By revising the system control software, it was possible to conduct the test program completely automatically, which considerably increased the number of measurement points and the accuracy of the switching times in comparison with phase I. Table 6.2 shows the overall result of the test. Throughout the entire period, the concentrations in the ON status were 6% lower than in the OFF status. It is possible to state with a confidence level of over 99.5% that the NO2 concentration is reduced due to the use of the activated carbon filter. This therefore confirms the feasibility of an NO2 reduction due to the filter systems. Due to the very low absolute values for the particulate matter fractions, their absolute changes between the ON and OFF status is low. However, as the standard error is also low, this still results in a confidence level of 90% for the evidence of the reduction of PM10. In addition to the NO2, the filters also separate off ozone, which is reflected in a reduction in the ozone concentration of 4.7%.

Table 6.2 – Results of the switching test for phase II. Integral result of the 30 min. average values of the LUBW measurement station.

Phase II – Overall result	**Pollutant**			
	NO_2	**PM10**	**PM2.5**	**O_3**
Average value ON [µg/m³]	**50.7**	19.8	8.6	35.1
Average value OFF [µg/m³]	**54.0**	20.7	9.0	36.8
Difference [µg/m³]	**3.2**	0.9	0.4	1.7
Percentage reduction	**6.0%**	**4.2%**	**4.2%**	**4.7%**
Number of intervals ON	640	644	644	628
Number of intervals OFF	653	660	660	643
Standard deviation ON [µg/m³]	21.0	12.2	4.2	25.0
Standard deviation OFF [µg/m³]	22.3	12.1	4.7	26.1
Standard error [µg/m³]	1.2	0.7	0.2	1.4
Confidence interval 95% [µg/m³]	±2.4	±1.3	±0.5	±2.8
Confidence level for evidence (one-sided)	99.6%	90%	94%	89%

6.1.3 Phase III – NO_2 separation

For the final expansion stage of the filter systems, a continuous switching test was carried out from 20/09 to 30/11/2019 with hourly operating status changes, the overall result of which is presented in Table 6.3. This shows a 7.5% reduction in the NO2 concentration. The PM10 values reduce by 6.2%. The high ozone reduction of 9.8% is also striking. In the ON phases of the switching test, the average NO2 concentration was around 45.2 µg/m³ and therefore only 13% above the limit value. However, the overall result of the switching test does not precisely reflect the results that would be expected in subsequent continuous operation. This is explained below.

Table 6.3 – Results of the switching test for phase III. Integral result of the 30 min. average values of the LUBW measurement station.

Phase III – Overall result	**Pollutant**			
	NO_2	**PM10**	**PM2.5**	**O_3**
Average value ON [µg/m³]	45.2	20.5	9.8	12.7
Average value OFF [µg/m³]	48.9	21.9	10.4	14.1
Difference [µg/m³]	3.7	1.4	0.6	1.4
Percentage reduction	**7.5%**	**6.2%**	**5.7%**	**9.8%**
Number of intervals ON	1630	1622	1624	1534
Number of intervals OFF	1647	1614	1614	1595
Standard deviation ON [µg/m³]	18.6	13.8	7.0	13.4
Standard deviation OFF [µg/m³]	20.7	14.8	7.4	14.9
Standard error [µg/m³]	0.7	0.5	0.3	0.5
Confidence interval 95% [µg/m³]	1.3	1.0	0.5	1.0
Confidence level for evidence (one-sided)	>99.99%	99.7%	99.0%	99.7%

Table 6.4 – Results of the switching test for phase III. Separate result for the 30 min. averages of the LUBW measurement station to clarify the switching on and decay effects after switching.

Phase III – 30 min. intervals after switching	**1st half hour**				**2nd half hour**			
	NO_2	**PM10**	**PM2.5**	**O_3**	**NO_2**	**PM10**	**PM2.5**	**O_3**
Average value ON [µg/m³]	46.3	20.8	9.9	12.5	45.6	20.8	9.8	12.5
Average value OFF [µg/m³]	49.4	22.0	10.3	13.8	50.0	22.3	10.5	14.1
Difference [µg/m³]	3.1	1.2	0.5	1.3	4.5	1.5	0.7	1.6
Percentage reduction	**6.3%**	**5.4%**	**4.6%**	**9.4%**	**8.9%**	**6.7%**	**6.8%**	**11.2%**
Number of intervals ON	773	774	774	715	789	774	774	762
Number of intervals OFF	791	777	777	767	791	775	775	764
Standard deviation ON [µg/m³]	18.6	14.0	7.0	13.5	18.5	13.9	6.9	12.9
Standard deviation OFF [µg/m³]	20.5	14.8	7.3	14.5	20.6	15.0	7.4	14.9
Standard error [µg/m³]	1.0	0.7	0.4	0.7	1.0	0.7	0.4	0.7
Confidence interval 95% [µg/m³]	±1.9	±1.4	±0.7	±1.4	±1.9	±1.4	±0.7	±1.4
Confidence level for evidence	>99.9 %	94.7%	90.7%	96.3%	>99.9 %	97.9%	97.4%	98.7%

A fundamental problem of the switching test is that the pollutant concentrations at the measurement points do not immediately reduce or rise when the systems are switched on or off, and instead this only occurs with a delay. The measurement of the official 30-minute averages, however, already starts when switching is carried out. As this means that the transition period is also included in the measurement, the reductions are lower than if the transition period were to be omitted (see 5.1.4). The distance of the measurement points from the systems and the dispersion speed of the pollutants determine how significant the delay will be. In the ON status, the flow from the systems supports the distribution of pollutants, particularly in the areas with restricted space on the western side. In the OFF status, a concentration increase at the measurement point only takes place if pollutants enter the balance area from outside or as a result of traffic. One solution to this situation results from the overall scope of the test. This makes it possible to achieve meaningful results for partial amounts of the test data. For example, the effects of selected influence factors on the test result can be examined (see 6.5), including the running in and switching off effects. For this purpose, the results of the first and second half hour after switching can be recorded separately. The transition effects described are evident in all data series in Table 6.4. Between the first and the second half hour, the pollutant concentrations either reduce or stagnate in the ON status, while they increase in the OFF status. However, if only the second half hour interval is included in the results, then the running in and decay delays are at least largely omitted. The resulting pollutant reductions are then higher than in the overall result, with 8.9% for NO2 and 6.7% for PM10. As it must be assumed that the framework test conditions for the second half hour are more similar to subsequent continuous operation than those for the entire switching interval, these partial results should be seen as the overall result of the switching test in phase III.

Further data is available for the measurement network established by MANN+HUMMEL at the Neckartor. This was expanded in two stages during phase III in order to be able to examine the spatial effect of the systems even away from the LUBW measurement station. In this case, the sensors were positioned centrally between the systems (see Figure 6.2) in order to avoid the near-field effects of the columns. The pollutant reductions measured there therefore tend to represent the worst case for the spatial effect in the walkway areas. Due to the ozone cross-sensitivity of the NO2 sensors used, the calculation of the NO2 reduction only considered time windows in which the molar ratio of O3 to NO2 was less than 1:10. Due to the effect of the systems on the ozone concentration being comparable with that for NO2, the measured NO2 reductions would otherwise be one to two percentage points higher.

Table 6.5 – Complete measurement results of the MANN+HUMMEL measurement network at the Neckartor.

	Position	LUBW Station				Admin. Building West (Am Neckartor 22)		Residential West (Am Neckartor 18)	
	Meas. Device	Födisch GSA19		Födisch FDS18		Födisch GSA19	Födisch FDS18	Födisch GSA19	Födisch FDS18
	Start of Measurement	19/10/31				19/10/31		19/10/31	
	Contaminant	NO2*		PM2.5		NO2*	PM2.5	NO2*	PM2.5
All intervals	Mean ON [µg/m³]	50.5	49.3	9.3	10.1	45.6	10.2	43.2	9.7
	Mean OFF [µg/m³]	54.4	52.5	9.9	10.6	51.3	11.4	46.9	10.3
	Difference [µg/m³]	3.9	3.3	0.6	0.5	5.7	1.1	3.7	0.7
	Reduction	**7.2%**	**6.3%**	**6.3%**	**4.8%**	**11.2%**	**10.0%**	**7.8%**	**6.3%**
Only 1st half hour	Mean ON [µg/m³]	51.5	50.7	9.3	10.1	47.0	10.3	46.8	9.6
	Mean OFF [µg/m³]	54.7	53.2	10.0	10.8	51.8	11.4	49.1	10.2
	Difference [µg/m³]	3.2	2.5	0.7	0.7	4.9	1.1	2.3	0.6
	Reduction	**5.8%**	**4.7%**	**7.0%**	**6.2%**	**9.4%**	**9.6%**	**4.8%**	**5.9%**
Only 2nd half hour	Mean ON [µg/m³]	50.0	48.5	9.3	10.2	45.1	10.2	40.6	9.7
	Mean OFF [µg/m³]	54.9	52.7	9.9	10.7	51.8	11.5	45.7	10.4
	Difference [µg/m³]	4.9	4.2	0.6	0.5	6.7	1.2	5.1	0.7
	Reduction	**8.9%**	**8.0%**	**6.3%**	**4.7%**	**12.9%**	**10.9%**	**11.2%**	**7.0%**

	Position	Park (North-West)					Commercial B. (South-East)	
	Meas. Device	Födisch GSA19	Födisch FDS18	Palas Fidas 200s		Födisch FDS18	Födisch GSA19	Födisch FDS18
	Start of Measurement	19/11/04		19/09/22			19/11/04	
	Contaminant	NO2*	PM2.5	PM10	PM2.5	PM2.5	NO2*	PM2.5
All intervals	Mean ON [µg/m³]	41.6	12.0	21.8	8.9	10.7	43.3	13.9
	Mean OFF [µg/m³]	49.9	14.0	27.9	10.9	13.3	46.2	14.1
	Difference [µg/m³]	8.4	2.0	6.1	2.0	2.6	2.8	0.3
	Reduction	**16.8%**	**14.3%**	**22.0%**	**18.2%**	**19.7%**	**6.2%**	**1.8%**
Only 1st half hour	Mean ON [µg/m³]	42.8	12.0	22.0	9.0	10.7	45.3	14.3
	Mean OFF [µg/m³]	50.4	14.0	28.4	10.9	13.3	46.2	14.1
	Difference [µg/m³]	7.6	2.0	6.4	2.0	2.6	1.0	-0.2
	Reduction	**15.0%**	**14.0%**	**22.6%**	**18.0%**	**19.6%**	**2.1%**	**-1.6%**
Only 2nd half hour	Mean ON [µg/m³]	40.9	11.9	22.4	9.0	10.7	42.2	13.4
	Mean OFF [µg/m³]	50.7	14.1	28.3	11.0	13.4	47.1	14.3
	Difference [µg/m³]	9.8	2.2	5.9	2.0	2.7	4.9	0.9
	Reduction	**19.4%**	**15.8%**	**20.8%**	**18.0%**	**20.2%**	**10.3%**	**6.5%**

**Due to sensor's cross-sensitivity to ozone only intervals with a molar ratio Ozon/NO2 < 10% were considered.*

The average NO2 concentrations in the OFF status fluctuate by only -6% to +11% from the value of the LUBW measurement station. The pollution therefore has a very much homogeneous distribution throughout the measurement area. The situation is similar for PM2.5. On the northern and eastern side, the PM2.5 values tend to be slightly higher than in the area of the District Court. Due to the high technical complexity, there is only one other PM10 measurement point. This shows considerably elevated PM10 values in comparison with the measurement station, which is presumably attributed to the direct positioning at the edge of the road.

Figure 6.2 shows a graphical summary of the results for the dataset for the second half hour intervals. Values for the overall result as well as the first and second half hour can be found in Table 6.5. In line with the simulation prediction from 4.4.5, relatively low reductions are achieved at the LUBW measurement station, which can be attributed to the system arrangement. The measurement station is in the area with the biggest gap in the installation site. In spite of the shorter measurement period, the reference sensors installed on the LUBW measurement station delivered comparable percentage reductions for NO2 and PM2.5 to the LUBW measurement station. Slightly higher reductions were achieved on the south-western side in front of the District Court and the residential houses, as well as on the south-eastern side in the area in front of the Schwabengarage. At the measurement point on the north-western park side, all sensors recorded considerably higher reductions than in the rest of the test area. The simulation results had already predicted an improved effect at this point, which is a phenomenon that can be attributed to the small space between the road and the park (see 4.4.5). The filter systems there generate clean air in zones characterised by flow situations that are mainly parallel to the road, in which the clean air streams of several columns overlap. For the overwhelming majority of the measurement variables, the fundamental evidence of an effect from the filter systems can be achieved with a confidence level of 95% or above. The corresponding statistical parameters for all measurement positions can be found in Table 10.2 and 10.3 in the Appendix.

At the measurement points near to the road there is an increased exchange of material with the road, for example due to vehicle-induced turbulence. At the same time, the measurement points there are each located between two filter systems. This results in a better air and pollutant exchange than at the LUBW measurement station or in front of the Schwabengarage. The better mixing results in a reduction of the delay when switching on and off and is expressed in lower differences between the first and second half-hour interval after the switching process. At the measurement point in front of the Schwabengarage, where there is a very big distance from the road and an increased distance from the closest columns, on the other hand, there are relevant delay effects which are evidence of a very restricted air exchange. The NO2 reduction there increased fivefold in the second half hour interval. The PM2.5 reduction also increased massively. This once again highlights the need to discard data from the first half hour interval in the quantitative assessment of the overall system capacity.

The pollutant reductions observed at the measurement points due to the system operation confirm the predictions of a locally variable effect for the systems from the simulations (see Figure 6.3). As technical reasons meant that the column positions from the simulations could only be achieved on a 1:1 basis on the south-western side, quantitative comparisons between the test and simulation are only possible there. The reference values for the north-eastern and south-western side have a higher quantitative uncertainty and therefore must be assessed as purely indicative.

Figure 6.2 – Reduction effect at the various measurement points for the second half hour of each switching interval. Purple: LUBW; yellow: Palas Fidas 200s; blue: Födisch FDS18/GSA19.

	LUBW Station	Building 22 GSA19	Building 20 GSA19	Park West GSA19	Commercial building GSA19
Measured reduction	8,9%	12,9%	11,2%	19,4%	10,3%
Prognosis	7.5% - 10%	15% - 20%	7.5% - 12.5%	12.5% - 35%	5% - 15%

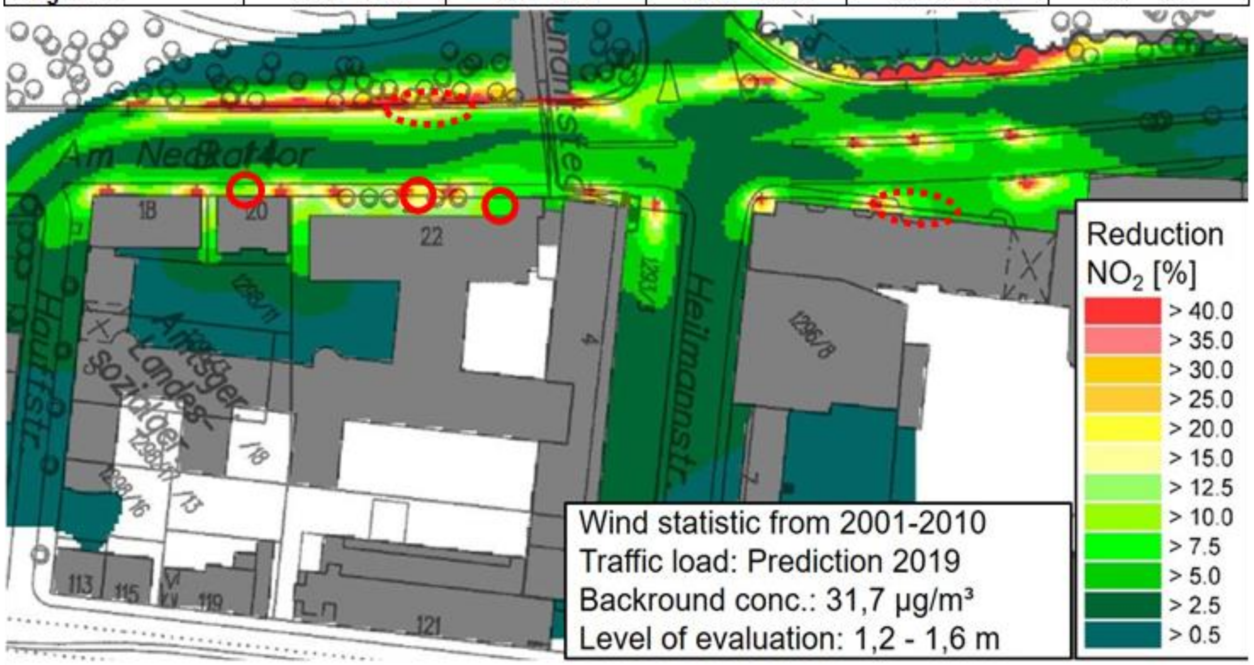


Figure 6.3 – Comparison between simulated forecast and measurement results from phase III.

In view of the model assumptions for the simulation (section 4.4) and the differing assessment level, there is a very good correlation between the simulation and test results. The resulting NO2 reduction of 8.9% at the LUBW measurement station corresponds excellently with the predicted value of 8.5%. At the other MANN+HUMMEL measurement points on the south-western side, there is also good correlation between simulation and experiment. In spite of the lack of reference values in the remaining area, the ratios of the reduction effect are consistent at the various measurement points. It can therefore be assumed that the simulation method used is suitable to predict the effect of the systems in the field. The NO2 reduction of 10% to 15% in the walkway area and 30% in the vicinity of the columns predicted in the simulation are therefore plausible.

6.2 Development of pollutant concentrations at the Neckartor

Figure 6.4 shows the long-term development of the NO2 concentration at the Neckartor and at the other continuous measurement points that the LUBW has in Stuttgart. This shows a continued positive development over the last four years, in particular at the Neckartor and Hohenheimer Straße traffic hotspots. Nonetheless, the annual average values have so far been above the emissions limit value of 40 µg/m³ of the 39th BImSchV (Regulation for the Implementation of the Federal Emissions Control Act) There is also a positive trend in the concentrations of the particulate matter fractions PM10 and PM2.5 (see Table 6.6 and Figure 6.5). The annual limit value for PM10 has been complied with since 2011, and for the second time in a row the number of exceedance days was below the permitted 35 events in 2019. This raises the question of how many exceedance days could have been avoided in 2019 due to the use of the filter columns. Due to the very high fluctuation range of the PM10 pollutant reduction (see Figure 6.1), it is not possible to make any clear statements for individual days as to whether they would have exceeded the limit value without the filter systems.

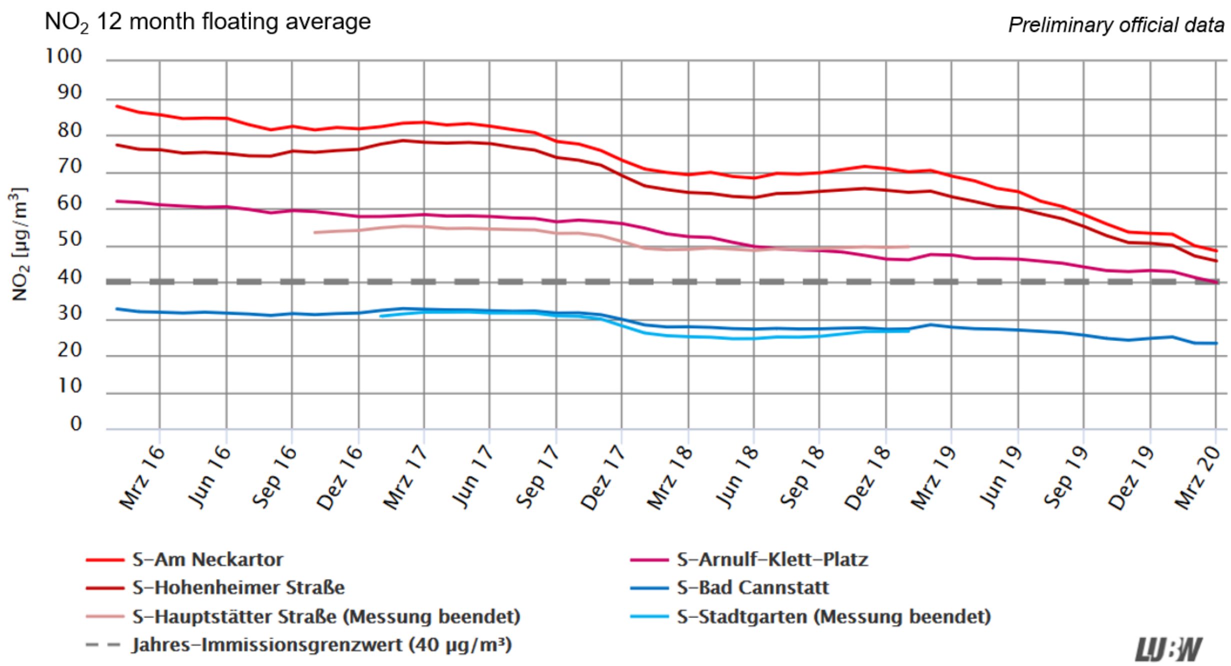


Figure 6.4 – Long-term cross-comparison of Stuttgart's LUBW measurement stations for NO2. Source: LUBW 2020a.

Table 6.6 – Comparison of the current pollutant concentrations with previous years and quarterly periods in previous years. Sources: LUBW (2020b), LUBW (2020c). Quarterly values Q1/2020 available up to and including 24/03 at time of publication.

	2019	**2018**	**2017**	**2020 Q1**	**2019 Q1**	**2018 Q1**	**2017 Q1**
PM10 average value [µg/m³]	28	29	35	21	32	34	54
PM10 exceedance days	27 (25)	21 (20)	45 (41)	7	19	16	35
PM2.5 average value [µg/m³]	13	14	16	9	15	16	27
NO2 average value [µg/m³]	53	71	73	40	59	67	83

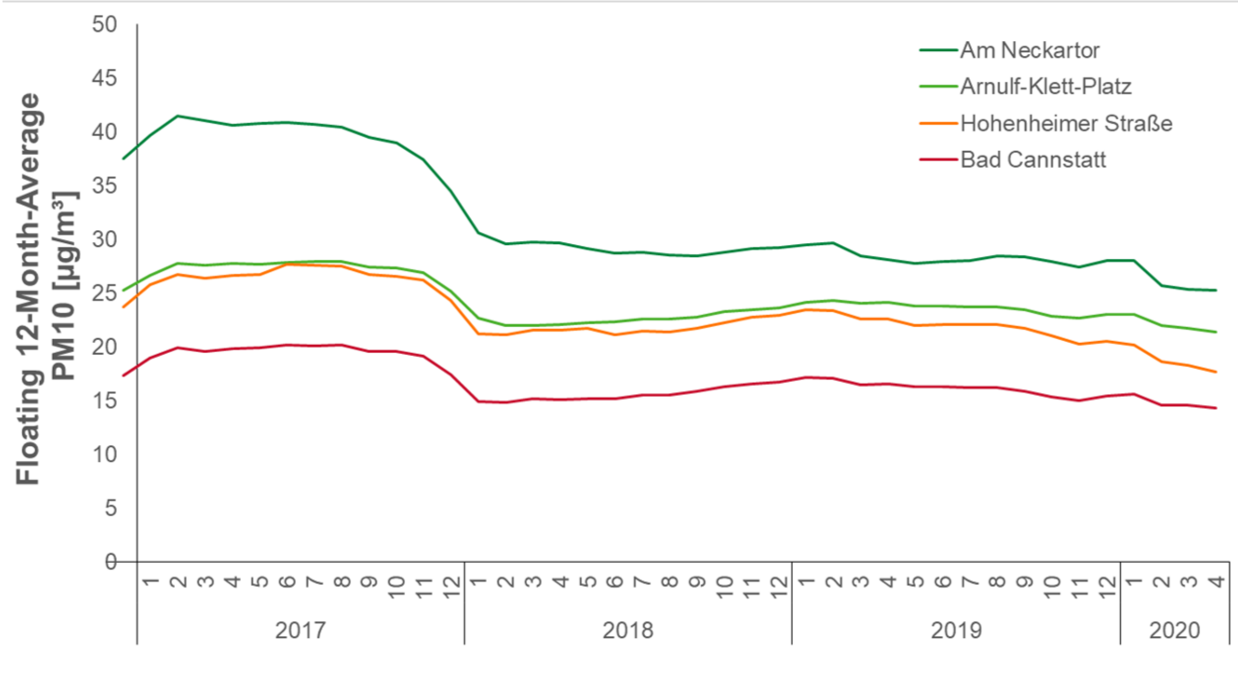


Figure 6.5 – Long-term cross-comparison of Stuttgart's LUBW measurement stations for PM10. Source: LUBW 2020a, status as of: 24/03/2020.

In this respect it is only possible to make an estimate. Days with PM10 average values of 45 µg/m³ to 50 µg/m³ were considered in particular for this purpose. There were 14 such days in 2019. If the respective daily average value is extrapolated with the average percentage pollutant reduction from the relevant phase as well as weightings of 100% for full operation and 50% for the switching test, then six of these days would be above the limit value. In consideration of the data available from the switching test about the days and the level of the extrapolated value, it is ultimately possible to make an estimate. For example, on 20/01/2019 it is extremely likely that an exceedance was avoided due to the operation of the Filter Cubes. This was also very probably the case on 22/03 and 16/12. The results are tighter on two further days. On 28/02 and 26/06, the tendency towards the values being below the limit is not as a result of the systems. Therefore it is estimated that around 3–5 exceedance days were avoided. Instead of the 27 exceedance days, there could therefore have been around 30–32 exceedance days in 2019. This also does not include any days in which disproportionately large PM10 fluctuations could have resulted in daily averages below 45 µg/m³.

The average values for the first quarter of 2020 in Table 6.6 show that the positive development has continued beyond the end of the project. The quarterly average values for NO2, PM10 and PM2.5 are at the lowest level ever measured. The average NO2 value is around 40 µg/m³. In comparison with the quarter in the previous year, the NO2 and PM10 values decreased by around a third. The only seven cumulative PM10 exceedance days to date are also reason for optimism that this criterion will be able to be met for a third time in succession in 2020. Even though the measurement station at the Neckartor continues to display the highest measurements of the continuous measurement points in the urban Stuttgart area, the difference in the concentrations of PM10 and in particular NO2 in comparison with the Arnulf-Klett-Platz and Bad Cannstatt measurement points is gradually decreasing.

In addition to the continuous spot measurements, in 2019 the LUBW carried out widespread measurements with NO2 passive samplers in the urban Stuttgart area in 2019 (LUBW, 2020d). The data is recorded on a quarterly basis. In addition to the Neckartor location, in the first weeks of October 2019 MANN+HUMMEL filter systems with activated carbon combi filters for NO2 separation were installed on Hohenheimer Straße and Pragstraße. They have been in continuous operation ever since. The phase III switching tests at the Neckartor started on 20/09/2019, i.e. shortly before the start of a new quarter. In relation to the measurement with the passive samplers, the switching test can be considered in simplified terms as a form of continuous operation with 50% of the system capacity. At all system locations, the filters should therefore have an effect on the values for the fourth quarter. Table 6.7 presents a quarterly comparison of the LUBW measurement data for all sites at which data is available from quarters three and four. The comparison of the measurements shows that at 10 out of 10 measurement points there is a decrease in the NO2 concentration in the fourth quarter in the area of the filter systems. The decrease is an average of 4.9 µg/m³, or 10%. At 37 of the 39 remaining measurement points without filter columns, on the other hand, there was an increase in the NO2 concentrations by an average of 6.5 µg/m³, or 28%. This also applies for the traffic hotspot at Arnulf-Klett-Platz, which is not equipped with filter systems. The concentration in the area of the systems is therefore declining in spite of a trend in the opposite direction in the urban background. Apart from the commissioning of the filter systems, the authors are not aware of any emissions reduction measure that was newly introduced in Stuttgart in the fourth quarter of 2019 (see Table 5.1). It must therefore be assumed that these improvements can at least partially be attributed to the filter systems.

Tabelle 6.7 – NO_2 – Messergebnisse von LUBW-Messstationen und Passivsammlern in Stuttgart im 3. und 4. Quartal 2019. Quelle: LUBW, partiell veröffentlicht in LUBW (2020e)

Messstelle	NO_2-Messzeitraum-mittelwert [µg/m³]		Differenz		Mess-verfahren	Kategorie
	2. Quartal	3.Quartal	[µg/m³]	[%]		
Stuttgart Am Kochenhof 5	21	29	8	38%	passiv	KOA
Stuttgart Am Kräherwald 91	18	28	10	56%	passiv	KOA
Stuttgart Am Neckartor	53	48	-5	-9%	kont.	Spot
Stuttgart Am Neckartor 18	48	42	-6	-13%	passiv	Spot Profil
Stuttgart Am Neckartor 20	44	41	-3	-7%	passiv	Spot Profil
Stuttgart Am Neckartor 22 am Baum	46	41	-5	-11%	passiv	Spot Profil
Stuttgart Am Neckartor 22 am Haus	44	38	-6	-14%	passiv	Spot Profil
Stuttgart Am Neckartor 22 auf Station (4 m)	50	49	-1	-2%	passiv	KOA
Stuttgart Arnulf-Klett-Platz	39	43	4	10%	kont.	LMN Verkehr
Stuttgart-Bad Cannstatt	19	28	9	47%	kont.	LMN städt. HG
Stuttgart Elbestraße 123	16	23	7	44%	passiv	KOA
Stuttgart Epplestraße 75	15	24	9	60%	passiv	KOA
Stuttgart Fellbacher Straße/Kilianstraße 28	14	23	9	64%	passiv	KOA
Stuttgart Freihofstraße 42	21	28	7	33%	passiv	KOA
Stuttgart Hallschlag 35	22	31	9	41%	passiv	KOA
Stuttgart Hauptstraße 69	23	29	6	26%	passiv	KOA
Stuttgart Hauptstraße 76	23	27	4	17%	passiv	KOA
Stuttgart Hedelfinger Straße 6	23	30	7	30%	passiv	KOA
Stuttgart Heilbronnerstraße 97	33	36	3	9%	passiv	KOA
Stuttgart Hohenheimer Straße	49	43	-6	-12%	kont.	Spot
Stuttgart Hohenheimer Straße 72	57	51	-6	-11%	passiv	KOA
Stuttgart Immenhofer Straße 42	26	26	0	0%	passiv	KOA
Stuttgart Imweg 47	21	30	9	43%	passiv	KOA
Stuttgart Kappelbergstraße 66	15	26	11	73%	passiv	KOA
Stuttgart Kirchheimer Straße 80	18	27	9	50%	passiv	KOA
Stuttgart Ludwigsburger Straße 115	25	31	6	24%	passiv	KOA
Stuttgart Ludwigsburger Straße 131	28	33	5	18%	passiv	KOA
Stuttgart Neckarstraße 94/96	32	38	6	19%	passiv	KOA
Stuttgart Neue Weinsteige 6A	28	33	5	18%	passiv	KOA
Stuttgart Olgastraße 121	23	30	7	30%	passiv	KOA
Stuttgart Pragstraße 88	50	47	-3	-6%	passiv	KOA
Stuttgart Pragstraße 90/92	59	51	-8	-14%	passiv	Sonder
Stuttgart Rohrackerstraße 22	27	30	3	11%	passiv	KOA
Stuttgart Römerstraße 20	20	27	7	35%	passiv	KOA
Stuttgart Rotebühlstraße 155	25	29	4	16%	passiv	KOA
Stuttgart Scharnhäuser Straße 18	18	25	7	39%	passiv	KOA
Stuttgart Schemppstraße 15 A/B	16	24	8	50%	passiv	KOA
Stuttgart Schwabstraße 8	24	29	5	21%	passiv	KOA
Stuttgart Schwieberdinger Straße 25	20	29	9	45%	passiv	KOA
Stuttgart Schubartstraße 20	20	30	10	50%	passiv	Spot HG
Stuttgart Solitudestraße 212	17	24	7	41%	passiv	KOA
Stuttgart Talstraße 41	49	47	-2	-4%	passiv	Sonder
Stuttgart Vaihinger Landstraße 111	11	20	9	82%	passiv	KOA
Stuttgart Vaihinger Straße 94a	26	27	1	4%	passiv	Sonder
Stuttgart Wagenburgstraße 78	30	38	8	27%	passiv	KOA
Stuttgart Wagrainstraße 73 A/B	18	24	6	33%	passiv	KOA
Stuttgart Waiblinger Straße	32	38	6	19%	passiv	Spot
Stuttgart Welfenstraße 63	21	26	5	24%	passiv	KOA
Stuttgart Wiener Straße 71	18	27	9	50%	passiv	KOA

Konto.: continuous measurement; passiv: passive measurement; KOA: supplementary measurements on behalf of the coalition committee; LMN städt. HG: urban background air measurement network; LMN Verkehr: air measurement network for location close to traffic; Sonder: special measurement at location close to traffic; Spot: spot measurement at location close to traffic; Spot Profil: spot measurement profile measurement point; Spot HG spot measurement background measurement point.

6.3 In-situ tests

The on-site tests were used to test and visualise the filter function in line with the design in real usage conditions, and to deduce meaningful test parameters. The former is particularly necessary on order to check the input parameters for the MISKAM simulations.

6.3.1 Measurement of the NO_2 separation efficiency using ICAD measurements

The reduction effect of the systems forecast using the MISKAM simulations is based on the assumption that on average over their service life the filters separate 80% of the intake NO2. Starting from values well above 90%, the NO2 separation efficiencies of the activated carbon filter elements used decrease as the operation time increases. In order to maintain the average value of 80%, the filters must be replaced regularly. The prediction of the change interval in turn required a technical component design based on laboratory data and the results of field tests. Under the boundary conditions of the simulation, a service life of 14 days was predicted for the activated carbon filters of Filter Cube generation 1 (phase II), and 30 days was predicted for generation 2 (phase III). In order to test this information, the Airyx ICAD Analyzer was used to directly determine the NO2 separation efficiency of the filter elements in the Filter Cubes. For this purpose, the measurement device was installed in a column on the Heilmannstraße/B14 corner (see 5.3.1) and the dirty and clean gas concentrations were measured continuously.

The results confirm the original service life prediction according to the component design, even in the real boundary conditions in the field test. The separation efficiency progressions for the two filter types determined in the test resulted in standard replacement intervals of 11 days for the elements of Filter Cube generation 1 and 32 days for Filter Cube generation 2. In spite of the higher volumetric flow of the second-generation Filter Cube, the service life of the optimised filter element is roughly three times that in the conventional design of generation 1.

6.3.2 On-site measurements to visualise the system effect on the particulate matter ambient concentration

In phase I, on-site measurement campaigns were carried out with mobile particulate matter measurement devices. For this purpose switching tests were carried out over a few hours. It is true that switching tests with this kind of restricted scope do not allow quantitatively reliable results to be achieved (see 5.1.1), but they are very well suited for visualising the surface effect of the systems. So that several ON and OFF statuses could be included within each test series, the switching interval had to be reduced to 20–30 minutes. As aggregated PM10 values in such short time intervals display considerably higher relative standard deviations than the particle count concentrations (see section 5.1.3), the measurement data is presented using this variable. The jumps in concentration between the ON and OFF status shown are then much lower than for PM10 because the filters have a lower separation efficiency for the fine fractions.

A test from 18/01/2019 will be presented here as an example. This test and others can be found in Yildiz (2019). The simulations from section 4.3 predicted steep gradients for the particulate reduction along the building development on the western side. The test presented in Figure 6.6 is intended to present the progression of the pollutant reduction between the LUBW measurement station and the closest Filter Cube at several support points. As a reference point, a measurement device was positioned outside of the immediate effective range of the systems in order to be able to balance out the changes in concentration due to the time of day between the switching phases.

The progression of the switching statuses is clearly visible in the measurement data in Figure 6.4. The concentrations decrease during the ON phases and increase again during the OFF phases. Immediately behind the Filter Cube the count concentration fluctuates by 25–30%. At six metres away the figure is roughly 10%, and at eight metres away it is only 5%. The concentration-reducing effect therefore reduces as expected as the distance from the columns increases. The effect to be expected at the LUBW measurement station is accordingly lower than in other areas of the installation, in which there is a higher density of filter columns.

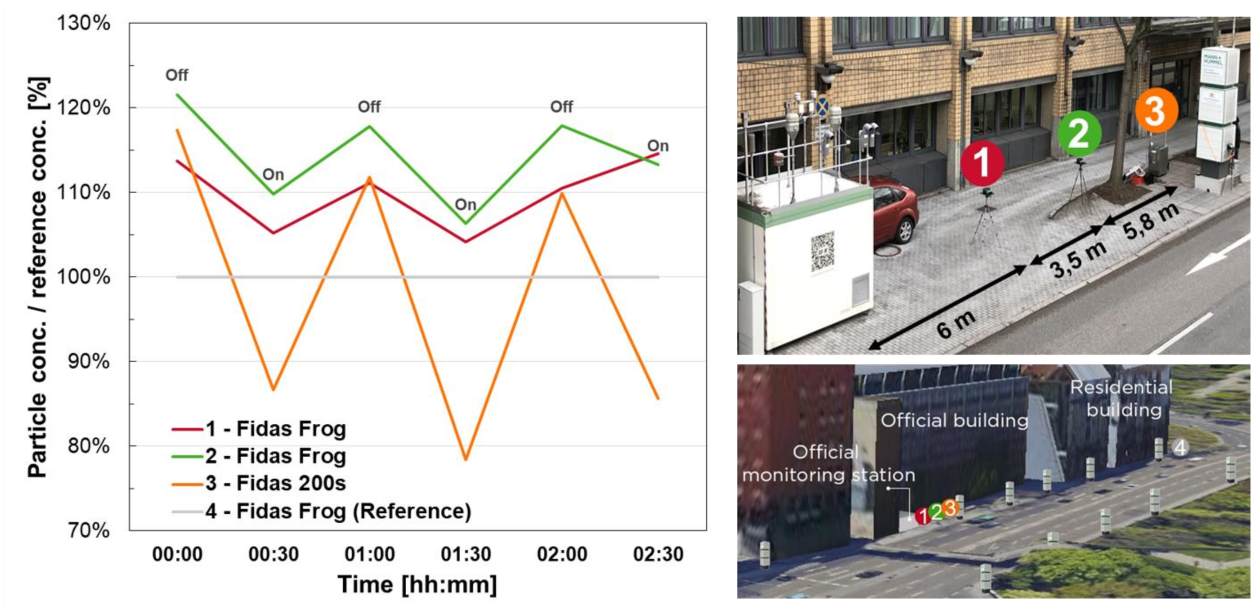


Figure 6.6 – Progression of the relative count concentration at several measurement points along the building development on the western side, 18/01/2019.

6.4 Assessment of control concepts on the basis of the switching tests

Adjusted control concepts allow site-dependent potentials to be used to reduce the power consumption of the systems. For this purpose it is first necessary to analyse the conditions in which the systems yield low pollutant reductions. The broad scope of the switching test in phase III made it possible to carry out a targeted investigation of the effect of the filter systems in various boundary conditions. This is done by dividing the dataset based on various parameters. When doing so, the sub-groups must each be sufficiently large in order to be able to provide meaningful average values. If this is the case, then it is possible to assess what influence the individual data groups have on the overall result and whether this is in an appropriate ratio to the amount of electricity saved. In order to implement this kind of control strategy, it is necessary for live measurement data to be available based on which the control can be carried out.

6.4.1 NO_2 concentration as a control variable

The NO2 concentration is a possible control parameter for the systems. The lower the dirty gas concentration, the lower the absolute quantity of NO2 collected by the filters per time unit. Operating hours with a very low concentration therefore make a below-proportional contribution to the total filtered amount. It is possible to introduce a threshold for the NO2 concentration as a control variable, below which the systems will be switched off. In order to assess the influence of this kind of threshold-linked switching off from the switching test, initially blocks of neighbouring OFF and ON intervals were formed. Then the dataset was subdivided using the concentration in the OFF status. Then the absolute concentration change and the proportion of the overall performance achieved in the time intervals below the threshold were calculated.

Table 6.8 shows the expected decrease in the pollutant reduction at the various measurement points for four thresholds of the NO2 concentration at the LUBW measurement station. The specified percentage values relate to the decrease of the reduction effects listed in 6.1.3 (e.g. 11% of 8.9% in the case of NO2 and a threshold value of 30 µg/m³). The proportion of the time window below the threshold in turn approximately corresponds to the proportion of electricity that can be saved by switching off. The lower the ratio between the reduction in performance and the operating time that can be saved, the more sensible the control system becomes.

The higher the threshold, the greater the volume of data in the data block under the threshold. In the case of the MANN+HUMMEL sensors, in some cases the volume of data available is so low that the values were ignored due to the low expected accuracy. Up to a threshold of 25 µg/m³, the decrease in performance to be expected for all pollutants is in the low to moderate single-figure percentage range. In the case of NO2, there are particularly favourable conditions because the ratio of the performance decrease to the number of operational interruptions is particularly small. This ratio tends to be more unfavourable for threshold values of 30 µg/m³ and above. The potential losses in performance are lower at the LUBW measurement station than at the MANN+HUMMEL measurement points. The reason for this is that the dataset for the measurement station is separated precisely at the threshold value, while the data for the data recorded at the same time at the remaining measurement points is still subject to the locally typical high fluctuations. An appropriate threshold value for system control using the NO2 concentration at the LUBW measurement station seems to be around 25 µg/m³. In the case of higher threshold values, the inclusion of further sensor data would be recommended in order to exclude situations in which there are considerably lower concentrations at the measurement point than in the surroundings.

Table 6.8 Dependence of the reduction in performance on the threshold when using the NO2 values from the LUBW measurement station as a reference. Numbers in brackets are based on very low data volumes.

		Erwarteter Rückgang der Schadstoffminderung			
Schwellwert NO_2 @ LUBW [µg/m³]		**20**	**25**	**30**	**35**
Zeitfenster unter dem Schwellwert		6%	10%	18%	26%
Messstation / LUBW	**NO_2**	1%	2%	11%	11%
Amtsgericht / GSA19		(6%)	(11%)	13%	26%
Wohnhäuser / GSA19		(8%)	(13%)	6%	23%
Park West / GSA19		(7%)	(6%)	11%	18%
Schwabengarage / GSA19		(10%)	(12%)	19%	31%
Messstation / LUBW	**PM10**	3%	7%	14%	18%
Park West / FIDAS 200s		1%	3%	11%	17%
Messstation / LUBW	**PM2.5**	3%	6%	24%	15%
Amtsgericht / FDS18		(0%)	(-1%)	27%	21%
Wohnhäuser / FDS18		(1%)	(-1%)	30%	18%
Park West / FIDAS 200s		1%	4%	16%	19%
Park West / FDS18		(0%)	(3%)	13%	16%
Park West / FDS18		(2%)	(-3%)	21%	15%
Schwabengarage / FDS18		(10%)	(-10%)	42%	29%

6.4.2 Wind force as a control variable

There are two data sources available for assessing the influence of wind on the test results. Firstly, the WS600 weather station was used via the Palas Fidas 200 to measure the wind direction and wind speed in the immediate vicinity of the road at a height of 1.5 m at the park side west measurement point. Secondly, the weather data of the LUBW Bernhausen station are available and can be used as indicators for the general weather situation in the Neckar valley.

The wind speeds from the on-site measurement are lower than the Bernhausen values. At the WS600, the median half-hourly average values for the wind speed in the test period were around 0.4 m/s, while in Bernhausen the figure was around 1.1 m/s. The wind direction also differs. At the WS600 the main wind direction in 92% of the intervals was east/north east and therefore parallel to the carriageway. The local flow conditions in the area of the systems are therefore significantly influenced by the traffic. The westerly and south-westerly winds prevailing in Bernhausen are very rare in the WS600 data and when they do occur it is only high to very high wind speeds of over 1 m/s.

Table 6.9 shows the overall result of the switching test for datasets that have been separated using the median wind speed. In this case it can first be seen that the percentage reductions in the pollutant concentrations are lower with a high wind speed than when the wind speed is lower. This results in the hypothesis that it could be beneficial to implement system control with wind speed as a control variable. However, the differences between the averages in the ON and OFF status, which are not bigger in all scenarios where there is little wind, are crucial in this case. At the WS600, the reverse case has even occurred for the concentrations of NO2 and PM10. This is probably due to the fact that the wind speed there correlates with traffic density. Therefore high wind speed implies heavy traffic and therefore heavy pollutant input. The use of a wind speed sensor in the vicinity of the road is therefore classified as unsuitable for system control at the Neckartor. As the division according to the Bernhausen wind speed, on the other hand, delivers the expected low concentrations for high wind speeds (see Table 6.9 below), the division was repeated with the 90% percentile of the wind speed there (3.2 m/s) as the threshold value. This corresponds to the system switching off in the top tenth of the time window with the strongest wind. Discarding this time window would ultimately result in a drop in system performance by more than 10%. Control based on the existing weather stations is therefore counter-productive. As the NO2 concentration has a negative correlation with the wind speed, strong wind scenarios are implicitly covered in the event of control using the NO2 concentration. Therefore the NO2 concentration is better suited as a control indicator than the wind force.

Table 6.9 Division of the switching test data according to wind force. Top: Measurements above and below the median from WS600. Bottom: Measurement from the LUBW Bernhausen measurement station.

		In-situ measurement at Neckartor (Park North-West)							
		Wind speed > 0.4 m/s				Wind speed < 0.4 m/s			
		Mean ON [µg/m³]	Mean OFF [µg/m³]	Difference [µg/m³]	Reduction	Mean ON [µg/m³]	Mean OFF [µg/m³]	Difference [µg/m³]	Reduction
LUBW Station	NO_2	47.9	50.4	2.5	**5.0%**	43.0	47.4	4.4	**9.4%**
Avg. M+H Spots	NO_2	50.1	55.2	5.0	**9.0%**	39.5	44.5	5.0	**11.1%**
LUBW Station	PM10	23.0	23.7	0.8	**3.3%**	18.4	19.8	1.4	**7.3%**
Avg. M+H Spots	PM10	29.7	35.0	5.3	**15.2%**	14.7	19.8	5.1	**25.6%**
LUBW Station	PM2.5	9.5	9.9	0.3	**3.3%**	10.0	10.9	1.0	**8.9%**
Avg. M+H Spots	PM2.5	11.2	12.4	1.2	**8.8%**	10.5	11.8	1.3	**11.0%**

		LUBW station @ Bernhausen							
		Wind speed > 1.1 m/s				Wind speed < 1.1 m/s			
		Mean ON [µg/m³]	Mean OFF [µg/m³]	Difference [µg/m³]	Reduction	Mean ON [µg/m³]	Mean OFF [µg/m³]	Difference [µg/m³]	Reduction
LUBW Station	NO_2	43.2	47.1	3.9	**8.2%**	47.4	51.0	3.6	**7.1%**
Avg. M+H Spots	NO_2	49.2	54.1	4.9	**9.0%**	40.1	45.2	5.1	**11.1%**
LUBW Station	PM10	16.6	17.7	1.1	**6.0%**	25.0	26.9	1.9	**7.0%**
Avg. M+H Spots	PM10	20.7	25.3	4.6	**18.2%**	23.3	31.5	8.2	**26.1%**
LUBW Station	PM2.5	6.9	7.3	0.4	**6.1%**	12.8	13.7	0.9	**6.5%**
Avg. M+H Spots	PM2.5	9.7	10.6	0.9	**8.4%**	12.3	14.3	1.9	**12.8%**

6.4.3 Effect of the systems according to time of day

Analogously to the previous considerations, it is also possible to assess the times of day at which the systems on the Neckartor yield below-proportional performance. For this purpose time blocks of at least three hours must be used in order for the resulting average values to be significant. The contribution of all possible three-hour and four-hour time windows to the overall performance of the filter systems has been calculated. Out of the three-hour time windows, the block from 1 am to 4 am local time contributed the least to the overall result with 3.1% for NO2 and 6.6% for PM10. This is contrasted with a 12.5% reduction in operating time. Out of the four-hour time windows, it was the block from 1 am to 5 am local time with 7.4% for NO2 and 9.2% for PM10 (operating time reduction of 16.7%). Switching the columns off at night is therefore an efficient way to achieve energy optimisation at the Neckartor and in terms of effect is comparable to controlling the system via NO2.

7 Summary

As part of a pilot project by MANN+HUMMEL, sponsored by the Baden-Württemberg Ministry of Transport and supported by the state capital Stuttgart, the first large-scale installation of 'Filter Cube' type filter columns was put into operation at Stuttgart's 'Am Neckartor' traffic hotspot in December 2018. Three hardware configurations were then tested over the course of 2019. Starting with 17 filter systems with purely particulate matter filters for PM10 reduction (phase I), a conversion was then carried out to activated carbon combi filter elements to test the fundamental potential to reduce NO2 using this kind of filter (phase II) and finally the project was expanded to 23 higher-performance filter columns with optimised NO2 filter elements (phase III).

Via endurance tests with a total duration of 144 measurement days, it was possible to confirm the stipulated aims of all three phases for pollutant reduction of NO2 and PM10. The test method was based on a permanent measurement of the pollutant concentrations with periodical switching of the operating status. The result was average values for pollutant concentrations when the systems were ON and OFF. The evidence of the reduction effect for the significant pollutant (phase I: PM10, phase II & III: NO2) was provided in each case with high statistical significance of 99.5% and above.

In the test period of the endurance tests, the following reductions were identified at the official 'Am Neckartor' measurement station of the Landesanstalt für Umwelt Baden-Württemberg (Baden-Württemberg Regional Environment Office, LUBW):

Phase I: PM10 reduction by 10.4%

Phase II: NO2 reduction by 6.0%

Phase III: NO2 reduction by 8.9%, PM10 reduction by 6.7%

In addition, during the course of test phase III, the official measurement data was supplemented by a measurement network set up by MANN+HUMMEL in order to examine the effect of the filter columns on NO2 and particulate matter concentrations at other points in the measurement area. This results in NO2 reductions of 8.0% to 19.4% (6 measurement points), PM10 reductions of 20.8% (1 measurement point) and PM2.5 reductions of 4.7% to 20.2% (7 measurement points).

The tests in phase I and III were preceded by preliminary investigations via MISKAM simulations carried out by an independent consultant (Ingenieurbüro Rau, Heilbronn), which presented the prospect of reduction effects of 10–30% in the area near the building that requires protection. There was a very good correlation between the test results at the measurement points and the numerical forecasts. Consequently, subject to the model assumptions made, it must be assumed that the simulation method is suitable for forecasting the effect of filter systems in the open air. This is particularly relevant for statements about the surface effect of systems, because even long-term experiments only allow for spatially-limited statements about concentration reductions. In this case the simulation can provide the missing surface information.

In addition to the switching tests, data from LUBW NO2 passive samplers in the urban Stuttgart area provide strong indicators of the effect of the filter systems. The MANN+HUMMEL filter systems at the Neckartor, Hohenheimer Straße and Pragstraße were put into operation between mid-September and mid-October 2019. At 10 out of 10 measurement points in the area influenced by the filter systems, the NO2 concentration subsequently reduced by an average of 10% (-4.8 µg/m³) from the third to fourth quarter. This is a striking contrast to the trend in the rest of the city area, where 37 out of 39 measurement points recorded increasing values (average value +28% or +6.8 µg/m³).

8 Acknowledgements

MANN+HUMMEL GmbH thanks Baden-Württemberg Ministry of Transport for sponsoring the project. The authors also thank Dr Rayk Rinke from Stuttgart Department for Environment Protection and Prof. Achim Dittler from the Karlsruher Institute of Technology for the specialist consultations as well as the Baden-Württemberg Regional Environment Office for providing the measurement data.

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10 Appendix – Statistical parameters for the switching tests

Table 10.1 – Values of the Welch test for the difference between the average values for the switching tests, based on the results for the LUBW measurement station.

Degree of freedom (Welch-Satterthwaite)	**Pollutant**			
	NO2	**PM10**	**PM2.5**	**O3**
Phase 1	859	883	916	-
Phase 2	1289	1301	1295	1269
Phase 3	3245	3216	3225	3113
Phase 3. 1st half h	1554	1545	1547	1480
Phase 3. 2nd half h	1560	1538	1541	1496

t-values	**Pollutant**			
	NO2	**PM10**	**PM2.5**	**O3**
Phase 1	0.05	2.72	1.70	-
Phase 2	2.67	1.30	1.53	1.20
Phase 3	5.33	2.70	2.34	2.72
Phase 3. 1st half h	3.13	1.61	1.32	1.79
Phase 3. 2nd half h	4.52	2.03	1.95	2.22

p-values (one-sided)	**Pollutant**			
	NO2	**PM10**	**PM2.5**	**O3**
Phase 1	48%	0.3%	4.5%	-
Phase 2	0.4%	9.7%	6.3%	11.4%
Phase 3	0.000005%	0.3%	1.0%	0.3%
Phase 3. 1st half h	0.09%	5.3%	9.3%	3.7%
Phase 3. 2nd half h	0.0003%	2.1%	2.6%	1.3%

p-values (two-sided)	**Pollutant**			
	NO2	**PM10**	**PM2.5**	**O3**
Phase 1	95.7%	0.7%	9.0%	-
Phase 2	0.8%	19.3%	12.7%	22.9%
Phase 3	0.00001%	0.7%	2.0%	0.7%
Phase 3. 1st haf h	0.2%	10.7%	18.6%	7.4%
Phase 3. 2nd half h	0.0007%	4.3%	5.1%	2.7%

Table 10.2 – Parameters of the Welch test for the difference between the average values for the switching tests, overall result for all data sources.

Position	Start of measure-ment	Datenquelle	Meas.	Results (1st and 2nd half hour): Mean ON [µg/m³]	Mean OFF [µg/m³]	Difference [µg/m³]	Reduction	Welch-Test: Std.-Dev. ON [µg/m³]	Std.-Dev. OFF [µg/m³]	Intervals ON	Intervals OFF	Standard Error [µg/m³]	t	Degrees of freedom	1-p (one-sided)	1-p (two-sided)
LUBW Station	19/09/22	LUBW	NO2	45.2	48.9	3.7	**7.5%**	18.6	20.7	1630	1647	0.7	5.32	3245	>99,99%	>99.99%
			PM10	20.5	21.9	1.4	**6.3%**	13.8	14.8	1622	1614	0.50	2.7	3216	99.7%	99.4%
			PM2.5	9.8	10.4	0.6	**5.9%**	7.0	7.4	1622	1614	0.25	2.4	3222	99.3%	98.5%
			O3	12.7	14.1	1.5	**10.3%**	13.3	14.9	1532	1595	0.50	2.9	3107	99.8%	99.6%
	19/10/31	Födisch GSA19	NO2*	50.5	54.4	3.9	**7.2%**	19.6	22.6	223	237	1.97	2.0	455	97.6%	95.2%
				49.3	52.5	3.3	**6.3%**	18.6	19.8	223	237	1.79	1.8	458	96.7%	93.3%
		Födisch FDS18	PM2.5	9.3	9.9	0.6	**6.3%**	5.9	6.1	532	533	0.37	1.7	1062	95.6%	91.3%
				10.1	10.6	0.5	**4.8%**	6.3	6.5	531	532	0.39	1.3	1060	90.2%	80.4%
Admin. Building West (Am Neckartor 22)	19/10/31	Födisch GSA19	NO2*	45.6	51.3	5.7	**11.2%**	16.1	17.5	354	376	1.24	4.6	728	>99,99%	>99.99%
		Födisch FDS18	PM2.5	10.2	11.4	1.1	**10.0%**	6.2	7.1	697	697	0.36	3.2	1371	99.9%	99.8%
Residential West (Am Neckartor 18)	19/10/31	Födisch GSA19	NO2*	43.2	46.9	3.7	**7.8%**	15.8	17.0	353	375	1.22	3.0	726	99.9%	99.7%
		Födisch FDS18	PM2.5	9.7	10.3	0.7	**6.3%**	6.1	6.7	691	693	0.34	1.9	1372	97.1%	94.1%
Park (North-West)	19/11/04	Födisch GSA19	NO2*	41.6	49.9	8.4	**16.8%**	14.0	15.1	326	346	1.12	7.5	670	>99,99%	>99.99%
		Födisch FDS18	PM2.5	12.0	14.0	2.0	**14.3%**	6.3	7.9	609	611	0.41	4.9	1163	>99,99%	>99.99%
	19/09/22	Palas Fidas 200s	PM10	21.8	27.9	6.1	**22.0%**	19.5	24.8	1654	1654	0.78	7.9	3131	>99,99%	>99.99%
			PM2.5	8.9	10.9	2.0	**18.2%**	6.3	7.7	1586	1599	0.25	7.9	3076	>99,99%	>99.99%
		Födisch FDS18	PM2.5	10.7	13.3	2.6	**19.7%**	7.0	8.5	1637	1635	0.27	9.6	3153	>99,99%	>99.99%
Commercial Building (South-East)	19/11/04	Födisch GSA19	NO2*	43.3	46.2	2.8	**6.2%**	15.5	17.2	339	359	1.24	2.3	694	98.9%	97.8%
		Födisch FDS18	PM2.5	13.9	14.1	0.3	**1.8%**	9.5	8.3	614	614	0.51	0.5	1204	68.9%	37.8%

Table 10.3 – Parameters of the Welch test for the difference between the average values for the switching tests, separate result for the first and second half-hour intervals for all data sources.

Position	Start of measure-ment	Datenquelle	Meas.	Results (only 1st half hour): Mean ON [µg/m³]	Mean OFF [µg/m³]	Difference [µg/m³]	Reduction	Welch-Test: Std.-Dev. ON [µg/m³]	Std.-Dev. OFF [µg/m³]	Intervals ON	Intervals OFF	Standard Error [µg/m³]	t	Degrees of freedom	1-p (one-sided)	1-p (two-sided)
LUBW Station	19/09/22	LUBW	NO2	46.3	49.4	3.1	**6.2%**	18.6	20.5	773	790	1.0	3.12	1552	99.9%	99.8%
			PM10	20.8	22.0	1.2	**5.4%**	14.0	14.8	771	775	0.73	1.6	1540	94.6%	89.3%
			PM2.5	9.9	10.3	0.5	**4.6%**	7.0	7.3	740	748	0.37	1.3	1485	90.2%	80.5%
			O3	12.5	13.8	1.3	**9.4%**	13.5	14.5	689	734	0.74	1.8	1421	96.0%	92.0%
	19/10/31	Födisch GSA19	NO2*	51.5	54.7	3.2	**5.8%**	18.9	22.0	109	113	2.75	1.2	217	87.5%	74.9%
				50.7	53.2	2.5	**4.7%**	18.5	20.0	109	113	2.58	1.0	220	83.1%	66.2%
		Födisch FDS18	PM2.5	9.3	10.0	0.7	**7.0%**	5.8	6.3	257	256	0.53	1.3	508	90.4%	80.8%
				10.1	10.8	0.7	**6.2%**	6.2	6.6	256	255	0.57	1.2	507	88.0%	76.0%
Admin. Building West (Am Neckartor 22)	19/10/31	Födisch GSA19	NO2*	47.0	51.8	4.9	**9.4%**	15.6	17.8	169	180	1.79	2.7	345	99.7%	99.3%
		Födisch FDS18	PM2.5	10.3	11.4	1.1	**9.6%**	6.3	7.0	335	334	0.52	2.1	658	98.2%	96.4%
Residential West (Am Neckartor 18)	19/10/31	Födisch GSA19	NO2*	46.8	49.1	2.3	**4.8%**	15.4	17.1	169	179	1.74	1.3	345	91.0%	82.0%
		Födisch FDS18	PM2.5	9.6	10.2	0.6	**5.9%**	6.1	6.6	334	334	0.50	1.2	662	88.9%	77.9%
Park (North-West)	19/11/04	Födisch GSA19	NO2*	42.8	50.4	7.6	**15.0%**	14.0	15.1	157	165	1.62	4.7	320	>99,99%	>99.99%
		Födisch FDS18	PM2.5	12.0	14.0	2.0	**14.0%**	6.5	7.9	294	292	0.60	3.3	563	99.9%	99.9%
	19/09/22	Palas Fidas 200s	PM10	22.0	28.4	6.4	**22.6%**	19.6	24.8	788	793	1.12	5.7	1503	>99,99%	>99.99%
			PM2.5	9.0	10.9	2.0	**18.0%**	6.3	7.7	757	774	0.36	5.5	1488	>99,99%	>99.99%
		Födisch FDS18	PM2.5	10.7	13.3	2.6	**19.6%**	6.7	8.5	783	787	0.39	6.8	1494	>99,99%	>99.99%
Commercial Building (South-East)	19/11/04	Födisch GSA19	NO2*	45.3	46.2	1.0	**2.1%**	16.2	16.6	162	172	1.80	0.5	332	70.3%	40.6%
		Födisch FDS18	PM2.5	14.3	14.1	-0.2	**-1.6%**	11.0	8.0	295	295	0.79	-0.3	535	38.6%	-

Position	Start of measure-ment	Datenquelle	Meas.	Results (only 2nd half hour): Mean ON [µg/m³]	Mean OFF [µg/m³]	Difference [µg/m³]	Reduction	Welch-Test: Std.-Dev. ON [µg/m³]	Std.-Dev. OFF [µg/m³]	Intervals ON	Intervals OFF	Standard Error [µg/m³]	t	Degrees of freedom	1-p (one-sided)	1-p (two-sided)
LUBW Station	19/09/22	LUBW	NO2	45.5	50.0	4.4	**8.9%**	18.5	20.6	788	790	1.0	4.51	1558	>99,99%	>99.99%
			PM10	20.8	22.3	1.5	**6.8%**	13.9	15.0	770	774	0.74	2.1	1534	98.1%	96.2%
			PM2.5	9.8	10.5	0.7	**6.8%**	6.9	7.4	741	749	0.37	1.9	1484	97.3%	94.5%
			O3	12.5	14.0	1.6	**11.2%**	12.9	14.9	730	732	0.73	2.2	1433	98.5%	96.9%
	19/10/31	Födisch GSA19	NO2*	50.0	54.9	4.9	**8.9%**	20.2	23.3	111	119	2.87	1.7	227	95.5%	91.0%
				48.5	52.7	4.2	**8.0%**	18.6	19.4	111	119	2.51	1.7	228	95.3%	90.6%
		Födisch FDS18	PM2.5	9.3	9.9	0.6	**6.3%**	6.0	5.9	255	256	0.53	1.2	509	88.5%	77.0%
				10.2	10.7	0.5	**4.7%**	6.4	6.4	255	256	0.57	0.9	509	81.3%	62.6%
Admin. Building West (Am Neckartor 22)	19/10/31	Födisch GSA19	NO2*	45.1	51.8	6.7	**12.9%**	16.3	17.2	177	185	1.76	3.8	360	>99,99%	99.98%
		Födisch FDS18	PM2.5	10.2	11.5	1.2	**10.9%**	6.2	7.1	334	336	0.52	2.4	656	99.2%	98.4%
Residential West (Am Neckartor 18)	19/10/31	Födisch GSA19	NO2*	40.6	45.7	5.1	**11.2%**	15.3	16.8	176	185	1.69	3.0	358	99.9%	99.7%
		Födisch FDS18	PM2.5	9.7	10.4	0.7	**7.0%**	6.0	6.8	331	334	0.50	1.5	656	92.8%	85.5%
Park (North-West)	19/11/04	Födisch GSA19	NO2*	40.9	50.7	9.8	**19.4%**	13.9	14.7	163	171	1.57	6.3	332	>99,99%	>99.99%
		Födisch FDS18	PM2.5	11.9	14.1	2.2	**15.8%**	6.1	7.9	291	296	0.58	3.8	554	>99,99%	99.99%
	19/09/22	Palas Fidas 200s	PM10	22.4	28.3	5.9	**20.8%**	19.9	25.1	792	795	1.14	5.2	1508	>99,99%	>99.99%
			PM2.5	9.0	11.0	2.0	**18.0%**	6.4	7.7	760	771	0.36	5.5	1485	>99,99%	>99.99%
		Födisch FDS18	PM2.5	10.7	13.4	2.7	**20.2%**	6.8	8.5	781	782	0.39	7.0	1489	>99,99%	>99.99%
Commercial Building (South-East)	19/11/04	Födisch GSA19	NO2*	42.2	47.1	4.9	**10.3%**	14.6	17.6	169	177	1.73	2.8	337	99.7%	99.5%
		Födisch FDS18	PM2.5	13.4	14.3	0.9	**6.5%**	7.7	8.6	295	295	0.67	1.4	582	91.6%	83.2%