# Implementation of air filter technology in road tunnels

## A study regarding air purification and health

Master’s thesis in civil engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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# Preface

Thanks to all the people involved who helped and made this education and master’s thesis possible to conduct.

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Kevin Walian
Chalmers University of Technology
Gothenburg, 2019

# Abstract

Road traffic is the major source of $PM_{10}$, $PM_{2.5}$ and $NO_x$ in ambient air, which all are evidently harmful to the human health. While infrastructure is continuously developed, pollutions in ambient air is increased as a result of rising traffic. Despite difficulties to collect emissions to prevent the harmful effects, one possible location of assembly is road tunnels. The aim of this study is to see what possibilities extract tunnel air may have of reducing negative impact on local human health and environment.

The method of this study is executed by a case study in Stockholm, Sweden. Possibilities to implement an electrostatic particle filter in one of Sweden's biggest infrastructure investments, the Stockholm bypass, is investigated. The bypass is to bind the southern and northern part of Stockholm with a 19 km long tunnel, with 6 different interchanges. The interchange with the most pollution, Kungens kurva, is to be studied further for implementation of electrostatic particle filter.

Results are retrieved from a dispersion calculation by the Swedish transport administration and filter results from ESP filter manufacturer Aigner. The dispersion calculation shows that the predicted most polluted interchange, Kungens kurva, is to exceed the EQS in terms of $PM_{10}$ outside the road area and $NO_x$ within the road area. Filter tests made by Aigner show a total suspension of particles by 77% AWG and 72% of $PM_{10}$.

The filter test was not identical to pre-sets of the projected tunnel ventilation system. EQS are shown to be exceeded outside the road area, exposing nearby residential areas to harmful levels of $PM_{10}$. The filter results show a great potential in intercepting this kind of harmful particle. No investigation has yet been done by the Swedish transport administration in regards of filter lifecycle costs or efficiencies of particle removal for the specific purpose of health impacts.

In conclusion the Swedish transport administration is suggested to further investigate the potential of electrostatic particle filter and compare similar reference projects provided in this study. An additional dispersion calculation is recommended to be conducted with ameliorated measurements, including such of an electrostatic particle filter. Studies regarding life cycle calculations of ESPs including natural resources required for the filter technology, energy consumption and waste-management is recommended for further studies.

Discussing ratios regarding socio-economic loss and moral terms in comparison to the avoidance of congestion is of importance. The bypass is shown to certainly increase the risk of negative health impacts along the suburban areas where it is to be built, whilst inner-city residentials are to be relieved of emissions. In order to prevent an inequity that may inflate segregation, politicians and authorities are urged to re-assess, investigate and analyse the available technology, such as the electrostatic particle filters.

# Table of content

# 1. Introduction

According to the world health organization (World Health Organization, 2018) air pollutions is the biggest environmental risk for human health. With 9 out of 10 people breathing air containing high levels of pollutants, it is estimated that 4.2 million premature deaths are a result of exposure to outdoor air pollution. The premature deaths are mainly linked to heart diseases, stroke, lung cancer, chronic pulmonary diseases and acute respiratory infections in children. There is strong evidence that the mentioned public health diseases are related to the exposure of particulate matter (PM), ozone, nitrogen dioxide and sulphur dioxide in ambient air. Especially documented is the associated health risks with PM of less than 10 and 2.5 µm, respectively, that can penetrate deep into lungs and into the bloodstream causing cancer and impacting vital respiratory functions (Naturvårdsverket, 2019).

The subject of the environment and human health is often closely connected to infrastructure projects. Larger infrastructure projects are not only analysed of the economic aspects, but also from the point of view of environmental and health benefits such as noise and ecological diversity. Inevitably, questions regarding air quality management arises, were tunnels often is a solution to reduce the direct impact on the environment such as noise and pollution, as is the case of most tunnel projects. However, in some circumstances, a tunnel may not be the most appropriate solution (Dix, 2006) **.** This is due to the direct local impact the tunnel and its air emission locations, which may change the air quality.

With regards to local impact of tunnel discharges, important social justice questions arise, in example local pollution of the area. Such questions are due to the people who benefit the tunnel generally do not live near it, but still belong to the transport network (Dix, 2006). Pollutants burden the people living nearby the tunnel outlets, where air quality changes may be located. This kind of benefit versus burden dilemma requires a deep socio-economic analysis and is often an essential discussion during the tunnel design (Dix, 2006). Hence, management of local air pollution by extract tunnel air is of importance in order to reduce the local burdens of the nearby community, so that the tunnel may benefit the society.

This M.Sc. thesis investigates the possibilities of benefiting the society in environmental and health aspects by extract road tunnel air treatment by filtration, as well as how authorities may proceed in order to also favour the society in a broader range.

## 1.2 Purpose

The purpose of this study is to see how extract tunnel air filtration may reduce negative impact on local human health and environment. The purpose of this paper is also to analyse the combination of infrastructure- and filter technology to preserve broader perspectives of socioeconomics and welfare.

## 1.3 Limitations

The study is limited to examining how the filtering extract air of a road tunnel may reduce harmful emissions, caused by traffic in tunnels. The study is restricted to road tunnels and concerns emissions from road traffic, i.e. cars, trucks and motorcycles. Specifically, this paper is examining the possibilities of treating extract tunnel air by filtration of the most polluted area in one of Sweden's largest infrastructure projects in history, Stockholm bypass (förbifart Stockholm).

## 1.4 Issue specification

The aim of this study is targeted within the limitations with following questions of issue:

- What levels of harmful pollutants is the specified area of Kungens kurva to have without extract air treatment and what would this result in?
- How can extract tunnel air be treated by filtration?
- What are potential results of such a treatment?
- How much would such treatment cost?
- What would the benefits of the society be as a result of the costs?

# 2 Method

A literature study is made for a wide perspective regarding the subjects of infrastructure and filter technology by providing solid facts with respect to current technology available. For current infrastructure situations, local and national authorities are contacted. Their current investigations within the field of extract tunnel air treatment, such as filtration is questioned. Filter technology companies are contacted in order to understand the immerse specifications of their products, how they may be applied in tunnel ventilation systems to enhance the reduction of emissions in the extract air and what the cost might be. The results show to what extent the filters may be applied in bypass Stockholm, what results they may provide and what price they are to cost. An analyse is made in order to discuss the socio-economic value of such technologic implementation.

# 3 Background

Passage of vehicles in road tunnels emit emissions such as $PM_{10}$, $PM_{2,5}$, soot, nitric oxide (NO) and nitric dioxide ($NO_2$)(Johansson, Silvergren, Norman, & Sjövall, 2013a). The sum of the nitric particles is called $NO_x$. All types of particles have been shown to have an impact on the environment and human health.

Particles from vehicles, tires and break wear, are let out with the extract air to the atmosphere. They are then inhaled and remain in the lungs, causing premature deaths. Some of the particles also get through the ventilation system of cars while in the tunnel (Johansson, Silvergren, Norman, & Sjövall, 2013). In order to prevent the vehicle discharges to be inhaled, both inside and outside the tunnel, effective ventilation and filtration is necessary. However, many tunnel ventilation systems fail to intercept these particles. In example, Stockholm bypass in Sweden (förbifart Stockholm) is an 18 km tunnel, binding the capitals highway in a circular form where the tunnel air is not filtered before extraction. As the polluted air is diluted in the atmosphere through extract air towers (Trafikverket, n.d.-a), it may be directly harmful to the environment. The bypass is estimated to cause 22-48 premature deaths yearly based on the daily emissions of the tunnel(“Luftkvalitet - Trafikverket,” n.d.). According to correspondence with the Swedish transport administration (personal communication, Mars 21, 2019) no investigations have been done by the Swedish authorities regarding cleaning or filtrating extract air before outlet**.**

# 4. Theory

As the aim of this study covers a wide range of subjects from infrastructure to filter technology, a brief summary is given in this chapter to understand the aim of this study thoroughly.

## 4.1 Emissions in road traffic

Extract tunnel air causes photochemical smog, acid rain and global warming (Sher, 1998). Whilst these substances are known to be harmful to the environment and human health, following chemical compounds and particles are also by-products produced by traffic.

***Nitrogen oxides $NO_x$ ($NO_2$, NO)***

Nitric oxide is completely harmless to the human body (Petros et al., 2008) but it is reactive and forms the toxic nitric dioxide. Inhalation of $NO_2$ causes respiratory problems, such as coughing or difficulty of breathing. It may also evolve to asthmatic and other respiratory diseases (Thomsen, 2011). In terms of environment, $NO_x$ can react with oxygen and other chemicals in the atmosphere and forms acid rain. Acid rain affects the environment in many ways, and wildlife in lakes, for example, is reduced as the pH is lowered drastically (US EPA, 2006).

***Sulphur dioxide ($SO_2$)***

Sulphur dioxide is an invisible gas with a distinct sharp smell. $SO_2$ is harmful to the human body as it may hurt the respiratory system, making it difficult to breathe (Department of the Environment and Energy, 2005). At high concentrations $SO_2$ is directly harmful to the nature, such as to trees and wildlife. Sulphur oxides may, as the case of nitrogen oxides, react with other chemicals in the atmosphere and form acid rain, causing damage to the environment with lower pH. Sulphur oxides may also react with other aggregates in the air which results in particulate matter (US-EPA, 2016).

***Particulate matter***

Particulate matter is a mixture of very small particles in the air, that can barely be seen by the human eye. Such particles may be dust, soot, dirt or chemical compounds that have been formed in the air as a result of combustion emission and other free radicals in the air (US EPA, n.d.). Particulate matter may be very harmful to humans, as they are easily inhaled and may not be exhaled as they penetrate deep to the lungs, causing lung diseases (Naturvårdsverket, 2018). Penetration levels of the different particulate matter varies from the nose to the blood stream depending on the particle size (Hummel, 2017) and can be seen in figure 1.

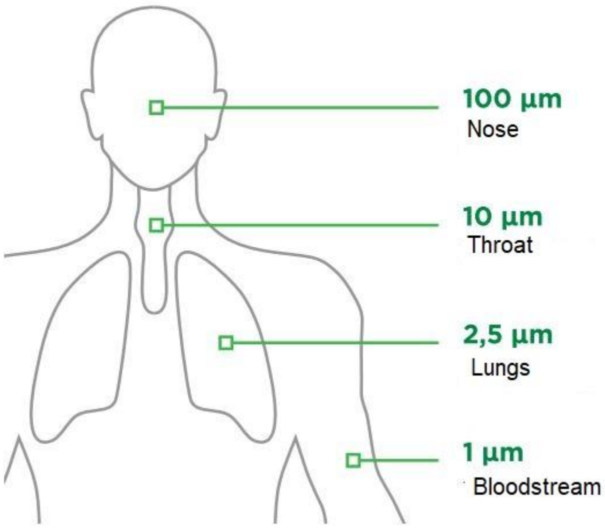



*Figure 1:* Penetration levels of particulate matter. Reprinted from *ISO 16890*, by Mann Hummel, 2017. Retrieved from [www.airfiltration.mann-hummel.com](www.airfiltration.mann-hummel.com)

Due to its effects, particulate matter is divided into two groups:

*$PM_{10}$*

Particulate matter with a diameter less than 10 µm in diameter *($PM_{10}$)* is a component of different particles. The particle may be so small that it may act as a gas, making it easy to inhale, and it therefore penetrates the lungs. Effects on human health of $PM_{10}$ are such as: coughing, asthma, bronchitis, high blood pressure, strokes, cancer and premature death ("Health effects of PM10 - Marlborough District Council," n.d.). According to a study based in Stockholm, Sweden (Orru, 2013) the daily amount of deaths is increased by 1.68% for each 10µgm$^{-3}$ of $PM_{10}$. The current amount of assumed premature death based on $PM_{10}$ in Stockholm is 35 deaths per year (Segersson et al., 2017). Road traffic is the major source of $PM_{10}$ (Segersson et al., 2017). The $PM_{10}$ particles may be formed from exhaust emissions, whilst mass concentration is 10 times higher in road dust, such as road wear, tire wear, and break wear (Cohen et al., 2017).

*$PM_{2,5}$*

Particulate matter with a diameter less than 2,5 µm in diameter, $PM_{2.5}$, is the designation of the smaller particulate matter than $PM_{10}$. The major difference between $PM_{10}$ and $PM_{2.5}$ in terms of health effects is the size. As $PM_{2.5}$ is smaller, it may penetrate the lungs further than the $PM_{10}$, as shown in figure 1. $PM_{2.5}$ has been shown to block important lung functions, impairing the lungs. Each increase of 10-µg/m$^3$ of $PM_{2.5}$ increases the risk of all-cause mortality by 4%, cardiopulmonary mortality by 6% and lung cancer mortality by 8%, with regards to solely $PM_{2.5}$ effects (Pope et al., 2002). $PM_{2.5}$ was the fifth among mortality risk factors in 2015 with 4.2 million deaths globally (Cohen et al., 2017) and 175 deaths in Stockholm (Segersson et al., 2017).

***Carbon monoxide (CO)***
Carbon monoxide (CO) is produced in the process of fossil fuel being burned, for example in a combustion engine of a vehicle. Carbon monoxide can reduce the oxygen transported in the blood by taking up the haemoglobin slots of oxygen, which can cause illness, unconsciousness, and death (Jilla & Kura, 2018; United States Environmental Protection Agency, 2016). Carbon monoxide may also be harmful as it reacts with other pollutants in the air, forming ozone at ground level (SEPA, 2018). Carbon monoxide is not considered to be a particulate matter (Mazzoleni et al., 2004). Whilst carbon monoxide occurs naturally in the environment, excess carbon monoxide from combustion engines is considered a greenhouse gas, contributing to global warming (National Pollutant Inventory, 2017).

***Carbon dioxide (CO2)***
Carbon dioxide is a gas that is naturally occurring in the atmosphere without being harmful to humans and is essential to the growth of plants due to the frontogenesis process (National energy technology laboratory, n.d.). However, carbon dioxide is also a by-product of burning fossil fuel and is therefore regarded as a greenhouse gas, contributing to global warming (Soon, Baliunas, Robinson, & Robinson, 1999).

***Benzene***
Benzene may contaminate outdoor air when vehicles combust fossil fuels. The gas causes cells to work incorrectly, for example not having enough red blood cells produced. Inhaling benzene causes nausea and headache, and at higher levels of exposure even unconsciousness or death (Center for Disease Control and Prevention, 2013).

***Ground-level ozone***
Ozone is naturally occurring in the atmosphere and protects living creatures from direct contact with ultra-violet radiation from the sun. However, ozone can also be formed at ground level when nitrogen oxides react with volatile organic compounds (VOC) in sunlight in elevated temperature. Ground-level ozone is harmful to humans as it can reduce lung function and harm lung tissue, leading to airway inflammations and diseases. It is also harmful to the environment and ecosystems. Ozone reduces photosynthesis and slows the growth of plants. During longer exposure it may even change water and nutrient cycles (US EPA, 2018).

## 4.2 Regulations

As mentioned in section 4.1 the emissions emitted in traffic, and therefore also from unfiltered extract tunnel air, is harmful to both environment and human health. To handle the amount of concentrations emitted, following regulations are set on international and national levels.

***European regulations***

The regulations control the limit values of the different pollution types. Threshold values are used for evaluating measurements made for human health as well as for protection of vegetation and natural. Regulations and thresholds set by the European Union (*Directive 2008/50/EC OF on ambient air quality and cleaner air for Europe*, 2008) is presented in table 1-5.

*Table 1: Limit values of Sulphur dioxide*

| **Limit type** | **Averaging period** | **Limit value** | **Threshold** | **Threshold type** |
|---|---|---|---|---|
| Protection of human health | 1 hour | 350 µg/m$^3$, maximum 24 times a year | 500 µg/m$^3$ | Alert threshold* |
| Protection of human health | 24 hours | 125 µg/m$^3$, not to be exceeded more than 3 times a calendar year | 75 µg/m$^3$, not to be exceeded more than 3 times in any calendar year | Upper threshold |
| | | | 50 µg/m$^3$, not to be exceeded more than three times per calendar year | Lower threshold |
| Protection of ecosystems | Calendar year and winter (1 October to 31 March) | 20 µg/m$^3$ | 12 µg/m$^3$ | Upper threshold |
| | | | 8 µg/m$^3$ | Lower threshold |

*Table 2: Limit values of Nitrogen oxides ($NO_x$)*

| Limit type | Averaging period | Limit value | Threshold | Threshold type |
|---|---|---|---|---|
| Protection of human health | 1 hour | 200 µg/m$^3$ $NO_2$, not to be exceeded more than 18 times a calendar year | 400 µg/m$^3$ | Alert threshold* |
| | | | 140 µg/m$^3$, maximum 18 times per calendar year | Upper threshold |
| | | | 100 µg/m$^3$, maximum 18 times per calendar year | Lower threshold |
| Protection of human health | Calendar year | 40 µg/m3 $NO_2$ | 32 µg/m$^3$ | Upper threshold |
| | | | 26 µg/m$^3$ | Lower threshold |
| Protection of vegetation | Calendar year | 30 µg/m3 $NO_x$ | 24 µg/m$^3$ | Upper threshold |
| | | | 19,5 µg/m$^3$ | Lower threshold |

*Table 3: Limit values of $PM_{10}$/$PM_{2,5}$*

| Limit type | Averaging period | Limit value | Threshold | Threshold type |
|---|---|---|---|---|
| Protection of human health | 24 hours | 50 µg/m$^3$ $PM_{10}$, 24 µg/m$^3$ $PM_{2,5}$ maximum 35 times a calendar year | 35 µg/m$^3$, maximum 35 times per calendar year | Upper threshold |
| | | | 17 µg/m$^3$ | Upper threshold $PM_{2,5}$ |
| | | | 25 µg/m$^3$, maximum 35 times per calendar year | Lower threshold |
| | | | 12 µg/m$^3$ $PM_{2,5}$ | Lower threshold $PM_{2,5}$ |
| Protection of human health | Calendar year | 40 µg/m$^3$ $PM_{10}$ | 28 µg/m$^3$ | Upper threshold |
| | | | 20 µg/m$^3$ | Lower threshold |

*Table 4: Limit values of carbon monoxide*

| Time period average | Limit value | Threshold |
|---|---|---|
| 8 hours | 10 $mg/m^3$ | Limit value |
| 8 hours | 7 $mg/m^3$ | Upper threshold |
| 8 hours | 5 $mg/m^3$ | Lower threshold |

*Table 5: Limit values of benzene*

| Time period average | Limit value | Threshold |
|---|---|---|
| Annual | 5 $\mu g/m^3$ | Limit value |
| Annual | 3,5 $\mu g/m^3$ | Upper threshold |
| Annual | 2 $\mu g/m^3$ | Lower threshold |

* *'alert threshold' - A level, where a risk to human health from brief exposure. Actions shall immediately be taken by the Member States as laid down in Directive 96/62/EC. Measured over three consecutive hours at locations representative of air quality over at least 100 $km^2$ or an entire zone or agglomeration, whichever is the smaller.*

**Swedish regulations**

There are requirements and target values for the PM content in outdoor air in Sweden. The Swedish environmental protection agency has created the environmental objective "Fresh Air" (Swedish: Frisk luft) to favour of the human health. The objective targets the annual and daily averages shown in table 6, assembled by the Swedish environmental protection agency (Naturvårdsverket, 2019).

*Table 6: Swedish regulations of $PM_{10}$, $PM_{2,5}$ and $NO_x$*

| Pollutant | Limit annual average | Limit daily mean | Limit hourly mean |
|---|---|---|---|
| $PM_{10}$ | 15 µg / m³ | 30 µg / m³ | |
| $PM_{2,5}$ | 10 µg / m³ | 25 µg / m³ | |
| $NO_x$ | 20 µg / m³ | | 60 µg / m³ |

## 4.3 Tunnel ventilation

There are multiple purposes of tunnel ventilation. One is to continuously provide the tunnel with fresh air whilst ousting emissions (Johansson, Silvergren, Norman, & Sjövall, 2013b). Having a system with the capacity to blow out the smoke in case of a fire event, as the smoke reduces visibility and causes deaths by suffocation is also a lethal intent with tunnel ventilation (“Public Roads - Tunnel Fire: Testing to Evaluate Ventilation Systems. , Winter 1995 -,” n.d.; Vauquelin, 2008). Smoke control is most efficient by using one of two structures; longitudinal or transversal smoke control (Chen, Hu, Tang, & Yi, 2013). Choice of structure depends on the tunnel length and traffic functions (unidirectional or bidirectional) (Chen et al., 2013).

***Transversal ventilation***

The structure of transversal ventilation is most effective for tunnels with high probability of congestion (bidirectional as well as unidirectional). The principle of transversal ventilation is to shorten the longitudinal distance, whilst evacuating people from the congested tunnel from both ways as seen in figure 2.

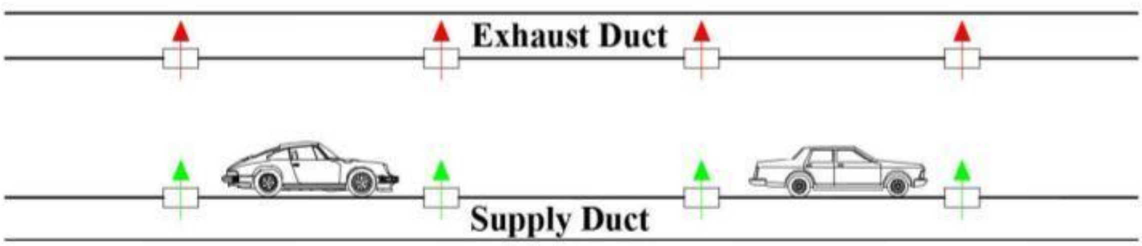



*Figure 2:* Transversal ventilation system. Reprinted from “Experimental study on thermal and smoke control using transverse ventilation in a sloping urban traffic link tunnel fire”, by L.X. Yu et al.*, 2017, Tunnelling and underground Space technology 71, p.81-93.*

***Longitudinal ventilation***

Longitudinal ventilation is to be implied in shorter unidirectional tunnels with less risk of congestion (Yu, Liu, Liu, Weng, & Liao, 2018). As can be seen from Figure 3, jet fans pushing the smoke downstream, making an evacuation upstream the fire safe.


*Figure 3: Transversal ventilation system.* Reprinted from “Experimental study on thermal and smoke control using transverse ventilation in a sloping urban traffic link tunnel fire”, by L.X. Yu et al.*, 2017, Tunnelling and underground Space technology 71, p.81-93.*

***Semi Transversal***

The combination of transversal and longitudinal ventilation is called semi-transversal. This system is made in order to force the smoke with mechanical jets used in longitudinal systems, towards the extract air outlet used in transversal systems (Sturm, Beyer, & Rafiei, 2017) and can be seen in figure 4.

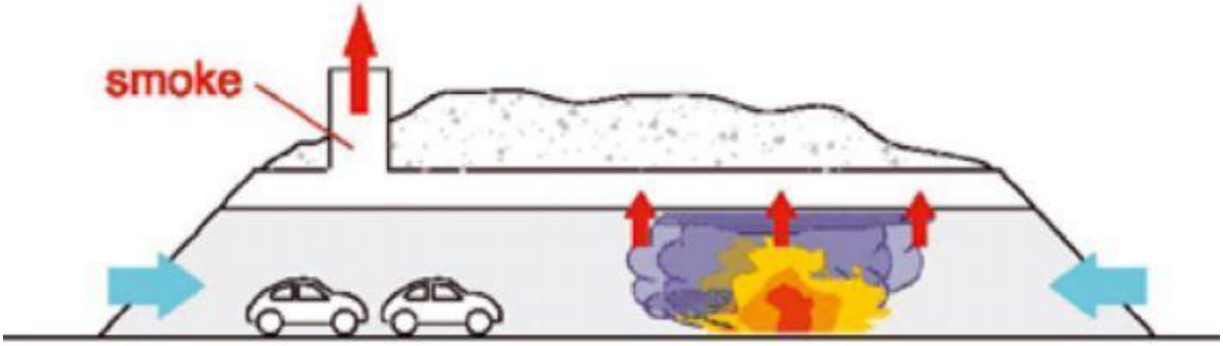



*Figure 4:* Semi-transverse ventilation system. Reprinted from "On the problem of ventilation control in case of a tunnel fire event", by P. Sturm et al., 2015, *Case Studies in Fire Safety journal, Volume 7, p. 36-43.*

***Natural convection***

For short tunnels (600-800m), the distance between jet fans and fire source might be too small for optimal smoke control. During these conditions, natural convection might be more beneficial than mechanical ventilation (jet fans) (Sturm et al., 2017).

## 4.4 Filter technology

Whilst there is great potential of abducting harmful particles in road tunnels due to assembly of particles there are some technical difficulties, such as space requirements. The technical aspects and different types of filtration is described in this chapter to further understand the challenges of optimizing extract air treatment.

***Electrostatic precipitator***

Electrostatic precipitators (EP) were introduced 1979 to improve visibility in of the long tunnels in Japan through filtration. Today, there are around sixty tunnels in the world equipped with air treatment systems. The air treatment systems are used to intercept particles by filtration for two purposes; Improve visibility in the tunnels, or to improve extract air quality from the contaminated tunnel air. This kind of particle filtration may also be combined with a pre-treatment system in order to divert gaseous emissions (CETU, 2010), see section *gas filters*.

***Implementations of electrostatic precipitator***

The filtration is processed using shafts for intake and exhaust air whilst having electrostatic filters adjacent the bypasses. Placing the filter by the bypass is more effective for improving sight in tunnels, as shown in figure 5. It is more effective with respect to the environment when placed at the exhaust ports (Dix, 2006) as shown in figure 6.

*Figure 5:* Schematic of filter by bypasses for improving sight in tunnel. Reprinted from *By-Pass Installation* by CTA. Retrieved from http://www.cta.no/bypass.html.

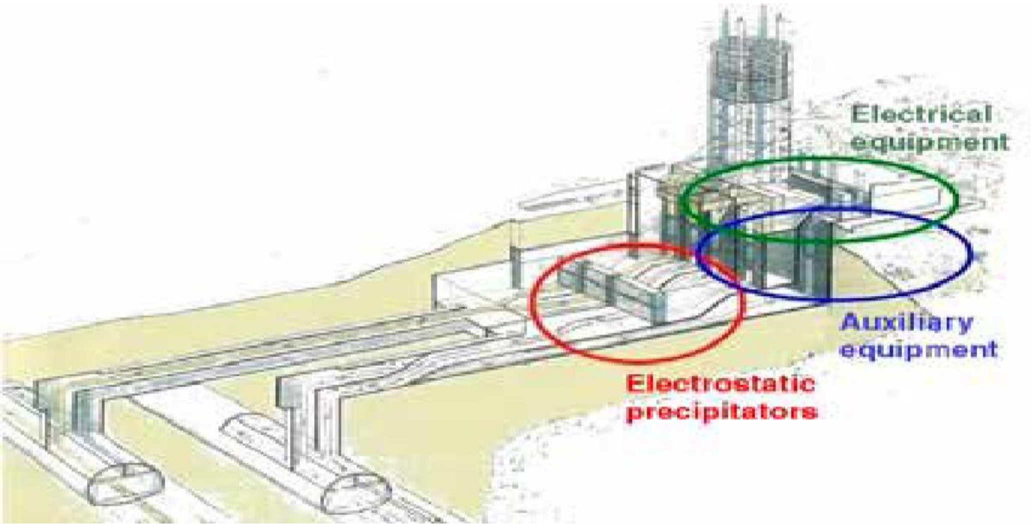



*Figure 6:* Schematic of electrostatic precipitators by the exhaust shaft to reduce the harmfulness on the environment. Reprinted from *Managing air outside of tunnels, report for The Rijkswaterstaat Department of Road and Hydraulic Engineering, The Netherlands,* by A. Dix, Counsel at Law, Adj. Professor of Engineering, 2006.

Whilst different manufacturers of electrostatic filters claim to be different or superior due to their results on mass-basis, the importance may rather lie in the percentage of particle removal. This is due to further analysis to be made by yielding a removal efficiency based on size-distribution (Dix, 2006). Repeating the precipitation process increases the efficiency (Aigner, 2006), as shown in figure 7.

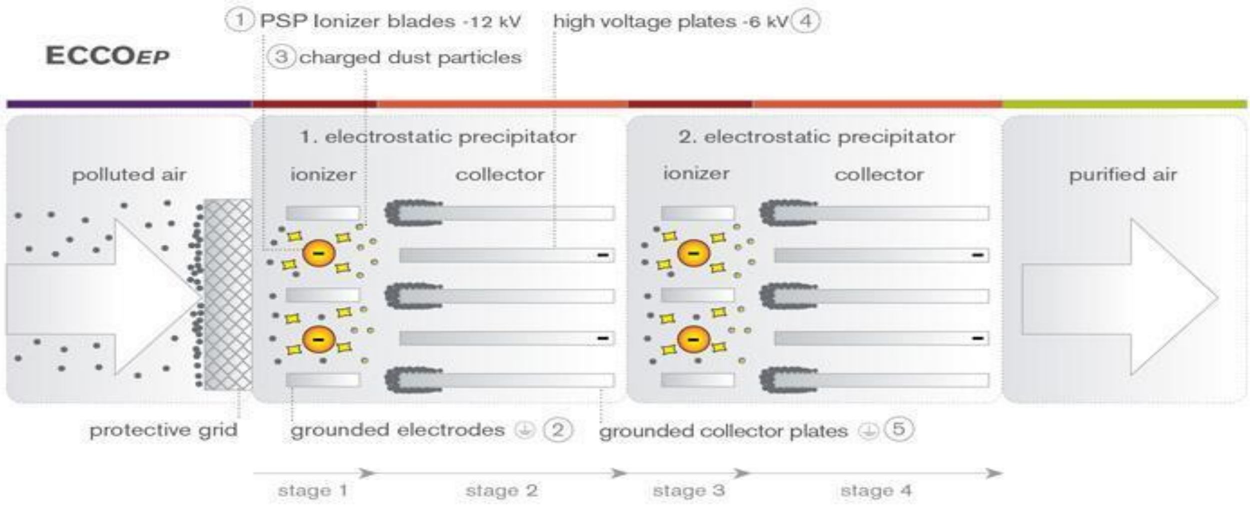


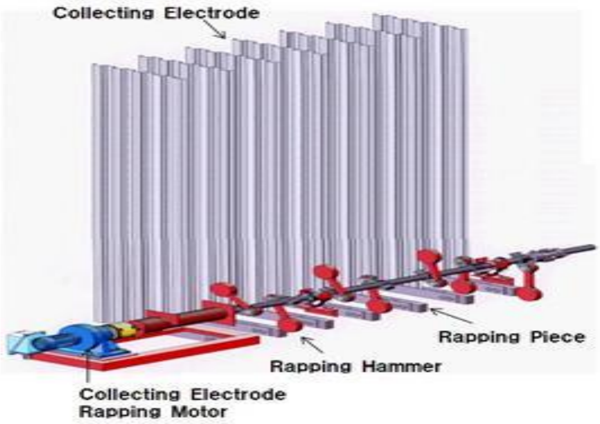

*Figure 7:* Function of electrostatic precipitator. Reprinted from Aigner tunnel Technology; *Mode of operation*, n.d. Adapted with permission.

The electrostatic precipitator ionizes particles with high voltage blades (1). This provides an electrostatic field, charging the particles (3). The particles are thereafter repelled by the grounded collector plates (5). The filter illustrated in figure 7 above repeats the process of electrostatic precipitation in order to increase the efficiency of the particle removal ("Aigner Tunnel Technology; Mode of operation," n.d.). Ideally, the filters are as small as possible to save the limited space provided in tunnels.

**Filter maintenance & regeneration**

As filters get contaminated over time reducing effectiveness, availability of filter maintenance and regeneration is of importance. Filter maintenance is dependent on whether the filter system is based on a wet or dry system. Dry regeneration of ESP filters can be categorized into two different methods. The first one is a fixed electrode method, where the dust is collected by using a collecting plate rapping device against the collecting plate which has accumulated dust on it.

The second method is the moving-electrode type, where the collecting plates are divided into shorter strips, rotating towards a scraper. The scraper gathers the dust on the collecting plates that is forwarded to the hopper and discharge. Both methods are shown in figure 8.



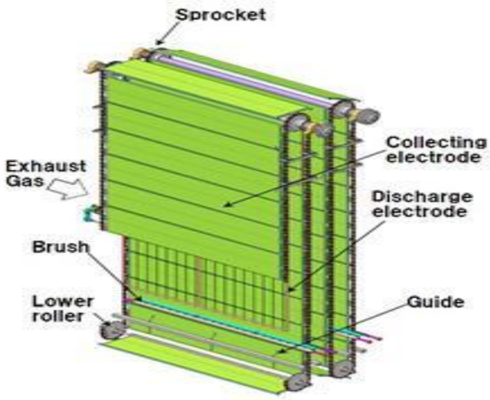




*Figure 8:* Comparison of fixed-electrode type and moving-electrode type Electrostatic precipitator. Reprinted from *Dry type Electrostatic particle Precipitator,* by Mitsubishi Hitachi Power Systems Environmental Solutions, 2019. Retrieved from https://www.es.mhps.com/en/products/dustcollection/e-precipitator/dry_e-precipitator/index.html

For situations were dry electrostatic precipitators are not suited, such as when particles may be of wet, sticky, flammable or explosive, the wet ESPs may be used (Envitech, 2014). The wet system uses a water nozzle to clean the electrostatic filters. The discharge is collected in a hopper, achieving a high dust removal efficiency (≦ $1 mg/m^3N$) without being influenced by the electrical resistivity of the dust. The gas purity is of very high degree, as the process is of high performance which is not available by the dry type of ESP. The system should be corrosion resistant due to gas and water properties in order to minimize maintenance (Maekawa, Yanagida, Kawabata, Orita, & Mochizuki, 2010). Wet filter regeneration system can be seen in figure 9.

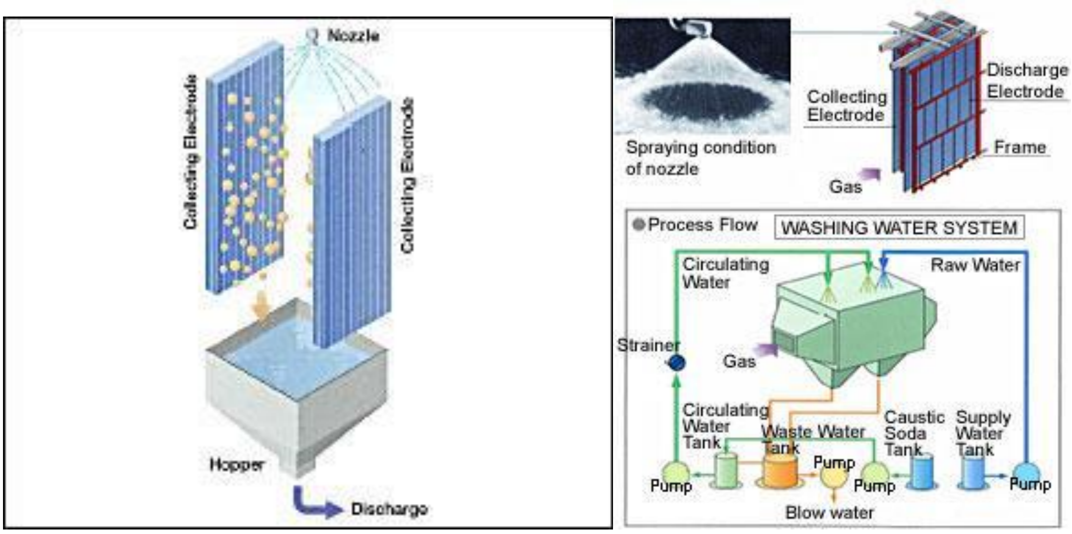



*Figure 9*: Wet filter regeneration system. Reprinted from *Wet Type Electrostatic Precipitator,* by Mitsubishi Hitachi Power Systems Environmental Solutions, 2019. Retrieved from https://www.es.mhps.com/en/products/atmosphere/dustcollection/electrostaticprecipitator/wetelectrostaticprecipitator/index.html

***Gas filters***

The processes of absorption or adsorption can be used to remove gases from the air, such as nitric oxides, sulphur dioxides, ozone and hydrocarbons (Katatani & Dix, 1969). A $NO_2$ removal plant is approximately half the size of the $NO_x$ removal plant whilst consuming a fifth of its energy and costs roughly half of $NO_x$ removal plant. It is therefore regarded more efficient to have a $NO_2$ removal plant with regards to human health benefits considering the costs of $NO_x$ plants (Katatani & Dix, 1969). $NO_2$ removal has been tried successfully in the Shinjuku line tunnel, whereas both systems of absorption (Panasonic) and adsorption (Nishimatsu) obtained a 90% ratio of $NO_2$ removal (Katatani & Dix, 1969). However, as the Shinjuku tunnel is a railway tunnel, there has been no further tests with regards to a road tunnel. A problem is that gas removal is not as beneficial without an electrostatic precipitator before $NO_2$ denitrification. The air should be pre-treated (dust-filtrated) to have efficient $NO_2$ removal. Further studies need to be made in this field (Katatani & Dix, 1969). A combined layout of both denitrification and ESP is shown in figure 10.

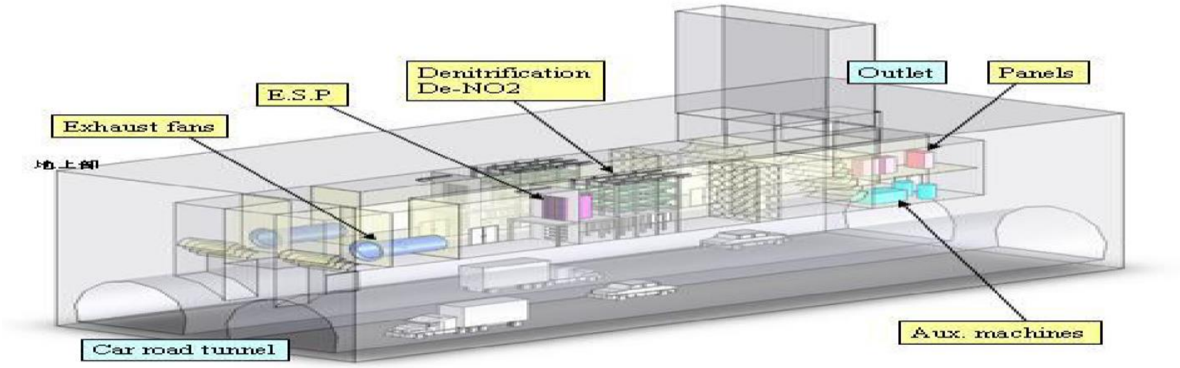



*Figure 10:* Ventilation system with both electrostatic precipitator and $NO_2$ denitrification. Retrieved from *Ventilation and Exhaust Purification of Motor Vehicle Tunnels in Japan* by A. Katatani, A.Dix, 1969.

***Reference projects & costs***
There is currently limited data on investment costs of filtration systems and maintenance costs. To get an overview of what costs this type of filter installations might have previous projects are presented.

The 1581m long tunnel in Cesena, Italy, consisted of two tubes with an airflow of 250 $m^3/s$ each and is estimated to cost approximately 2,5 million Euros per installation. ESP filters by Aigner (ECCO type) including maintenance equipment are used (Dix, 2006).

In Australia, ESP was installed in a 1.6 km long twin tube tunnel of the Eastlink with three lanes in each direction and air flow of 200 $m^3/s$.  The maintenance of the tunnel has been estimated of approximately 658 000 Euros (CETU, 2010).

Hideto Mashimo estimates installation cost of an tunnel with nearly 24 hours running time per day to approximately 3,5 million euros and a maintenance cost of 45 000 euros per year for a filtration flow with 700 $m^3/s$ (CETU, 2010).

Heinz Aigner, CEO of air filter manufacturer Aigner (personal communication, May 9, 2019) states in mail exchange that the installation of ESP for a tunnel with the air flow of 200 $m^3/s$ would approximately cost around 6 million euros.

As a large part of the costs of ESP filters is related to energy consumptions (Dix, 2006), a consistent MCA with regards to energy consumption in terms of loss of pollution removal would be favourable. Such an analysis could be combined with a life cycle analysis to consider a larger width of environmental and economic factors. There is no such study as of this date.

## 4.5 Air pollution in Sweden

As the aim of this paper is to examine the possibilities of treating extract tunnel air by filtration for one of Sweden's biggest infrastructure projects, the current impacts of air pollution in the area is presented.

### *Impacts of air pollution in Sweden*

A Swedish study (Gustafsson et al., 2018) estimated that about 7600 deaths yearly are due to exposure to fine particles $PM_{2.5}$ and $NO_x$, based on the value of 2015 exposure to the pollutants. The European environment agency, EEA, estimates the yearly amount of deaths related to exposure to fine particles $PM_{2.5}$ and $NO_x$ in Sweden is 4850 of year 2015. The estimation of EEA is based on a lower dose-response ratio for $NO_x$. Both reports are based on the number of deaths due to air pollution concentrations in urban and regional background environments. It is likely that the calculations would lead to higher exposure levels and thus higher social costs, if they were based on levels in street canyons instead of levels in background air. There are currently no established dose-response ratios for concentrations of air pollutants in the street canyons (Naturvårdsverket, 2019). In a more local area of the traffic dense parts of Sweden, the Public Health Authority estimates that 600 youths per year will grow up with reduced lung function due to air pollution (Folkhälsomyndigheten, 2017). These are the results from the BAMSE-study, were more than 4000 of Stockholm county inhabitants were studied for 24 years born -94 to -96 up to adulthood (Melén, 1994).

### *Diseases related to air pollutions in Sweden & costs*

Health effects due to exposure to $PM_{2.5}$ and $NO_x$ can be expected to cause socio-economic costs in Sweden of approximately 56 billion SEK, in rates of year 2015. Most of the costs, 76 percent, are due to premature death, while long-term illness after heart attack and stroke account for three percent of the costs (Gustafsson et al., 2018). In addition to these costs, productivity losses due to sickness absence are added, which are estimated to cause socio-economic costs of about 0.4 percent of Swedish GDP (Gustafsson et al., 2018).

## 4.6 Swedish Case study – The Stockholm Bypass

The capitol of Sweden is undergoing a transformation with a major infrastructure project called *The Stockholm bypass.* The bypass is to change the current infrastructural situation and environmental situation in Stockholm, in regards of traffic as well as emissions emitted in Stockholm.

***The Stockholm bypass***

The Stockholm bypass is one of the largest infrastructure projects to be made in the Swedish history. It is to be made as an effort to bind the north and south county parts of Stockholm which offloads the main highway of Stockholm, Essingeleden. The bypass starts in Kungens Kurva in the south and finishes in Häggvik in the north of Stockholm. Along the bypass there will be six interchanges. The journey from south to north is estimated to be 15 minutes and 18 of the 21 km will be in tunnels. With the linking between the tunnels it is to be one of the world's longest tunnels. The project is estimated to take 10 years with traffic start in 2026 (Trafikverket, n.d.-a). The Swedish transport administration has estimated the usage of the bypass by 140,000 vehicles per day by year 2035. The Stockholm bypass is estimated to costs 31,5 billion SEK, equivalent to approximately 3.8 billion euro as of the 2013 rate. The project is partly financed by the Swedish government whilst the main finance is secured by current congestion charges. The bypass is not planned to be charged by congestion charges in the future (Trafikverket, n.d.-a).Throughout the entire bypass, there will be around 250 reversible jet fans, 47 axial fans and one smoke gas station with a capacity of 600 $m^3$/s. In addition, four air extract stations with locations and capacities of: Hjulsta (600 m3/s), Vinsta (200 m3/s), Smista (200 m3/s), Kungens kurva (600 m3/s) (Trafikverket, n.d.-b). Locations of the extract stations are seen in figure 11.

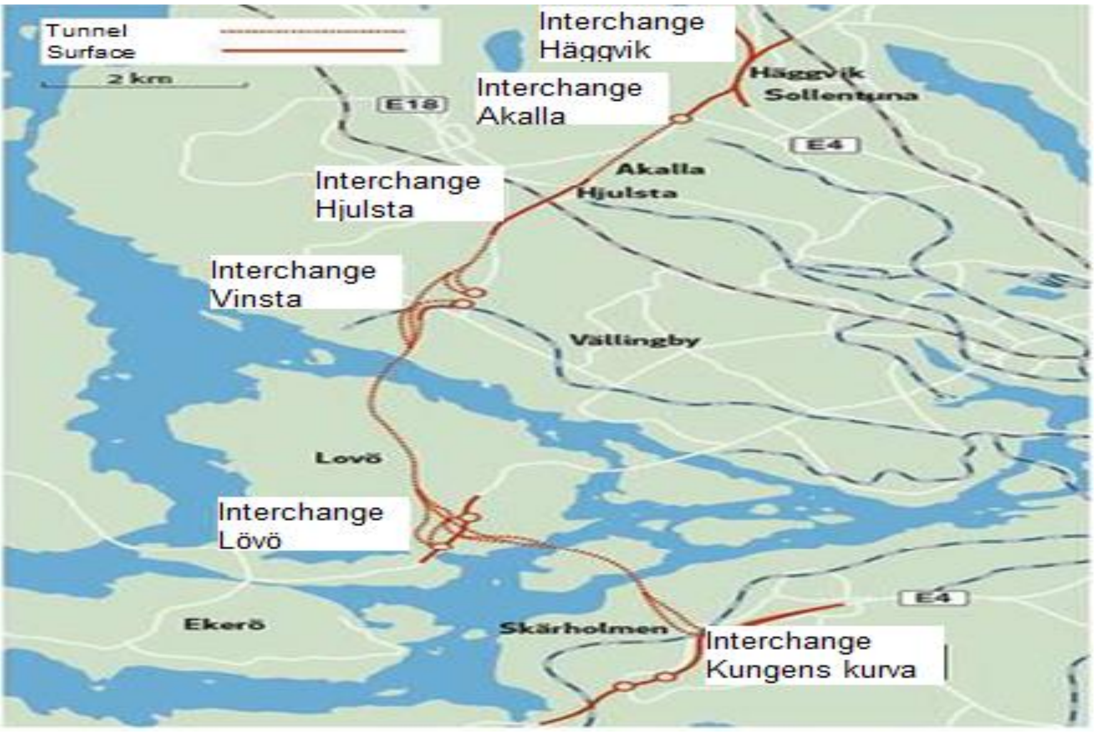



*Figure 11:* Overview of bypass Stockholm with extract stations.

***Stockholm bypass: Kungens kurva***

The interchange of the start of the bypass, Kungens kurva, is estimated to be the most polluted location of the whole Stockholm bypass, whilst also possessing the longest tunnel length of the bypass with the distance of 16 km to the exit of Lunda (Trafikverket, n.d.-b). Its layout can be seen in figure 12. Kungens kurva, together with its nearby shopping malls, such as Skärholmen Centrum and Ikano Centrum is today one of Scandinavia's biggest retail centres and is visited by about 30 million people yearly (Huddinge Kommun, n.d.). There are currently about 37,000 residents around the area of Kungens Kurva. There are plans to build an additional 3,500 residential apartments next to the intended bypass distanced by approximately 50m (Huddinge Kommun, n.d.). The residents by the site of Kungens kurva are to be highest exposed to air pollutions throughout the bypass, which indicates a risk of being exposed to an exceedance of the set environmental quality standards (Lövenheim, 2011). The responsible municipality of the buildings, municipality Huddinge, currently have no intentions of estimating exposure to the emissions emitted by the interchange Kungens kurva. In discussion municipality Huddinge (personal communication, May 16, 2019) it is stated that no further calculations are to be made before the buildings are finished. In mail exchange with the Swedish transport administration (personal communication, February 13, 2019) it is mentioned that a dispersion calculation has been made to map the pollutants in the surrounding area. The Swedish transportation administration has published that 22 to 48 premature deaths are to be related as a consequence of the bypass, where the lower number is to be compared with the current situation in a typical large Swedish city (“Luftkvalitet - Trafikverket,” n.d.).


*Figure 12:* Overview of interchange Kungens kurva.

***Aspects of the Swedish transport administration***

The Swedish transport administration states that the current environmental situation in Kungens kurva, with regards to $PM_{10}$ is 20 μg/m³ and its future scenario with interchange Kungens is not to exceed 30 μg/m³, which is within the range of the environmental quality standard of 50 μg/m³ ("Luftkvalitet - Trafikverket," n.d.). The Swedish transport administration's view on ESP for interchange Kungens kurva is that particulate filter cleaning is very costly. The statement is solely based on tunnels in Oslo that use ESP that have been judged to be very expensive and ineffective (Swedish transport administration, personal communication, February 18, 2019). The Swedish Transport Administration considers that the environmental improvements that can be achieved with devices for dust removal are relatively limited and are not in reasonable proportion to the investment and operating costs that this entails. The Swedish transport administration have currently not further investigated the possibilities regarding extract tunnel air filtration, nor any other precautions (Swedish transport administration, personal communication, Mars 21 ,2019). The current emission control solution of the Swedish transport administration is to force the emission through an exhaust tower of 10 meter of height with a flow capacity of 600 $m^3/s$, whereas there have only been a dispersion calculation of 200 $m^3/s$ ("Luftkvalitet - Trafikverket," n.d.). The same principal is to be done with the additional 3 extract outlets throughout the bypass as well. Further investigations regarding the emission control are to be after the tunnel-opening (Swedish transport administration, personal communication, Mars 21, 2019).

# 5. Results

Results have been acquired by inquiring the Swedish transport administration of current and future scenarios of Stockholm bypass, regarding its infrastructure and environmental aspects. Future measures in regards of emission Stockholm bypass is examined. Literature study of current technology available for tunnel extract air filtration shows what extents such technology is applicable. Extents of particle removal is provided by questioning one of the leading filter companies Aigner.

## 5.1 Swedish transport administration – pilot studies

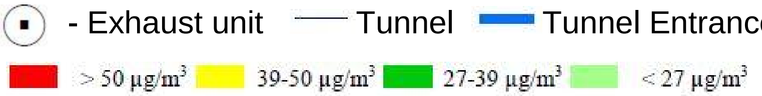
The Swedish transport administration has conducted pilot studies of filter technology in order to investigate the reduction of particles in terms of *sight problems inside the tunnel*. The pilot studies consisted of judgement by the use and efficiency of current ESP preventing sight problems inside the tunnels in Oslo. The Swedish transport administration has not done studies of filter technology in order to investigate the reduction of particles *in terms of health and environmental problems outside the tunnel*, as it has not been of any topical worth of discussion.

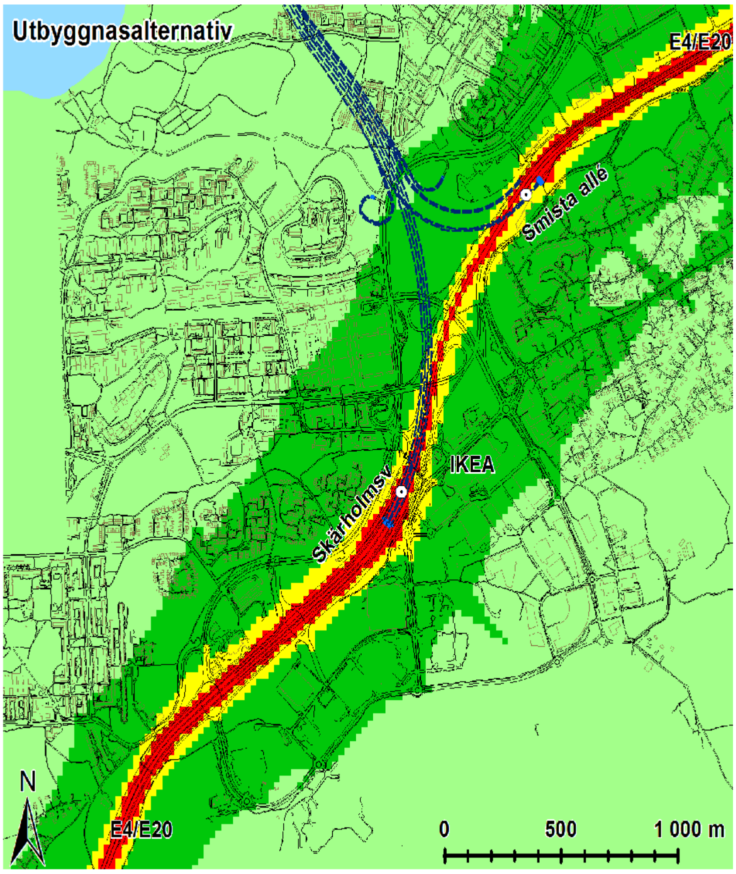
## 5.2 Swedish transport administration - Dispersion calculations

Future scenarios in environmental and health aspects of the Stockholm bypass is presented by the Swedish transport administration through a dispersion calculation to predict the dispersion of the emitted emissions by the traffic inside the tunnel. The calculation shows what extent $PM_{10}$ and $NO_x$ is to spread post emitted through tunnel extract air tower with 10 metres of height. The calculations have been done with assumptions such as:

- *Concrete surface is being used.*
- *Dust binding is used.*
- *Speed is reduced.*
- *Air exchange stations are used almost round-the-clock.*
- *Usage of studded tires is to be 50% of the car's year 2030.*
- *Extract air is forced through and emitted by an exhaust tower of 10 meters of height.*
- *An extraction air flow of 200 $m^3/s$.*
- *Extraction flow speed of 7 m/s.*
- *The traffic will emit a total of 11,5 tonnes of $PM_{10}$ of which 3,8 tonnes will be emitted from the extract air.*
- *Grid size of 25x25m is used.*
- $PM_{10}$ concentration is at most 800 $\mu g/m^3$ inside the tunnel

***Dispersion calculation of $PM_{10}$. Bypass Stockholm, Kungens kurva tunnel.***
Figures 13a-c have been simulated by a dispersion calculation made by B. Lövenheim, 2011, on behalf of the Swedish transport administration. Reprinted with permission.



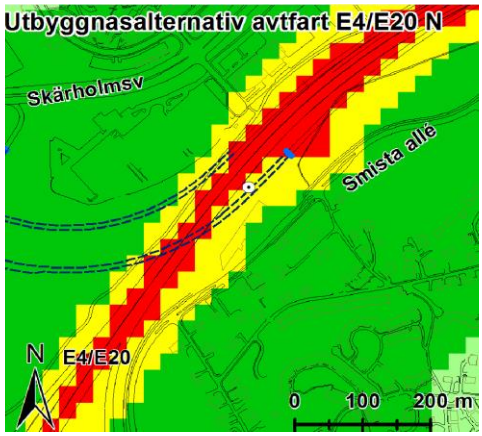




*Figure 13b:* E4/E20 northbound.

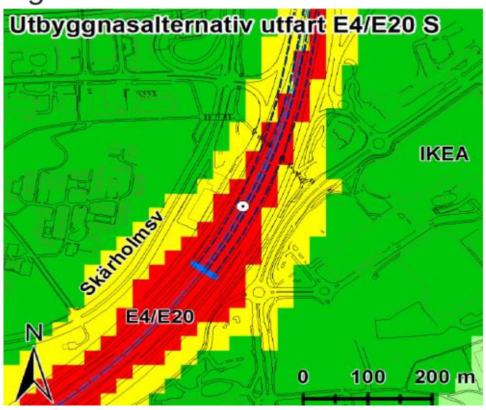
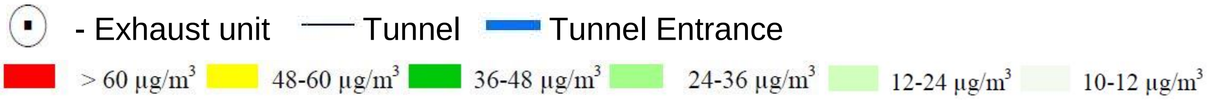



*Figure 13a:* Kungens kurva interchange year 2030. *Figure 13c:* E4/E20 southbound.

Figure 13a-c above show the daily average of PM10 during the 36th worst day of year 2030.The total outlet emissions of bypass Stockholm contributes to the exceeding the environmental quality standard's daily value for PM10 of 50 µg/m$^3$ in the area. The exceedance of the environmental quality standard generally takes place within the road area and in the areas adjacent about 20 meters outside the road area.

***Dispersion calculation of $NO_2$. Bypass Stockholm, Kungens kurva tunnel.***
Figures 14a-c have been simulated by a dispersion calculation made by B.Lövenheim, 2011, on behalf of the Swedish transport administration. Reprinted with permission.



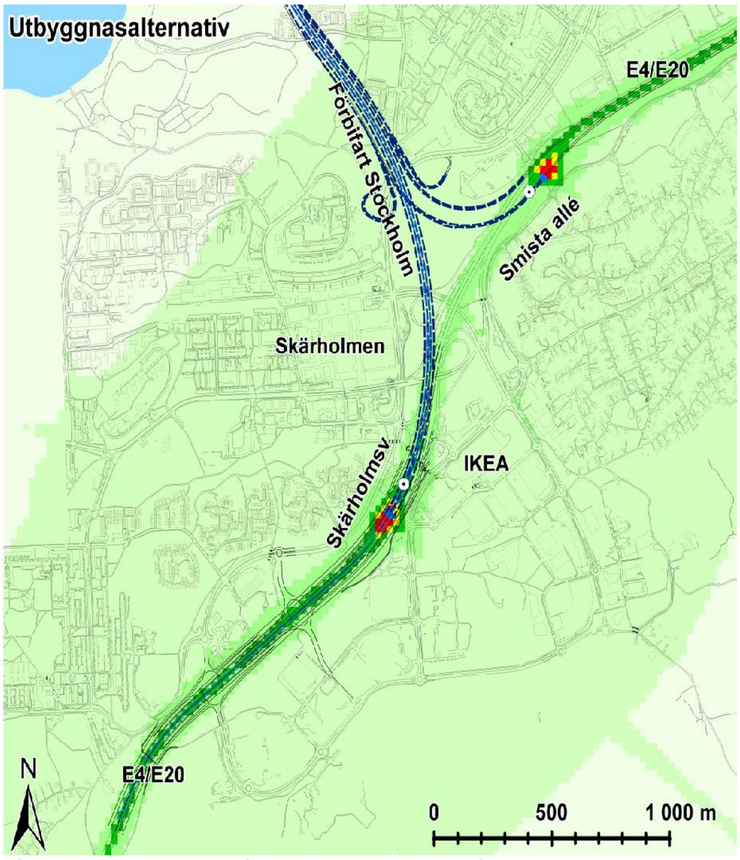




*Figure 14a:* Interchange Kungens kurva.

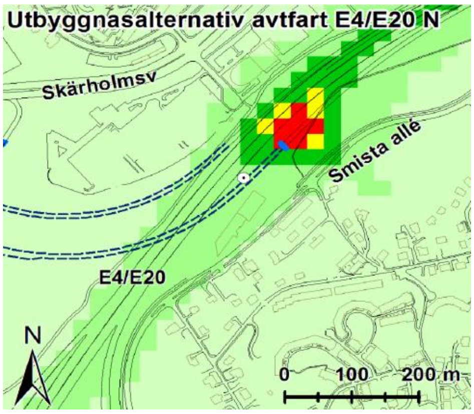



*Figure 14b*: Northbound exit.

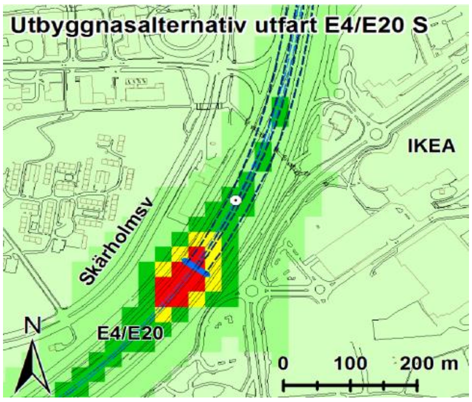



*Figure 14c:* Southbound exit.

Figure 14a-c show the daily average of $NO_2$ during the 8th worst day of year 2030. The dispersion calculations show that environmental quality standards are to be exceeded only within the road region by the tunnel entrances.

## 5.3 Filter technology

To investigate possibilities of tunnel ventilation with electrostatic precipitators in tunnel conditions, results of an Aigner filter technology report is used. Figure 15a-c show recorded mean values of a 2-day measurement using a G4 filter medium with an ECCO DUST filter system (pressure loss of 500 Pa). Airflow in the following tests is set as 1,54 $m^3/s$ (=100% airflow), with an air speed of 2,7 m/s. Results are shown in figure 15a-c.

***Total tunnel dust total suspended particles (TSP)***

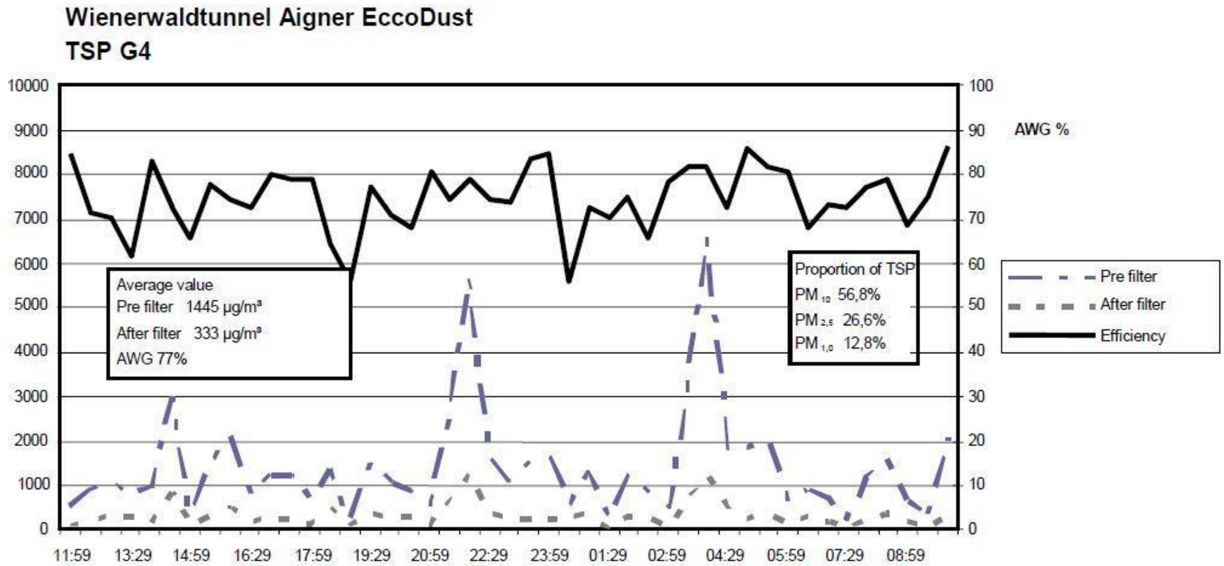



*Figure 15a:* Total suspended particles during a tunnel recording using EP “Ecco” with filter medium G4. Reprinted from “Use of dust filters during the construction of tunnel systems”, by H. Aigner, 2006, *International conference “tunnel safety and ventilation”, 3,* p. 135-144. Reprinted with permission.

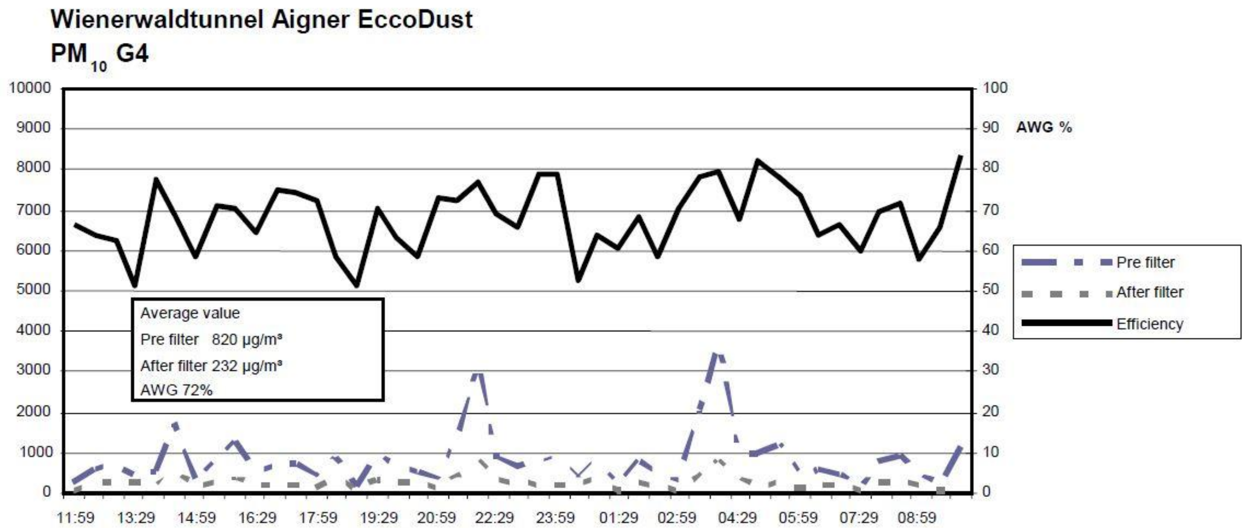



*Figure 15b:* Proportion of fine dust $PM_{10}$ measured during tunnel recording using EP “Ecco” with filter medium G4. Reprinted from “Use of dust filters during the construction of tunnel systems”, by H. Aigner, 2006, *International conference “tunnel safety and ventilation”, 3,* p. 135-144. Reprinted with permission.

***Filter efficiency, fine dust medium***
A fine dust medium was used for the very same layout of the test as described for TSP, where a 2-day measurement was recorded with half-hour mean values. The fine dust filter medium F5 provided a smoother filter efficiency as shown in figure 15c and table 7 below.

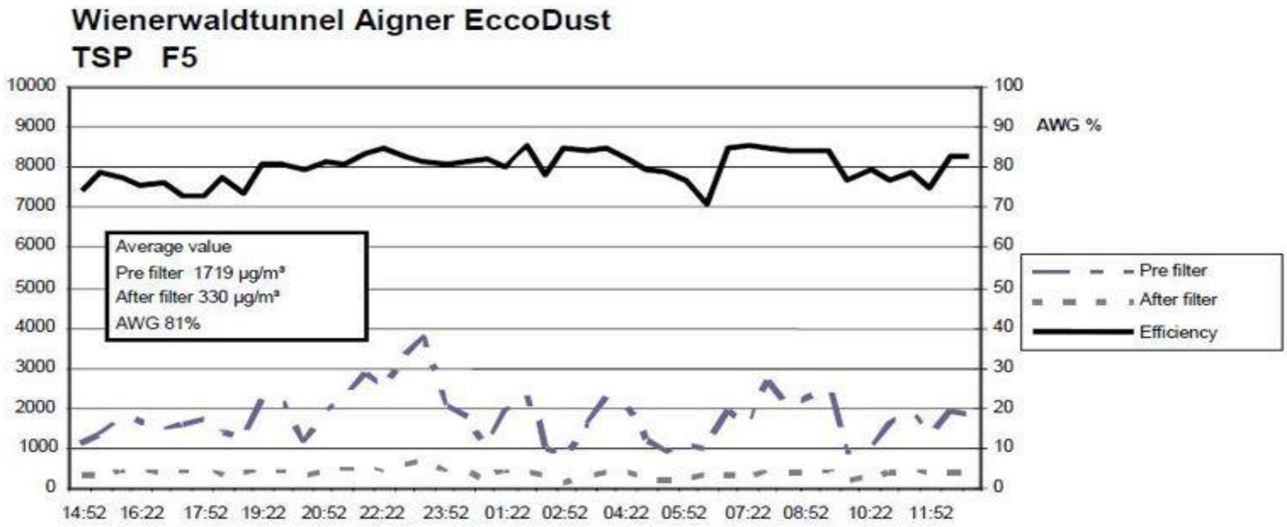



*Figure 15c:* Aigner "EccoDust" measured during a 2-day recording with normal tunnel conditions, using filter medium F5. Reprinted from "Use of dust filters during the construction of tunnel systems", by H. Aigner, 2006, *International conference "tunnel safety and ventilation", 3,* p. 135-144. Reprinted with permission.

*Table 7:* Particle distribution of coarse dust as presented in figure 14c. Largest fraction proportions are highlighted in grey, clarifying the determining proportion between 1 and 10 µm.

| Particle size µm | 0.3-0.4 | 0.4-0.5 | 0.5-0.65 | 0.65-0.8 | 0.8-0.9 | 0.9-1.0 | 1.0-2.0 | 2.0-3.0 |
|---|---|---|---|---|---|---|---|---|
| Proportion in % | 5 | 3 | 3 | 2 | 2 | 5 | 5 | 17 |
| Particle size µm | 3.0-4.0 | 4.0-5.0 | 5.0-7.5 | 7.5-10 | 10-15 | 15-20 | >20 | |
| Proportion in % | 16 | 14 | 18 | 6 | 4 | 1 | 1 | |

Further detailed tests of Aigner filters were different percentages of the airflow is tested are attached in the appendix section.

## 5.4 Costs of implementing ESP

Certain information regarding implementing cost of electrostatic particle filters is currently not available other than costs of reference projects. An estimated cost for exhaust air filtration of bypass Stockholm, interchange Kungens kurva with airflow of 200 $m^3/s$ is requested. Aigner filter technology estimates the cost to approximately 6 million Euros as of year 2019 value. Reference projects mentioned in section *Reference projects & costs* show that costs including maintenance products may cost approximately 2.5 million euros at 2006 year's value. Maintenance costs of reference projects with similar input values as interchange Kungens kurva is approximately of 685 000 euros per year.

# 6. Discussion

The results of the electrostatic particle filter of Aigner indicate great potential regarding possibilities of reducing harmful particles emitted from tunnel outlets. The filter tests made by Aigner show a total suspension of particles by 77% AWG and 72% of $PM_{10}$. The initial value of $PM_{10}$ used in the Aigner test of 820 µg/m$^3$ is similar to the assumed 800 µg/m$^3$ used in the dispersion calculations. The airspeed used in the Aigner test is however 2,7 m/s compared to 7 m/s used in dispersion calculation. The difference in velocity is likely to affect the filter efficiency, due to pressure loss. If the tunnel ventilation of interchange Kungens kurva would to reduce air velocity, consequently reducing air flow, it would be theoretically possible to achieve the same results as in the Aigner test using the "Ecco Ep" filter. However, low airflow is a crucial factor as it potentially may result in an increase of pollutants by the tunnel muzzles. Further studies need to be made to ensure filter capacity of faster air velocities as well as necessary airflow to prevent particles from staying outside tunnel muzzles. If such an optimum is reached, the output of the Aigner "Ecco EP" filter test resulting in 232 µg/m$^3$ can be used. An additional dispersion calculation based on the filtered value of 232 µg/m$^3$ would be of interest to run due to the current dispersion calculation, suggesting that the EQS and the Swedish regulations are to be exceeded in regards of $PM_{10}$. Such a dispersion calculation with initial value of 232 µg/m$^3$ would most likely pass the EQS.

The results indicate a total cost of approximately 2,5 - 6 million euros, without the costs of civil engineering and annualized costs included. A maintenance cost is to be added of approximately 685,000 euros per year. From the perspective of a health optimal scenario, the ESP filters would have to be installed throughout the whole bypass of 18 km tunnel, with a total 4 outlets. Such an investment would hence cost between 10-24 million euros and additional 2,8 million euros per year in maintenance costs. The insecurity within the cost-span of the installation can be compared with the accumulated costs the alternative of not having such an installation would result in. For current situation, an estimation of 4850-7600 premature deaths in Sweden (section *4.5*) due to exposure to $PM_{10}$ and $NO_x$ is made. The correlating expected socio-economic cost is 56 billion SEK, approximately 7,3 million SEK per premature death. According to the Swedish transport administration in section *4.6*, the tunnel will result in 22-48 deaths yearly related solely to $PM_{10}$ in Stockholm, whilst currently having 22 deaths per year. This indicates an increase of premature deaths related to $PM_{10}$, thus also an increase of costs for the society. From an economic perspective tunnel ESP would be an investment regarding the society as whole. Tunnel ESPs would however not reduce traffic, why it might not concern the Swedish transport administration in the first place. Although, as the dispersion calculation show that EQS is to be exceeded after tunnel opening, the authority is responsible of the remedy. If that is the case, electrostatic particle filters may be a cost efficient and long-term solution in regards of human health. There is yet no analyse made by the Swedish transport administration regarding the matter of electrostatic particle filters or why they have been judged of being inefficient.

The purpose of the Stockholm bypass, to reduce traffic of the main highway of Stockholm, indirectly causes a socio-economic problem by displacing the location of the area that is to be polluted by traffic. With the bypass suburban areas are to be polluted whilst offloading of the inner-city of Stockholm traffic. As shown in the results, these pollutions may exceed the EQS in some of the areas of the bypass. Whether such inequity has been considered during the decision of not use ESP in these bypasses is questioned. The Swedish transport administration has currently not given any explanation for not further investigating ESP filtration other than the cost. Even so, due to the issue of insufficient of space in the tunnel, it is of importance for the Swedish transportation administration to investigate the alternative of having an ESP filter by the tunnel extract prior to constructing the tunnel. If this is to be investigated post the opening of the tunnel, the costs to adjust the tunnel to fit such an installation may be extreme. No such investigation has currently been made by the Swedish transport administration. The authority should furthermore compare such an investment to what costs it may save in the society in terms of social-care costs, during the life-length of an ESP. Studies regarding life cycle calculations of ESPs including natural resources required for the filter technology, energy consumption and waste-management is recommended as there currently are no such studies.

The results of this paper could be a foundation for a further study to compare an investment costs with the cost of not installing an ESP. As stated in section 4, each $10 \mu g m^{-3}$ of $PM_{10}$ increases the daily amount of deaths by 1.68%. The Aigner ESP filters is shown to reduce amount of $PM_{10}$ by 72% with specified conditions. The extract air outlet of the interchange Kungens kurva is calculated to emit 33% of $PM_{10}$. With the 72% removal of the 33% emitted particles throughout the extract air tower is possible. The corresponding value of $PM_{10}$ would hence be a removal of 11,8 $\mu g/m^3$ of the 16,5 $\mu g/m^3$ tunnel $PM_{10}$ emission. The removal may, with the related relation mentioned above, be interpreted as a 1,98% reduction of the premature deaths due to exposure of $PM_{10}$ within the area. This would however presume the current airflow of the Kungens kurva extract flow to be the same and that the assumptions of the dispersion calculation to be correct. Whilst the conditions used in the Aigner ESP filter test does not fully fit the scenario of the specific extract air flow, it implies that it is of interest to simulate the scenario of an ESP filter used in the tunnel extract air. Results of what level of $PM_{10}$ is to be reduced by using such a filter will directly indicate what reduced risk of premature death due to $PM_{10}$ exposure will be. The result would show socio-economic win of the society and how many lives that theoretically may be spared yearly. Further studies within this field is to be strongly recommended as a basis for future projects to come by the Swedish transport administration.

Although $PM_{2.5}$ is shown to be an important factor in terms of health-related exposure in polluted environments, results from the dispersion calculations does not consider the dispersion of $PM_{2.5}$. For $PM_{2.5}$ dispersion, the results refer to a dispersion calculation of $PM_{2.5}$ in a general simulation of the inner city of Stockholm 2010. The referred area is not relevant for investigating the area of Kungens Kurva. Thus, no certainty, proof or calculations are provided by the Swedish transport administration regarding passing the EQS of $PM_{2.5}$ in the nearby area of Kungens kurva for bypass Stockholm. The Swedish transport administration should further investigate within the field of $PM_{2.5}$ dispersion.

The dispersion calculation follows the standards in terms of data collection, although no background is presented to the initial values of the simulation. Specifically, initial value of $NO_x$ in the tunnel is not provided and the initial value of $PM_{10}$ of 800µg/m$^3$ is not commented. The usage of studded tires is set to 50%, while no such evidence is existing in the referred source other than a current use of approximately 65%. Due to the lack of information, there is an uncertainty that is not presented in the dispersion calculation. Furthermore, a grid size of 25 x 25 meters is used in the dispersion calculation. It would be of interest to reduce grid size to get a more reliable and exact results. The result would more precisely show how inhabitants nearby the bypass will be affected by the unfiltered extract outlet. As of the current dispersion calculation, it is not certain what exact level of pollutants the simulations result in within the nearby residential areas such as Lindholmsbacken, Smista Allé and the upcoming neighbourhood of 3500 residentials of Diagonalvägen.

Generally, it may be of use to look at the issue of air treatment in tunnels in comparison to the background of road-related atmospheric pollution. It is not the tunnel itself that creates pollutions, but the traffic running through. Tunnels are merely a tool to channel the traffic and hence the pollution, in order to make it possible for air treatment. Tunnel-related pollution is limited to localised issues. This type of issues creates a moral dilemma when it comes to re-directing the traffic, which is the idea of the Stockholm bypass. Such solutions solve, at least in the short term, the congestion problems, to the price of polluting the suburban area. Congestion is avoided to the price of certainly exposing the local area and residents to environmental impacts, higher risk for health-related issues and premature death. Ultimately, the solution of choice becomes a political discussion in terms of social economical disadvantages, living standards, moral and segregation. None of these subjects to have our knowledge yet been treated.

# 7. Conclusion & Findings

The electrostatic filters are proven to reduce the number of free particles in the air by TSP, indicating great potential regarding possibilities of reducing harmful particles emitted from tunnel outlets. The capacity of the filters regarding air velocity needs further investigation to meet the attributes of the Kungens kurva tunnel.

The technology is not planned in the bypass Stockholm although environmental quality standards are shown to be exceeded in the dispersion calculation conducted. The impact of $PM_{2.5}$ has not been considered in the dispersion calculation even though being defined by the environmental quality standards. Uncertainties of the dispersion calculation such as initial values of $PM_{2.5}$ and $NO_x$, usage of studded tires and grid size have been pointed out.

Current judgement of ESP filters by Swedish transport administration is solely based on technology used in Oslo, without providing cost-calculations or life cycle analysis. Technology used in Oslo is for tunnel visibility, which undermines the judgement done by the Swedish transport administration.

Investment cost for ESP compared to costs of the society in whole, such as health related costs, is rather small. Studies regarding life cycle calculations of ESPs including natural resources required for the filter technology, energy consumption and waste-management is recommended for further studies as there currently are none. The life cycle calculation can then be compared to the current health related costs of the society due to extract tunnel air emissions.

For further studies, it is recommended to review any available filtration technology that may remove pollutants by tunnel muzzles. Based on the current emission ratio, 66% of the pollutants are emitted by the tunnel muzzles. Such filtration would be more effective than by filtrating the extract air through the outlet.

The Swedish transport administration is recommended to investigate possibilities to implement the current available technology in order to reduce emissions harmful to humans and the environment. Such implementation should be investigated before tunnel-opening, rather than after, in order to prevent expensive and inefficient solutions. Emitting extract tunnel air nearby the residential area should be carefully considered to prevent negative health and environmental impacts that may occur. Thus, overall judgement of filtration technology in road tunnel by the Swedish transport administration is questioned, as it is lacks fundamental facts.

Discussing the ratio in regards of socio-economic loss and moral terms in comparison to the avoidance of congestion is of importance. The bypass is shown to certainly increase the risk of negative health impacts along the suburban areas where it is to be built, whilst inner-city residentials are to be relieved of emissions. In order to prevent inequity that may inflate segregation, politicians and authorities are urged to re-assess, investigate and analyse available technology, such as the electrostatic particle filters.

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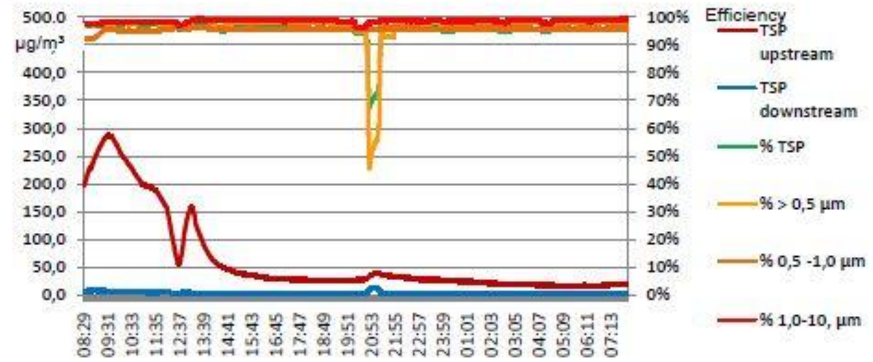
# Appendix

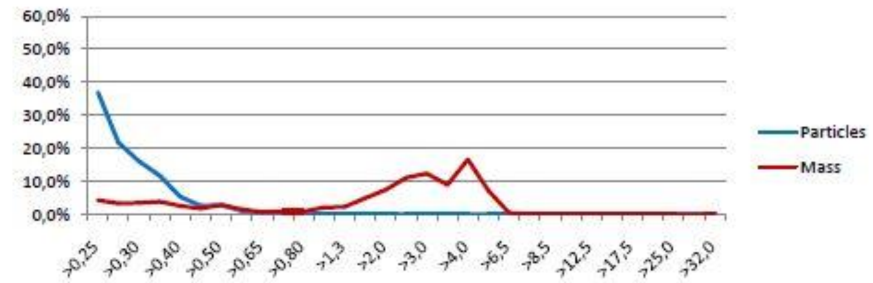
## ECCO*EP* 70% nominal Airflow

15.12.2008 - 16.12.2008

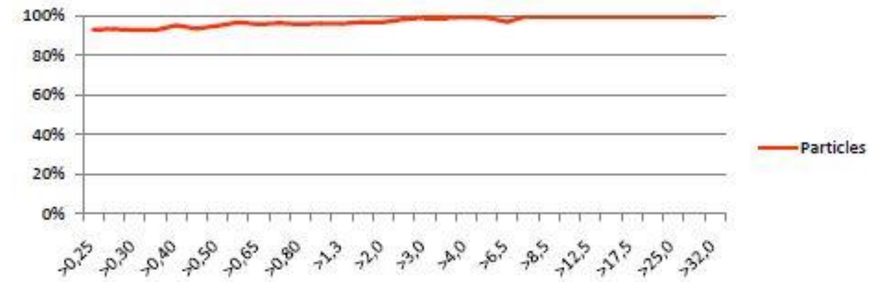
| Efficiency | TSP | > 0,5 µm | > 1,0 µm | 0,5-1,0 µm | 1,0-10,0 µm |
|---|---|---|---|---|---|
| ø % | 97% | 97% | 98% | 96% | 98% |




| Size Distribution | < 0,5 µm | 0,5-1,0 µm | 1,0-10 µm | > 10 µm |
|---|---|---|---|---|
| Mass | 19,4% | 6,8% | 73,3% | 0,5% |
| Particles | 94,4% | 4,8% | 0,8% | 0,0% |




**Efficiency vs. Particle Size**



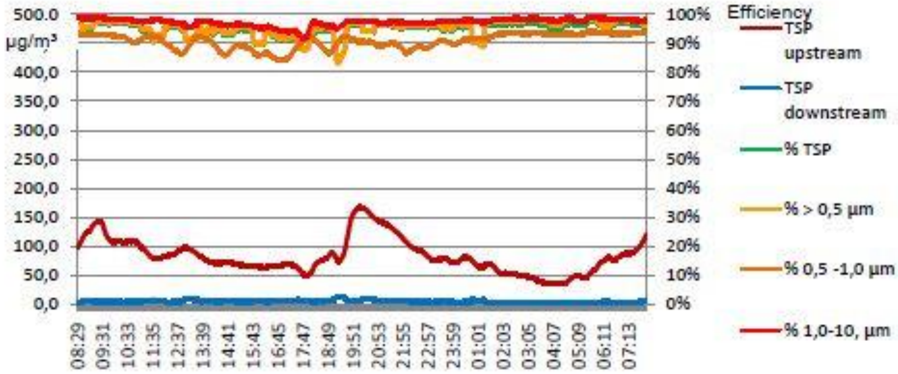

## $PM_{10}$ /$PM_{2,5}$

| Aerodynamischer ø µm | $PM_{10}$ % | $PM_{2,5}$ % | Durchschnitt Messung: Messwert upstream µg/m³ | Durchschnitt Messung: Messwert downstream µg/m³ | Anteil $PM_{10}$: upstream µg/m³ | Anteil $PM_{10}$: downstream µg/m³ | Anteil $PM_{2,5}$: upstream µg/m³ | Anteil $PM_{2,5}$: downstream µg/m³ |
|---|---|---|---|---|---|---|---|---|
| 1,0 | 100,0% | 99,5% | 18,1 | 1,1 | 18,1 | 1,1 | 18,1 | 1,1 |
| 2,0 | 94,2% | 85,5% | 9,4 | 0,3 | 8,8 | 0,3 | 8,0 | 0,3 |
| 3,0 | 92,2% | 6,7% | 15,0 | 0,2 | 13,9 | 0,2 | 1,0 | 0,0 |
| 4,0 | 89,3% | | 16,4 | 0,1 | 14,6 | 0,1 | 0,0 | 0,0 |
| 5,0 | 85,7% | | 4,6 | 0,0 | 3,9 | 0,0 | 0,0 | 0,0 |
| 6,0 | 81,2% | | | | 0,0 | 0,0 | 0,0 | 0,0 |
| 7,0 | 75,9% | | 0,3 | 0,0 | 0,2 | 0,0 | 0,0 | 0,0 |
| 8,0 | 69,7% | | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| 9,0 | 62,8% | | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| 10,0 | 55,1% | | | | 0,0 | 0,0 | 0,0 | 0,0 |
| 11,0 | 46,5% | | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| 12,0 | 37,1% | | | | 0,0 | 0,0 | 0,0 | 0,0 |
| 13,0 | 26,9% | | | | 0,0 | 0,0 | 0,0 | 0,0 |
| 14,0 | 15,9% | | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| 15,0 | 4,1% | | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| | | | | | 59,6 | 1,8 | 27,1 | 1,4 |
| | | | $PM_{10}$ Abscheidegrad | | 97,0% | | 95,0% | |

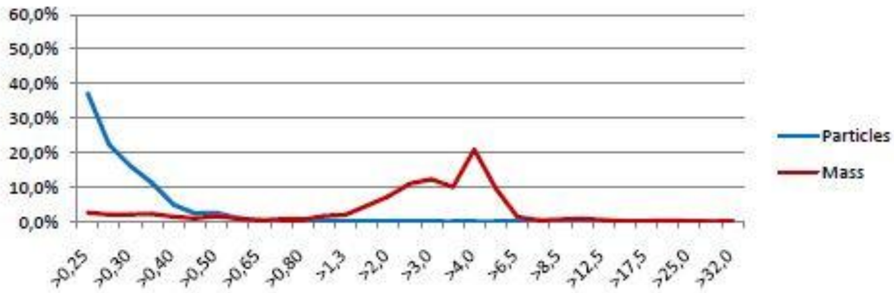
# ECCO*EP* 85% nominal Airflow

14.12.2008 - 15.12.2008

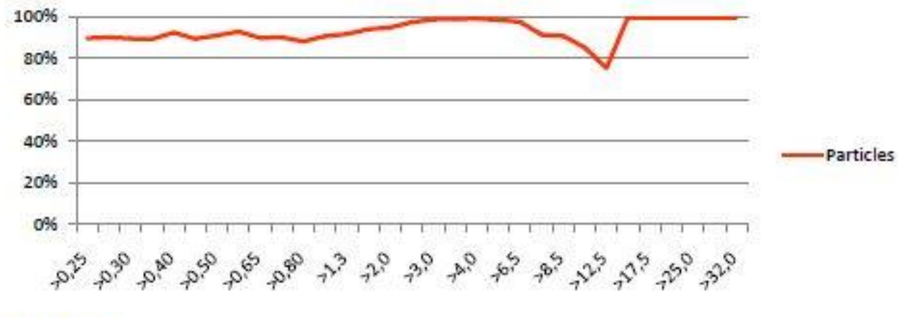
| Efficiency | TSP | > 0,5 µm | > 1,0 µm | 0,5-1,0 µm | 1,0-10,0 µm |
|---|---|---|---|---|---|
| ø % | 95% | 96% | 96% | 91% | 97% |




| Size Distribution | < 0,5 µm | 0,5-1,0 µm | 1,0-10 µm | > 10 µm |
|---|---|---|---|---|
| Mass | 11,6% | 4,1% | 81,8% | 2,5% |
| Particles | 94,3% | 4,5% | 1,2% | 0,0% |




**Efficiency vs. Particle Size**



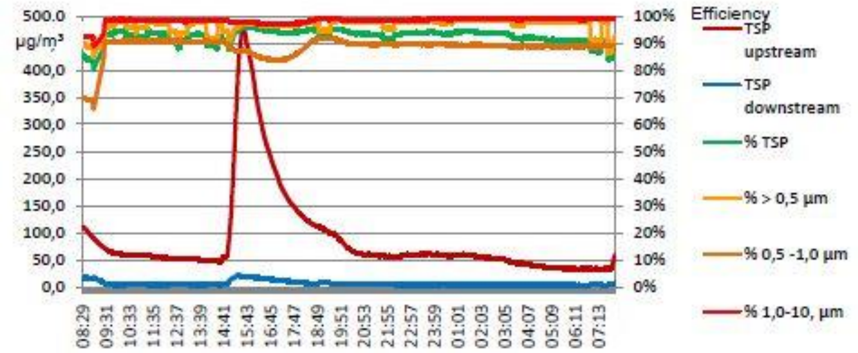

## $PM_{10}$ / $PM_{2,5}$

| Aerodynamischer ø µm | $PM_{10}$ % | $PM_{2,5}$ % | Durchschnitt Messung: Messwert upstream µg/m³ | Durchschnitt Messung: Messwert downstream µg/m³ | Anteil $PM_{10}$: upstream µg/m³ | Anteil $PM_{10}$: downstream µg/m³ | Anteil $PM_{2,5}$: upstream µg/m³ | Anteil $PM_{2,5}$: downstream µg/m³ |
|---|---|---|---|---|---|---|---|---|
| 1,0 | 100,0% | 99,5% | 14,3 | 1,4 | 14,3 | 1,4 | 14,3 | 1,4 |
| 2,0 | 94,2% | 85,5% | 11,6 | 0,7 | 10,9 | 0,7 | 9,9 | 0,6 |
| 3,0 | 92,2% | 6,7% | 19,3 | 0,4 | 17,8 | 0,4 | 1,3 | 0,0 |
| 4,0 | 89,3% | | 25,7 | 0,3 | 23,0 | 0,2 | 0,0 | 0,0 |
| 5,0 | 85,7% | | 8,0 | 0,1 | 6,8 | 0,1 | 0,0 | 0,0 |
| 6,0 | 81,2% | | | | 0,0 | 0,0 | 0,0 | 0,0 |
| 7,0 | 75,9% | | 1,2 | 0,0 | 0,9 | 0,0 | 0,0 | 0,0 |
| 8,0 | 69,7% | | 0,3 | 0,0 | 0,2 | 0,0 | 0,0 | 0,0 |
| 9,0 | 62,8% | | 0,5 | 0,0 | 0,3 | 0,0 | 0,0 | 0,0 |
| 10,0 | 55,1% | | | | 0,0 | 0,0 | 0,0 | 0,0 |
| 11,0 | 46,5% | | 0,7 | 0,1 | 0,3 | 0,1 | 0,0 | 0,0 |
| 12,0 | 37,1% | | | | 0,0 | 0,0 | 0,0 | 0,0 |
| 13,0 | 26,9% | | | | 0,0 | 0,0 | 0,0 | 0,0 |
| 14,0 | 15,9% | | 0,4 | 0,1 | 0,1 | 0,0 | 0,0 | 0,0 |
| 15,0 | 4,1% | | 0,2 | 0,1 | 0,0 | 0,0 | 0,0 | 0,0 |
| | | | | | 74,6 | 2,9 | 25,4 | 2,0 |
| | | | $PM_{10}$ Abscheidegrad | | 96,1% | | 92,0% | |

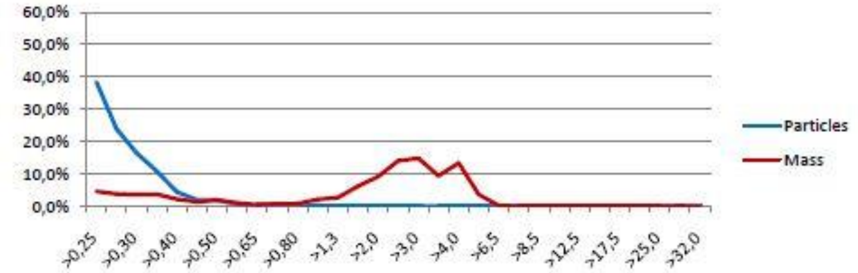
# ECCO*EP* 100% Airflow

11.12.2008 - 12.12.2008

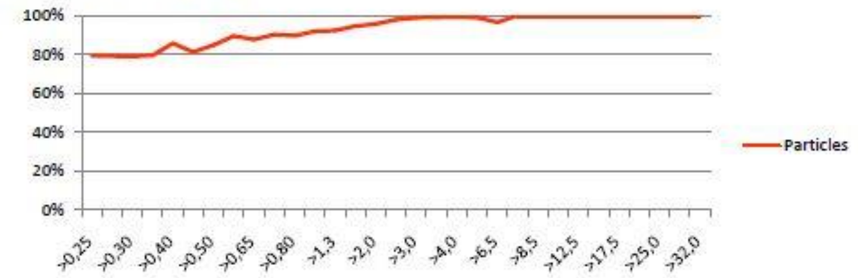
| Efficiency | TSP | > 0,5 µm | > 1,0 µm | 0,5-1,0 µm | 1,0-10,0 µm |
|---|---|---|---|---|---|
| ø % | 93% | 96% | 97% | 88% | 98% |




| Size Distribution | < 0,5 µm | 0,5-1,0 µm | 1,0-10 µm | > 10 µm |
|---|---|---|---|---|
| Mass | 19,2% | 4,9% | 75,6% | 0,3% |
| Particles | 95,9% | 3,3% | 0,9% | 0,0% |




Efficiency vs. Particle Size




## $PM_{10}$ / $PM_{2,5}$

| Aero-dynamic ø µm | $PM_{10}$ definition % | $PM_{2,5}$ definition % | Average of measurment | | Part $PM_{10}$ | | Part $PM_{2,5}$ | |
|---|---|---|---|---|---|---|---|---|
| | | | Value upstream µg/m³ | Value downstream µg/m³ | upstream µg/m³ | downstream µg/m³ | upstream µg/m³ | downstream µg/m³ |
| 1,0 | 100,0% | 99,5% | 22,9 | 4,0 | 22,9 | 4,0 | 22,8 | 4,0 |
| 2,0 | 94,2% | 85,5% | 15,7 | 0,8 | 14,8 | 0,8 | 13,4 | 0,7 |
| 3,0 | 92,2% | 6,7% | 25,1 | 0,4 | 23,2 | 0,4 | 1,7 | 0,0 |
| 4,0 | 89,3% | | 19,8 | 0,2 | 17,7 | 0,1 | 0,0 | 0,0 |
| 5,0 | 85,7% | | 3,2 | 0,0 | 2,7 | 0,0 | 0,0 | 0,0 |
| 6,0 | 81,2% | | | | 0,0 | 0,0 | 0,0 | 0,0 |
| 7,0 | 75,9% | | 0,1 | 0,0 | 0,1 | 0,0 | 0,0 | 0,0 |
| 8,0 | 69,7% | | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| 9,0 | 62,8% | | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| 10,0 | 55,1% | | | | 0,0 | 0,0 | 0,0 | 0,0 |
| 11,0 | 46,5% | | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| 12,0 | 37,1% | | | | 0,0 | 0,0 | 0,0 | 0,0 |
| 13,0 | 26,9% | | | | 0,0 | 0,0 | 0,0 | 0,0 |
| 14,0 | 15,9% | | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| 15,0 | 4,1% | | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| | | | | | 81,4 | 5,3 | 37,9 | 4,7 |
| | | | Efficiency | | 93,4% | | 87,5% | |

# Efficiency ECCO*EP* v. Airflow

Measurements from Plabutsch tests in December 2008
Monitoring system: Grimm
PM values are calculated with separation curves.

| | ø in µm / Medium ø | TSP | >0,25 / 0,265 | >0,28 / 0,29 | >0,30 / 0,325 | >0,35 / 0,375 | >0,40 / 0,425 | >0,45 / 0,475 | >0,50 / 0,54 | >0,58 / 0,615 | >0,65 / 0,675 | >0,70 / 0,75 | >0,80 / 0,9 | >1,0 / 1,15 | $PM_{10}$ | $PM_{2,5}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Airflow 1,54 m³/s = 100% | 100% | 93 | 79 | 79 | 79 | 80 | 86 | 81 | 85 | 90 | 88 | 90 | 90 | 92 | 93,4 | 87,5 |
| | 85% | 96 | 89 | 89 | 89 | 89 | 92 | 88 | 91 | 93 | 91 | 92 | 91 | 93 | 96,3 | 92,5 |
| | 70% | 97 | 93 | 93 | 93 | 93 | 95 | 93 | 95 | 97 | 96 | 96 | 96 | 96 | 97,0 | 95,0 |
| | 55% | 97 | 96 | 96 | 96 | 96 | 97 | 96 | 97 | 98 | 98 | 98 | 98 | 98 | 97,7 | 96,8 |
| | 40% | 99 | 97 | 98 | 97 | 98 | 98 | 98 | 98 | 99 | 98 | 98 | 98 | 98 | 98,8 | 97,9 |
| | 25% | 99 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 99 | 99 | 99 | 99 | 99 | 99,2 | 98,4 |