Cleaner Air in Copenhagen: Mitigating Traffic-Related Particle Pollution

Clean|Air

for the City of Copenhagen

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Sponsor

MILJØPUNKT
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Abstract

Ultrafine particle (UFP) pollution produced from diesel vehicle exhaust is a global problem that threatens the health of citizens living in urban areas. UFPs are less than 0.1 µm in diameter and have been associated with serious health problems such as chronic COPD, heart failure, and cancer. The goal of our project, sponsored by Miljøpunkt Indre By & Christianshavn, was to identify political, technological, and social solutions to lower traffic-related UFP exposure for citizens in Copenhagen. Based on the investigation, which consisted of literature reviews, key interviews, and field data collection, Copenhagen should focus efforts on enforcing new DPF technology and regulating modern diesel emissions tests during the transition to emissions-free transportation.

An Interactive Qualifying Project submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science

WPI

Ultrafine Particles:
The Dangers of Hidden Pollution

Ambient outdoor air pollution causes an estimated 4.2 million premature deaths worldwide per year, mainly due to exposure to small particulate matter.[1] Particles less than 2.5 µm in diameter can penetrate deeply inside the lungs and enter the bloodstream, which contributes significantly to the development of cardiovascular and respiratory diseases.[1] Perhaps the most serious health concern is the genetic damage caused by exposure to ultrafine particles (UFPs), which can lead to carcinogenic mutations and the germination of pulmonary disease.[2] The highest concentrations of UFPs are usually found in heavily trafficked urban areas, since street-level particle pollution is primarily produced by the burning of diesel fuel in vehicle engines.[3] Figure 1 shows a heat map of particle pollution along the road network of Copenhagen. The darker regions indicate where high vehicle density has produced greater particle pollution.[4] To reduce particulate pollution, the Euro emission standards have required the use of diesel particulate filters (DPFs) that are capable of removing particles from vehicle exhaust.[6] However, even with the emission standards and additional political efforts, the city of Copenhagen still reports high premature death rates due to particulate pollution.[6] The absence of programs that target UFP concentrations and lack of widespread monitoring stations in the city has complicated efforts to reduce particulates and the related health concerns. As a result, our sponsor, Miljøpunkt Indre By & Christianshavn, has identified several topics worthy of investigation that could lead to further reductions in particle pollution (eg. idling prevention, maintenance of particle filters, measurement pollutants in diesel exhaust, and alternative technology for cleaner transportation.)

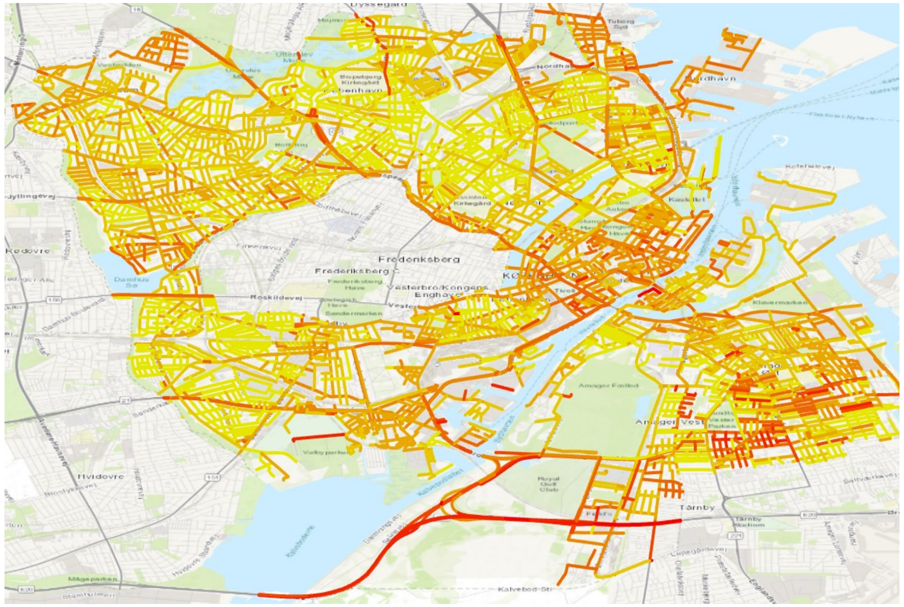

Figure 1: Heat map of street-level particle number concentrations in Copenhagen, 2019[5]

To expand Copenhagen's particle reduction efforts and ultimately improve the environmental sustainability of transportation within the city, our team outlined three major objectives:

1. **Investigate how leading international cities have reduced particle pollution (UFP) in the transportation sector;**
2. **Determine the challenges and limitations encountered during attempts to reduce traffic-related UFP pollution in Copenhagen;**
3. **Develop feasible solutions to reduce UFP pollution from diesel vehicles in Copenhagen.**

First, our team conducted an international study via literature reviews and analyses of past case studies to identify how leading cities worldwide have reduced particulate pollution. After researching successful global efforts, we conducted a thorough investigation in the City of Copenhagen to determine the complications that have prevented attempts to reduce UFP pollution. We performed literature reviews of air pollution reports and technical studies, and interviewed local environmental leaders, technical experts, and key stakeholders within the city who are involved with particle reduction efforts. Finally, our team completed a careful information analysis to determine the best course of action to reduce UFP pollution in the city. The recommendations were presented to our sponsor, Miljøpunkt Indre By and Christianshavn, who determined the appropriate way to implement our suggestions using their numerous contacts within the local government and community.

Particle Pollution in Urban Areas

Particle pollution is a global problem that threatens the health of people who live, work, and travel within highly urbanized cities. Particulates are clusters of solid and liquid particles produced by the combustion of fuel (diesel and petrol) in vehicles, solid fuel (coal) combustion for commercial energy production, industrial processes (construction and manufacturing), and roadwear (pavement erosion, tire/break abrasion).[7] The particles can be emitted directly into the atmosphere as primary PM or formed in the air through the reaction of gaseous precursors as secondary PM.[7]

Classification of Particulates

The classifications of particulate pollution (summarized in Table 1) are determined by the size of the particle diameter (usually expressed in micrometers, µm). Ambient (atmosphere) concentrations of particle pollution can be measured in mass per measured in mass per volume or number per volume. Concentrations of smaller particles are measured using number density, due to their near negligible mass, whereas larger particles are measured using mass density (which have small number counts relative to the smaller particles.)

Table 1: Classification of Different Particles

PARTICLE TYPE	ABBREVIATION	DIAMETER (µm)	METRIC
coarse particles	PM_{10}	2.5 - 10	$\mu g/m^3$
fine particles	$PM_{2.5}$	< 2.5	$\mu g/m^3$
ultrafine particles	$PM_{0.1}$	< 0.1	$number/m^3$
nanoparticles	$PM_{0.02}$	< 0.02	$number/m^3$

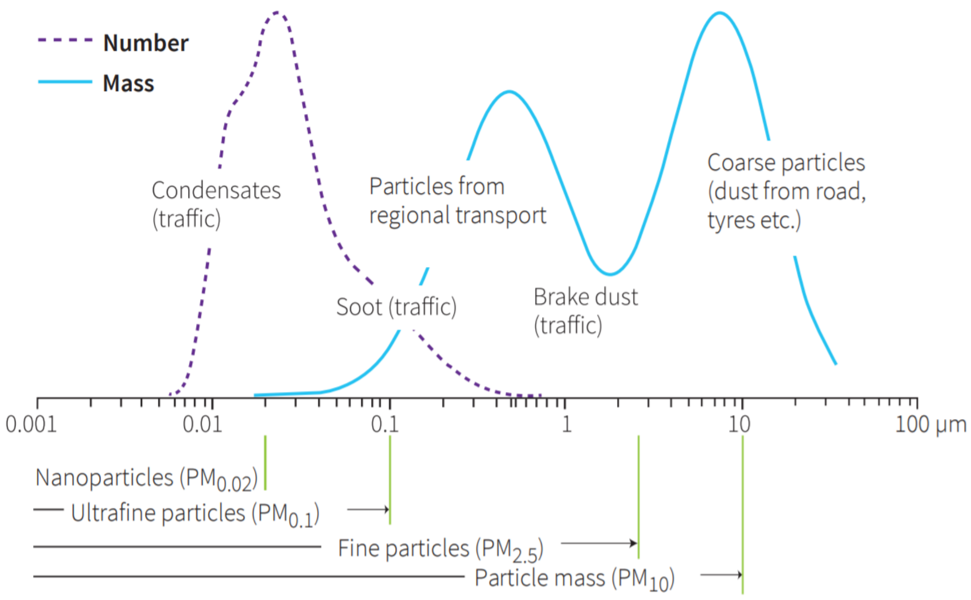

Figure 2: Source and distribution of particle sizes by mass and

Figure 2 illustrates the distribution of particle mass and particle number for each of the classifications. Nanoparticles and ultrafine particles are typically produced by combustion of fuel and reactions between gaseous precursors.[8] Larger coarse particles are primarily produced by roadwear and long range transport of suspended dust.[7,8] Particulates can increase in size via condensation (vapors condense on the particle) or coagulation (combination of two or more particles).[8]

Impact of Particle Pollution on Urban Populations

There is strong documentation about the health effects caused by short term (hours, days) and long term (months, years) exposure to particulate pollution.[7] Particulates can enter the body in multiple ways (via inhalation through the mouth/nose or by penetrating the skin) and contribute to a variety of health problems with some relation to different particle sizess.[7,8] Short term exposure to both large and small particles damages the respiratory and cardiovascular systems, which aggravates asthma/respiratory symptoms and increases hospital admissions.[7] Long term exposure is associated with great risk of cardiovascular and respiratory diseases, chronic obstructive pulmonary disease (COPD), and cancer.[3] Prolonged exposure can also affect the heart and central nervous system, leading to Parkinson's and Alzheimer's disease.[3] Groups with pre-existing cardiovascular or respiratory diseases, young children, and the elderly are the most sensitive to particulate exposure.[7] An overview of the various health problems associated with particle pollution can be found in Figure 3.

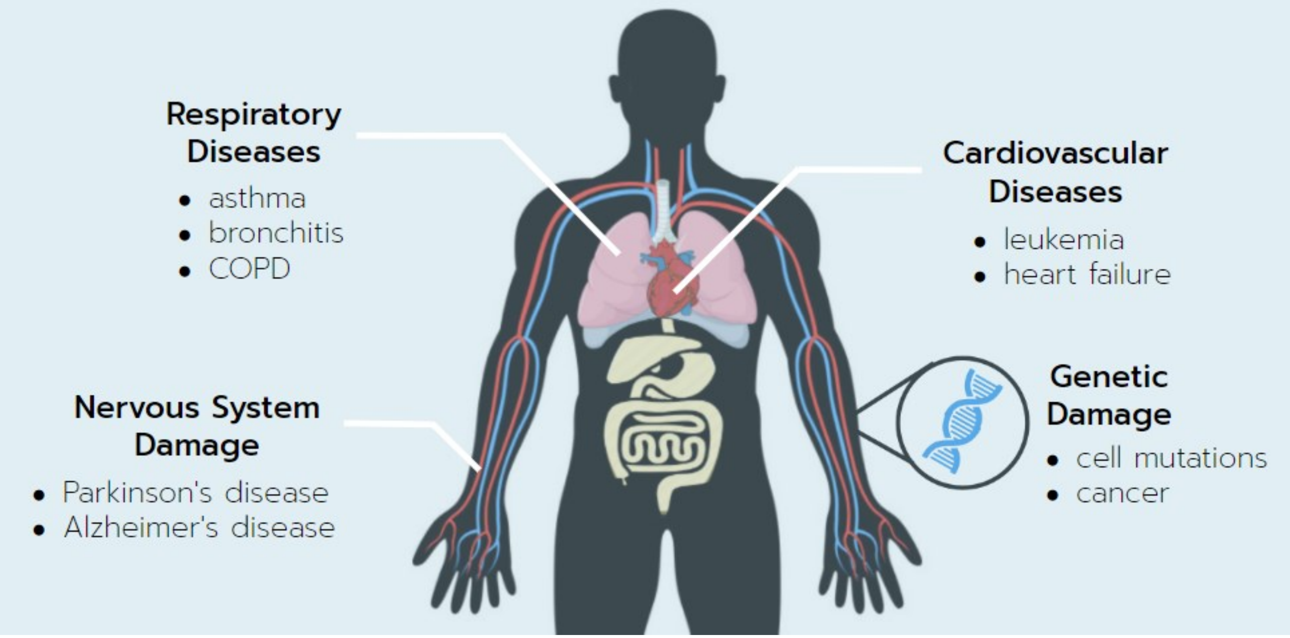

Figure 3: Health risks associated with particle pollution exposure

Smaller particles are a stronger risk factor for more serious, long term health effects (eg. chronic COPD, leukemia, cancer, and cardiopulmonary mortality) than larger particles.[3,7] Smaller particles have a greater surface area relative to the size of the particle which allows more toxins to be carried into the body.[8] The smaller size also enables the particles to travel deep into the body and become embedded in the lungs or absorbed into the bloodstream.[8] Exposure to high levels of smaller particles causes oxidative stress and inflammation in the lungs, contributing to the onset or exacerbation of asthma, pneumonia, COPD, chronic bronchitis and emphysema.[8] Larger particles present a less serious threat since they are typically caught in the nose and throat and cleared from the respiratory tract by coughing or swallowing.[8]

There is growing documentation about permanent DNA damage caused by exposure to the smaller particles produced by fuel combustion.[9] Many of the chemical components of particulates are toxic or carcinogenic which damage the individual DNA strands that circulate through blood cells.[9] As a result, mutated and cancerous cells are created, which are also transmitted to future generations.[9] A research study in 2005 observed a clear correlation between UFP exposure in cyclists and immediate DNA damage even in a short time period of 5 days.[2] In cities, daily exposure to particulates is ubiquitous and involuntary.[7]

The European Environment Agency (EEA) estimated that there were approximately 432,000 premature deaths in Europe during 2012 because of long term exposure to $PM_{2.5}$.[7] Due to the dangerous health effects of particulates, there are numerous multinational monitoring programs of particle pollution. The Ambient Air Quality Directive (AAQD) sets thresholds for various air pollutants and is enforced by the European Union via infringement procedures for member states who exceed the thresholds.[10] The World Health Organization (WHO) also sets their own air quality target limits that, if achieved, would significantly reduce risks for acute and chronic health effects from air pollution.[7] However, **"There is no evidence of a safe level of exposure or a threshold below which no adverse health effects occur."**[7] The thresholds are not indicative of definitive 'safe' concentrations for citizens that cities must reach.[11,12] Instead the guidelines should encourage cities to gradually reduce pollution levels "to minimize health effects in the context of local constraints, capabilities, and public health priorities."[7]

Despite the global monitoring and concentration thresholds set for coarse and fine particulates (PM_{10} and $PM_{2.5}$), no concentration limits for UFPs have been established since there is very limited data for ultrafine particulate (UFP) concentrations. Assessment of particulate levels and trends requires extensive efforts: remote (satellite) sensing and modelling is combined with data from ground level PM monitoring stations.[7] However, very few ground level monitoring stations monitor UFP concentrations, which is especially an issue due to the sporadic geographic distribution of UFPs. The baseline particle number concentration, uninfluenced by human activity, is a few hundred particles per cubic centimeter.[8] In urban areas, the concentrations increase to levels between a few thousand particles to twenty thousand particles per cubic centimeter.[8] However, number concentrations can exceed levels of 100,000 particles per cubic centimeter, over 10 times higher than background concentrations.[8] In contrast, PM_{10} and $PM_{2.5}$ (mass) concentrations are only 25% to 30% higher than background levels.[8] Figure 4 provides a visual representation of geographic particle trends. UFP concentrations are very dynamic; the atmospheric lifetime of the particles can be as short as 20 seconds before they combine with vapors and other particles.[12] Thus, there is a large gradient

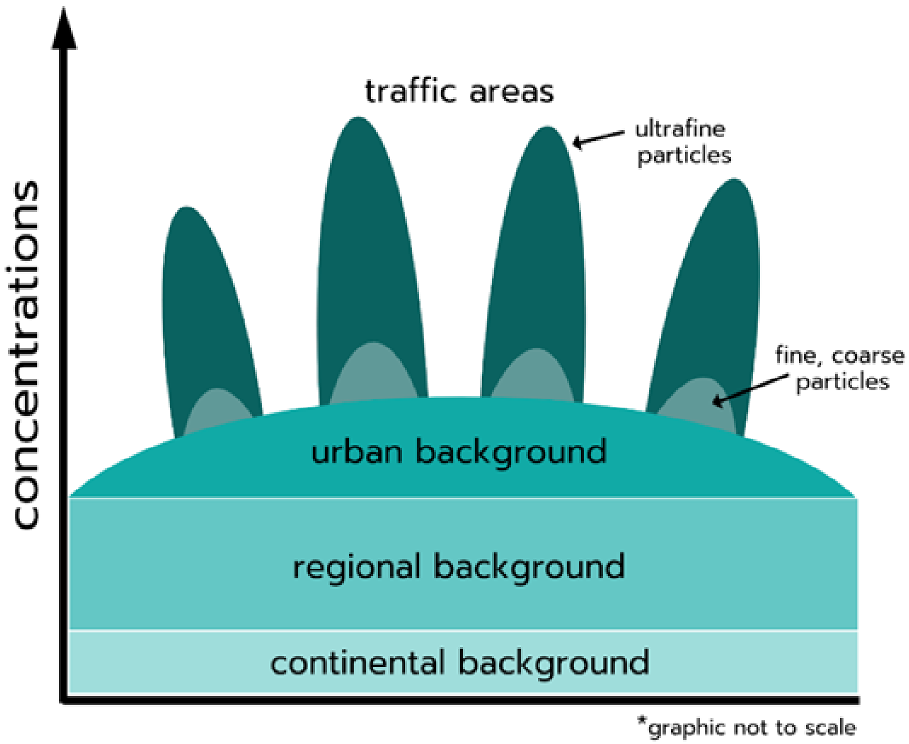

Figure 4: Distribution of particulate concentrations in different geographic sectors

in particle number concentration between heavily trafficked areas and rural areas.[11] The highly localized nature of UFP concentrations and quick dispersion/combination properties of the particles makes UFP monitoring extremely difficult without an abundance of measuring stations near pollution sources.[11] This also stresses the importance for the development of validated models for UFPs to provide the spatial variation of particulate distribution.[11] To better understand the sources, trends, and geographic distribution of UFPs, localized measurements must be taken continuously over a long period of time. However, for current analysis of UFP pollution, alternative short-term methods must be utilized, such as consulting studies and observation-based measurements using mobile equipment.

Table 2: Annual mean concentration limits and reported 2017 level on H.C. Andersens Blvd.

PARTICLE TYPE		EU Limit (µg/m³)	WHO Limit (µg/m³)	HC Andersens Blvd. (µg/m³)
coarse particles	PM_{10}	40	20	25
fine particles	$PM_{2.5}$	25	10	13

Assessment of Particle Pollution in Copenhagen, Denmark

The annual report for the Danish Air Quality Program provides an assessment of certain air pollutants in Denmark and has tracked particulate pollution on H.C. Andersens Boulevard in Copenhagen since 2001.[13] The 2017 mean concentrations for PM_{10} and $PM_{2.5}$ were below the EU limit, but still exceed the WHO guidelines (see Table 2). The mass concentrations for PM_{10} and $PM_{2.5}$ have gradually decreased at all (street-level and rural) measuring stations since 2001,[13] indicating that background pollution includes a significant portion of PM_{10} and $PM_{2.5}$ concentrations.[11] Denmark's Regional background pollution is largely comprised of long-range transported particulates from Western and Central Europe.[14] Unlike PM_{10} and $PM_{2.5}$, UFPs are highly localized and unstable, but high levels of exposure occur close to the pollution sources.[11,12] The 2017 average number concentration in the ambient air at the street station on H.C. Andersens Blvd. was approximately 13,000 particles per cubic centimeter and 4.5 times higher than the rural background average concentration.[13] However, the number of particulates measured at the busy street station has decreased over 40% between 2002 and 2017.[13] Nonetheless, "no threshold for PM has been identified below which no damage to health is observed."[6] Therefore, more focus, monitoring, and reduction efforts must extend to UFP pollution to protect the health of citizens who directly inhale the high concentrations of toxic PM emissions in Copenhagen's heavily trafficked areas.

There has been one attempt to collect hyperlocalized data of street-level air pollution in Copenhagen, which began in 2018 with a partnership between Copenhagen Solutions Lab and Google.[15] Utrecht University equipped pollutant sensors on a Google street-view car (seen in Figure 5) that drove on every street in Copenhagen for over a year, collecting pollution data between 7 am and 11pm.[12] The project is still in progress, but the data will be used to create a hyperlocal map of black carbon, fine & ultrafine particles, and NOx throughout the city.[12] It is also projected that a correlation analysis of the data to various health problems will also be performed.[12] The Copenhagen AirView Project will be *the first* global effort to measure UFPs on a city-wide scale.[12] The project is a big step towards a greater understanding of street-level UFP concentrations in Copenhagen and may demonstrate a more accurate means of measuring certain air pollutants than at scattered permanent stations.[12] However, it is also important to understand the limitations of the project due to the high variability of measurement conditions and dynamic nature of UFPs.[11,16] UFP concentrations are extremely sensitive to meteorological conditions, such as wind, which has a profound impact on the ability for UFPs to disperse.[11,12,16] Furthermore, high fluctuations in particle concentrations can occur depending on the proximity to the particle emission source.[12] Since the Google car drives on each road at different times of the day, over different seasons, with various weather conditions, the actual additional value provided by the measurements is questionable.[11]

Figure 5: Google Car for Copenhagen's AirView Project [15]

Other forms of mobile data collection, such as measurements of particle number concentrations from a handheld device (eg. P-Trak), are also greatly affected by volatile conditions. However, mobile data collection does hold indicative value if the measurements can be connected to situational observations.[11] Despite the uncertainty about whether the Google car project will produce definitive results, the project will provide another strategy for understanding the sources and impacts of UFP pollution. By utilizing indicative measurement techniques, additional insights about the volatile concentrations of elevated levels of UFPs in Copenhagen can be provided. Ultimately, exploring mobile UFP monitoring strategies and investigating the sources of UFP pollution can supplement long-term data from permanent street stations to better inform solutions for how the city can improve air quality.

Determining Strategies for UFP Reduction in Copenhagen

The goal of this project was to evaluate the state of ultrafine particle pollution in Copenhagen and to define an approach for improving environmental conditions. Three primary objectives were defined to achieve the project goal:

Objective 1: Investigate how leading international cities have reduced particle pollution (UFP) in the transportation sector;
Objective 2: Determine the challenges and limitations encountered during attempts to reduce traffic-related UFP pollution in Copenhagen;
Objective 3: Develop feasible solutions to reduce UFP pollution from diesel vehicles in Copenhagen.

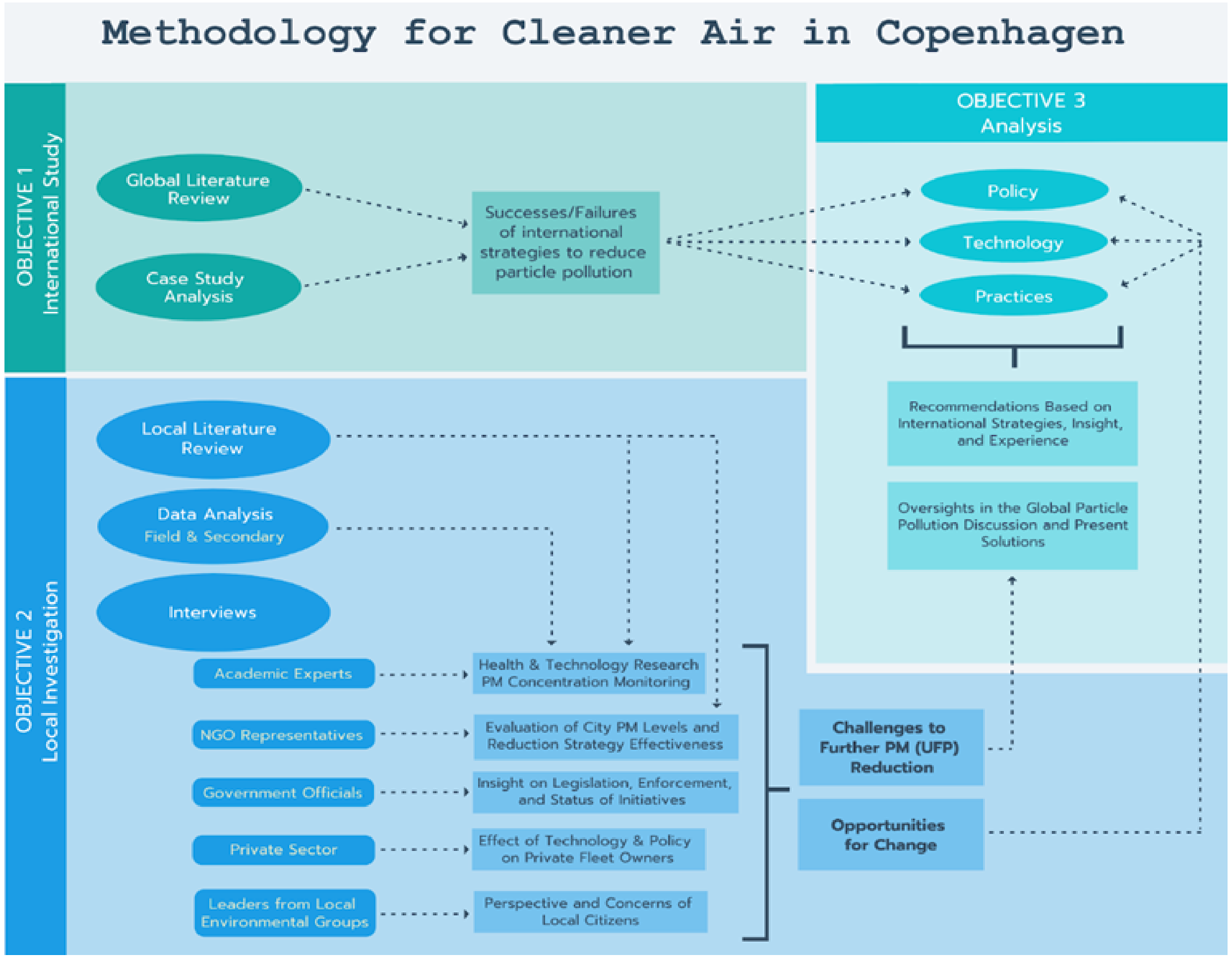

Figure 6: Diagram of project methodology

By addressing the objectives through a series of international and local literature reviews, data collection, and interviews with key figures within the public and private sectors, we were able to understand the social, political, and technical context of particle pollution and reduction strategies. Furthermore, we investigated current solutions and particle pollution reduction efforts in the city to determine why Copenhagen has continued to report high number concentrations of particulates (UFPs.) Finally, we provided our sponsor, Miljøpunkt Indre By & Christianshavn, with our investigation findings and the recommendations we developed based on our understanding of successful global practices. The process of our project and organization of our methods by objective is summarized in Figure 6.

Objective I: Investigate how leading international cities have reduced particle pollution (UFP) in the transportation sector

A comprehensive research study was required to fully understand how ultrafine particle pollution has been addressed by cities around the world. We completed an extensive literature review and interviewed experienced particle pollution experts to gather knowledge about current reduction strategies, existing trends, and how successful efforts have overcome challenges to reduce street-level particulate concentrations.

Literature Review

A global literature review was conducted to identify and evaluate a variety of techniques that have been employed to reduce levels of particulate matter. Relevant legislative documents, technical studies, and reports provided insight about how environmental initiatives have made progress or met resistance. A breakdown of the research areas that were explored in the literature review is displayed in Table 3.

Expert Interviews

Our literature review was supplemented by interviews with international experts who have careers relating to the study or mitigation of particle pollution.

Objective II: Determine the challenges and limitations encountered during attempts to reduce traffic-related UFP pollution in Copenhagen

After completing our global study, we investigated the political, technical, and social facets of particle pollution in Copenhagen to identify the challenges the city has faced. We conducted literature reviews regarding Copenhagen's current policies, technologies, and practices, collected data on particulate emissions, and interviewed key informants within the city to gain local insight about Copenhagen's attempts to limit UFP pollution.

Literature Review

To understand the extensive and complex problem of particle pollution specifically within the city of Copenhagen, we initiated a thorough local literature review. A detailed investigation of the political strategies (regulation, implementation, and enforcement), the measured effect of technological solutions, and the influence of social practices was required to identify possible areas for improvement in the steps Copenhagen has taken to reduce levels of particulate matter.

Table 3: Features of the air pollution problem

POLICY	TECHNOLOGY	PRACTICE
• Legislation • Enforcement • Adjustment over time	• Proactive vs. Reactive technology • Economic feasibility • Logistics of integration	• Cultural influence • Transportation habits • Nature of community interaction

Data Analysis

To evaluate the actual state of UFP pollution in Copenhagen, we conducted two types of data collection. First, we gathered UFP concentration field data using a TSI P-Trak monitoring device at key taxi and bus congregation spots and high traffic areas within the city. To supplement the numerical data on particulate concentrations, we observed and recorded patterns and behaviors of traffic, buses, and taxis associated with the numerical emission data. The observations were used to provide situational context during analysis of the data points to help identify the particle emitting source(s) when the measurements were taken. The collection protocol using the P-Trak device can be found in the supplementary materials file.

Action Shot: Students collecting data with P-Trak device

Interviews with Key Informants in Copenhagen

In Copenhagen, we conducted interviews with specific individuals to gain additional information to build on what we gathered from the local literature review. We interviewed a variety of local informed leaders, including technical experts, chairmen of municipal environmental groups, and key stakeholders such as bus and taxi company representatives. Local technical experts deepened our understanding of diesel emissions and greatly contributed to our investigation about the actual extent to which DPFs reduce particle emissions. Conversations with local environmental leaders provided a more direct citizen perspective about the present problem of particle pollution in Copenhagen, the effectiveness of government initiatives, and insight about potential opportunities for change. Within the transportation sector, we interviewed representatives of Movia, Zealand's largest public bus company,[17,18] in addition to contracted maintenance companies to examine their practices (idling & maintenance) and technologies (types of vehicles & DPFs). Copies of the questions for each interviewee, their responses and a list of scheduling/contact information can be found in the supplementary materials file.

Objective III: Develop feasible solutions to reduce UFP

After objectives 1 and 2 were completed, the team had the necessary information to formulate potential solutions to reduce UFP pollution emitted from diesel vehicles in Copenhagen. We had acquired knowledge about successful international approaches, investigated the present technological solutions, identified the strategies Copenhagen had implemented, and gained insight about the challenges Copenhagen faces for further reducing particulate concentration. By carefully considering our findings, we were able to present feasible solutions to our sponsor, Miljøpunkt Indre By & Christianshavn.

Information Analysis

An extensive information analysis was required to formally address all of the information gathered through our prior tasks: literature reviews, data collection, and interviews. Figure 7 depicts our approach to organizing and analyzing all the pertinent information we collected over the course of the project. The overlaps in the diagram indicate the connections between successful global efforts to reduce particle pollution in the spheres of policy, technology, & practice and the conditions within the city of Copenhagen that presented challenges/ opportunities for environmental change. By following the analysis process displayed in the diagram, we were able to develop a strong understanding of the particle pollution problem in Copenhagen and recommend the most appropriate course of action for the city. The best solutions as determined by the team, inspired our sponsors expectations, are designated in the diagram as asterisks in each region of overlap, and were formally recommended to Miljøpunkt Indre By & Christianshavn.

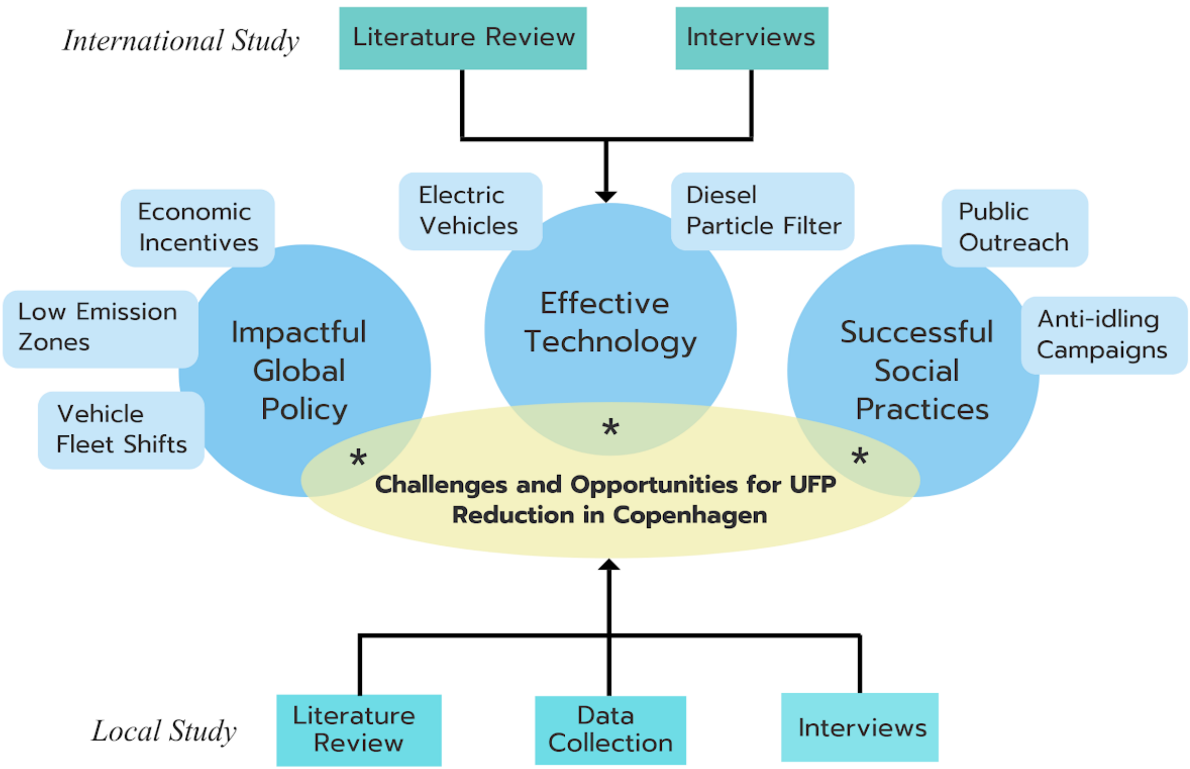

Figure 7: Information analysis process

Traffic Significantly Increases Street Level UFP Pollution

Although the data for UFPs is limited, the Danish Air Quality Monitoring Program and air pollution modelling software, AirGIS, do point to an important message: reducing traffic-related sources of UFPs is important. Thus far, Copenhagen has focused its reduction efforts on PM_{10} and $PM_{2.5}$ with regard to particle pollution and has successfully brought down concentrations below the EU limits.[10,12,19] Copenhagen is now in a position to shift its attention to smaller particles in light of the growing documentation about the dire health effects of UFPs.

Based on the progress Copenhagen has made with reducing PM_{10} and $PM_{2.5}$ and the fact that the background particulate levels comprise approximately 55% and 70% of street-level PM_{10} and $PM_{2.5}$ concentrations, respectively,[13] local focus should be on reducing smaller particles -- which are primarily traffic emissions. In a 2017 research article about vehicle-related UFP pollution, it was determined that road traffic was the “key cause of UFP emissions,” contributing to 90% of the particle number count along the streets in polluted city areas.[3] The data collected by the Danish Air Quality monitoring program supports this finding. In the annual report of 2015 air pollutant data, the plot of particle number concentrations over time clearly indicates that the street level concentration is far greater than urban and rural background concentrations (Figure 8).[20] The number of particles in ambient air on H.C. Andersens Blvd. was 3 times higher than Copenhagen's urban background (H.C. Ørsted Institute) and 4 times higher than the rural background (Lille Valby/Risø).[20]

Furthermore, the composition of UFPs from vehicular exhaust is highly toxic because of the high organic carbon content and other dangerous compounds in diesel fuel.[8] Thus, the commuters who travel along the roads not only inhale high concentrations of particles, but more harmful concentrations of particles produced by the diesel vehicles.[3] Studies indicate that "people residing, working or travelling near major roads have shown escalation in the incidence and severity of many health issues, especially at traffic intersections."[3,21]

Besides traffic-related sources of particle pollution, many citizens in Copenhagen are also concerned about the pollution from other local sources.[22,23] In light of the citizens' concerns, it is important to consider that all pollutants are harmful to health and **no amount of pollutants can be considered a "safe" amount; it's about the margin for risk**.[11,12] Contrarily, the Danish society and political system thinks largely in terms of limit values.[19] Since the annual mean concentrations for PM_{10} and $PM_{2.5}$ in Copenhagen are far below the EU limit values, particulate pollution is not considered as high of a priority in Danish politics.[19] However, there are still components of the issue that have retained citizen attention, namely the pollution contributed by cruise ships and wood stoves.

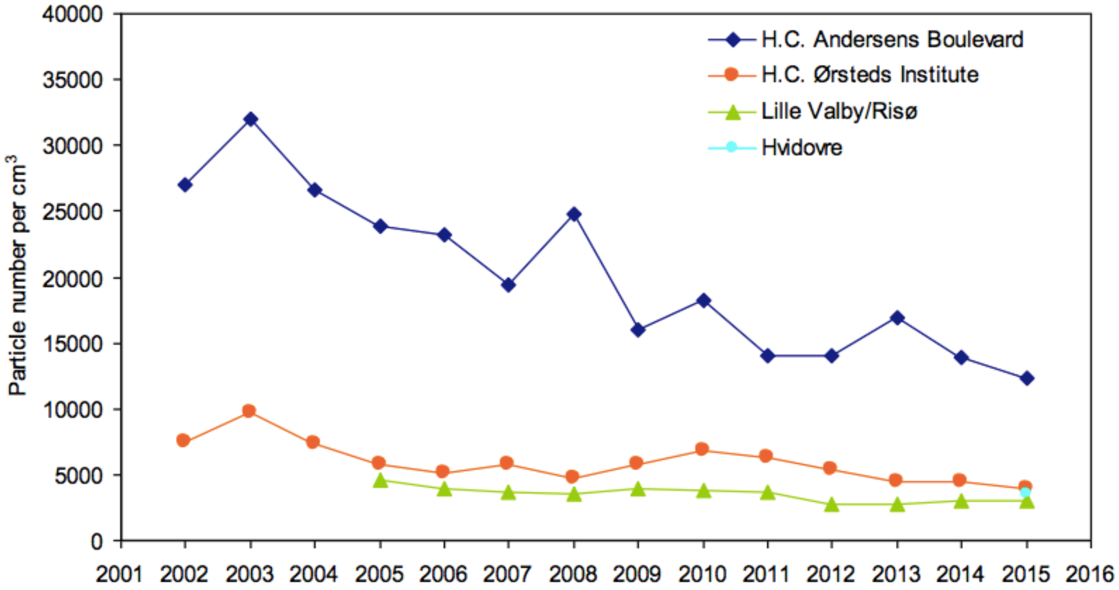

Figure 8: Particle number (UFP) concentrations (sizes 6nm to 700nm)[21]

Pollution from cruise ships does not pose as great of an immediate threat to the overall city population. The levels of air pollution from cruise ships are higher in Danish marine areas,[14] but the pollutants can quickly disperse in the open harbors. Thus, the emissions from ships are certainly local problems and contribute to background levels of air pollution, but not to the exorbitant particle number concentrations along city streets. Wood burning stoves, however, are the main constituent of non-industrial primary PM in Denmark[14] and contribute to extremely high levels of indoor particle concentrations.[8] There are 16,000 wood burning stoves in Copenhagen that contribute as much to particle pollution as all of the emissions produced by traffic in a year.[19] However, wood stoves "only cover 0.4% of the energy consumption and could really be replaced by district heating tomorrow"[19] -- therefore, the solution for eliminating particle emissions from residential burning is quite simple.[19] Conversely, mitigating UFPs from traffic-related sources is far more complicated. Thus, determining solutions for reducing PM pollution from vehicle exhaust should still be made a priority, especially because of the tremendous number of cyclists and pedestrians along city streets who are directly exposed to the dangerous diesel emissions. Furthermore, other studies have even found that people inside of vehicles are not protected from the high concentrations of particle pollution.[24,25] Since all road users are susceptible to high street-level UFP concentrations as a result of dangerous diesel emissions, it is crucial that Copenhagen engages in efforts to limit harmful traffic-related UFP pollution.

Questioning the Effectiveness of DPFs

Both political and technological mechanisms cooperate to enable widespread reduction of pollution from on-road vehicles. The Euro emission standards (also called Euro Norms) are limits on engine emissions from vehicles and are enforced in member-states of the EU.[6] The standards are based on measurements of pollutants in the exhaust, and therefore do not specify installation or production of certain pollutant reduction technologies which permits market freedom to achieve the pollution limits.[6] Diesel particle filters (DPFs) are currently the most common technology for reducing the particle pollution in exhaust from diesel vehicles. During the implementation of newer Euro Norms, the particle mass limit has been consecutively reduced (see Table 4) and necessitated DPF technology to also improve. However, Copenhagen's on-road vehicle fleet has yet to fully implement newer filtration technology and has been experiencing low performance and malfunction of old DPF technology.

More recently, The introduction of particle number emission limits in the Euro 5 and Euro 6 standards made it necessary for diesel passenger cars and heavy-duty diesel vehicles to eliminate a greater range of particle sizes.[6] Prior to the introduction of particle number limits, DPF technology was only required to remove larger particles, which comprised the majority of the particle mass, to meet the Euro Standards.

Table 4: Euro 1 through Euro 6 Emission Standards for diesel vehicles (data[6])

	Diesel Vehicle	Effective Date Factory/Sale	Particle Mass Limits	Particle Number Limits
Euro 1	Passenger Car	1992/1993	140 mg/km	--
Euro 2	Passenger Car	1996/1997	100 mg/km	--
Euro 3	Passenger Car	2000/2001	50 mg/km	--
	Truck/Bus	2000/2001	100 mg/km	--
Euro 4	Passenger Car	2005/2006	25 mg/km	--
	Truck/Bus	2005/2006	20 mg/km	--
Euro 5	Passenger Car	2009/2010	5 mg/km	6e11 part./km
	Truck/Bus	2009/2010	20 mg/km	--
Euro 6	Passenger Car	2014/2015	5 mg/km	6e11 part./km
	Truck/Bus	2013/2013	10 mg/km	8e11 part./kWh

However, to achieve the new particle number limit, the filters were redesigned to eliminate the high number of small particulates (ie. UFPs).[26] In July 2019, the Conference on Combustion Generated Nanoparticles concluded that Euro 6 DPFs were effective at filtering out particulates as small as 0.01 µm, assuming the filters are properly maintained.[27] However, Copenhagen has not regulated installation of the new Euro 6 standard filters on current on-road vehicles. Thus, many of the diesel vehicles on the streets still use old technology, which does not remove the high number of harmful UFPs.[6] Furthermore, the neglect to regulate filter technology can be observed in second-by-second data of ambient particle number concentrations along busy streets in Copenhagen. The graph in Figure 9 shows the data collected along H.C. Andersens Boulevard during twelve minutes of continuous sampling.

During the sampling period, the traffic flow of diesel cars, vans, tour buses, and public buses produced various spikes in the particle number concentrations. Although there is too much uncertainty (fluctuating meteorological conditions, high traffic speed, and heavy traffic flow) to identify a certain source to each concentration spike, the large number of spikes indicates there are many vehicles that do not filter the abundance of UFPs in the exhaust.

Vehicles may fail to filter particulates for two primary reasons: (1) the vehicle is using old filter technology, which is also more prone to malfunction, or (2) the vehicle is using a broken filter for removing UFPs. Key DPF design characteristics between different filters can account for the variation in filter performance and explain the observed peaks in streetside particle number concentrations in Copenhagen.

Older Vehicles Use Ineffective Open Filters

There are two prevalent designs of DPFs that vary considerably in filter effectiveness. Old DPF technology, specifically open filters, do not

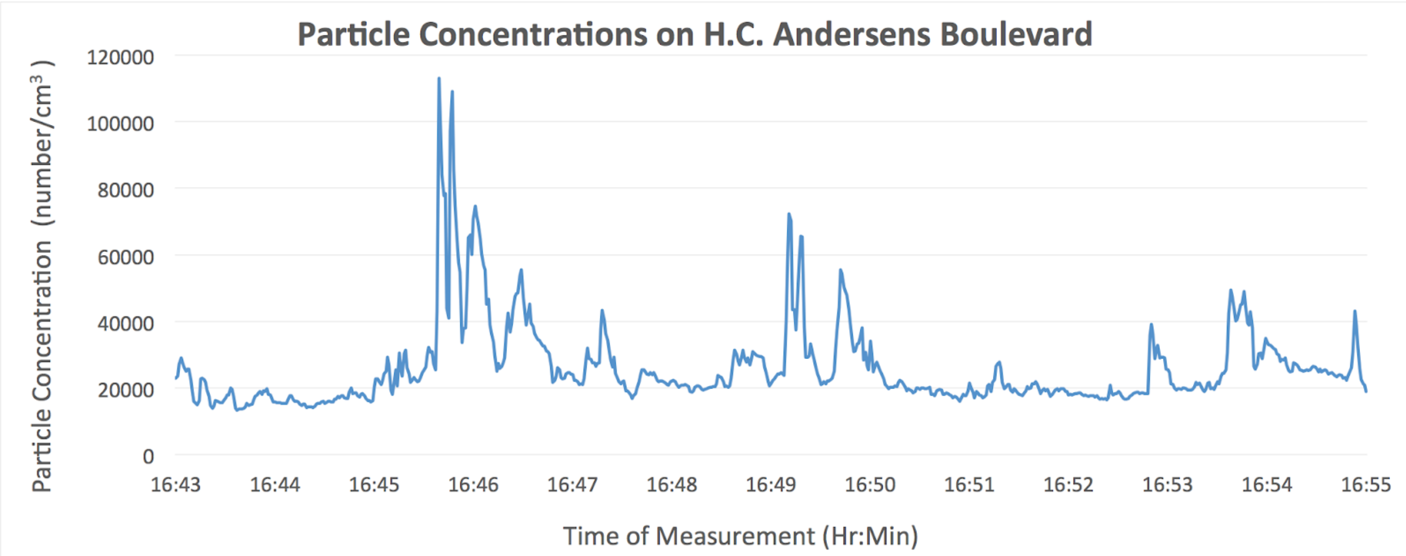

Figure 9: Plot of continuous data collection (one sample per second) of particle number concentra-

remove UFPs and are significantly affected by city driving conditions. The open filter channels, depicted in Figure 10, allow a large number of particles to pass through the filter which can only remove 30% to 50% of particle mass from the exhaust under ideal conditions.[6] The removal effectiveness of open filters can decline to as low as 5% in cities due to slower driving speeds and stop-and-go traffic patterns.[6] Conversely, closed particle filters are far more effective and can

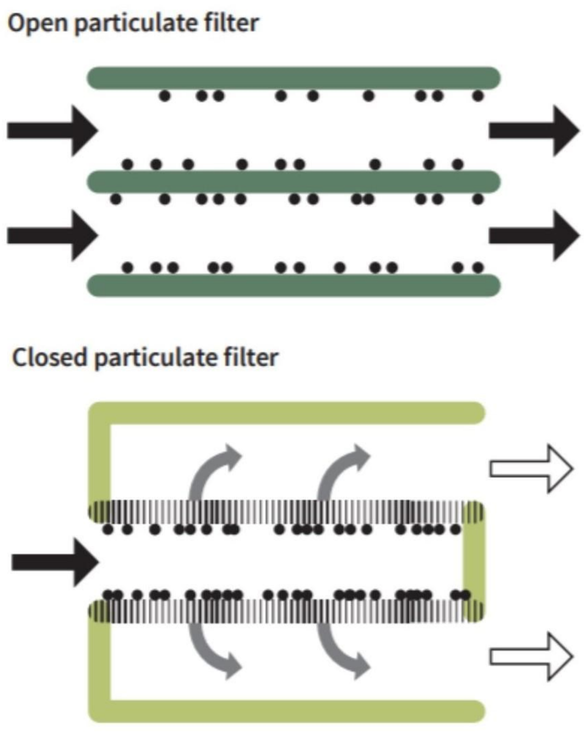

Figure 10: Open vs. closed filter design[6]

remove approximately 99% of particle mass from diesel exhaust.[6,26,28] However, closed filter technology has only recently been required in new production line vehicles to meet the Euro 5 and Euro 6 diesel emission standards.[6] Zealand's largest public bus company, Movia, manages 1,314 diesel buses (1,392 total buses) and as of 2019, ~50% of them still operated with open filters (open filter buses denoted by asterisks in Table 5).[17] The open filters reportedly reduce the buses' particle emissions by only 20% to 30%.[28] Closed filter retrofits have been between 90% and 95% effective in practice.[17] The large number of ineffective filters in Copenhagen's public bus fleet is a serious problem because it means that high concentrations of toxic particulates are inhaled by cyclists and pedestrians who pass directly next to the tailpipe when a bus stops to load/unload passengers. If Movia retrofits the remainder of diesel buses with closed filters (which is ~10% the cost of purchasing new buses[17]), PM pollution in diesel bus emissions can be reduced significantly, which helps protect the health of citizens. Widespread reduction to PM pollution, and specifically UFP pollution, can be made if *all diesel vehicles in Copenhagen use closed DPFs.*

Table 5: Composition of Movia bus fleet

VEHICLE TYPE	TECHNOLOGY SPECIFICATION	# OF BUSES	
Euro 2	CRT	1	*
Euro 3	CRT	73	*
Euro 4	----	96	*
	SCRT Retrofitted to Euro 6	12	
Euro 5	----	93	*
	SCRT Retrofitted to Euro 6	7	
EEV	----	400	*
	SCRT Retrofitted to Euro 6	179	
Euro 6	----	453	
Electric	----	78	
Total		1,392	

CRT = Continuous Regeneration Technology
SCRT = Selective Catalytic Reduction Technology
EEV = "Enhanced Environmentally-Friendly Vehicle"

Passive Regeneration is More Prone to Failure

Another key design component of DPFs is the cleaning mechanism--called 'regeneration'--which is crucial for maintaining proper function of the filter.[29] Regeneration is the process of incinerating accumulated particles on the filter to prevent clogging in the filter channels.[29] If a filter fails to regenerate and becomes oversaturated, backpressure can build in the exhaust system and cause damage to the engine and/or create cracks in the filter structure.[26,30] Small cracks in the filter can be more problematic than large cracks because they often do not create a large enough pressure change to be detected by the vehicle's backpressure sensor.[28] Furthermore, the small cracks (especially when present in large quantities) can still allow a high number UFPs to escape.[28] Thus, reliable regeneration is essential to ensure continued function of the DPF. However, the reliability varies greatly between the types of regeneration.

There are two primary types of regeneration: passive and active. In passive regeneration, a catalyst coating on the filter is used to lower the required engine temperature to incinerate the trapped particles, enabling regeneration to occur during regular vehicle operation.[26,29] However, reaching necessary regeneration temperature is not always possible under certain driving conditions.[26] For example, the engine does not operate at high temperatures when driving in the city at slower speeds with stop-and-go traffic.[19,26,29] If the engine does not reach high enough temperatures, the filter may fail to regenerate or only partially regenerate.[29] Alternatively, active regeneration does not depend on driving conditions because an external energy source is used to reach the necessary incineration temperature of the trapped particles.[26,29] Since active regeneration can automatically initiate incineration of the trapped particles as needed, the risk of incomplete regeneration, filter malfunction, and engine damage is significantly lowered.[26] Movia buses primarily use active regeneration,[28] but at least 74 of them use passive regeneration.[17] The Euro Norms do not indicate whether DPFs use active or passive regeneration to meet the emission standards; thus, the number of vehicles in Copenhagen that use less reliable passive regeneration is unknown. Yet, it is likely that many of the passive regenerating filters fail to perform properly due to the unfavorable driving conditions in the city, and many drivers may be unaware of malfunction since their backpressure sensor does not always detect filter cracks.[26,28]

Ultimately, the high frequency of spikes in roadside particle number concentrations suggests that many vehicles in Copenhagen are using inadequate emissions control technology. Furthermore, there are no regulations that require effective Euro 6 filters or active regeneration, thus permitting continued use of old, less effective, and unreliable DPF technology. As a result, an immeasurable number of diesel vehicles are heavily contributing to dangerous street-level PM pollution.

Maintaining DPFs is a Major Challenge

Maintenance of diesel particle filters is also a major challenge in Copenhagen due to the current lack of standardized emissions testing and use of outdated testing techniques/equipment. Although filtration technology has improved in newer cars with tightened Euro emission standards, maintenance often fails to preserve effective filter performance. Maintenance issues and inadequate emissions tests for both private and public diesel vehicles has allowed a large number of vehicles to continue polluting at high rates, often unbeknownst to the vehicle owners.

Passenger Cars

Over the past several years, many car manufacturers have attempted to evade the tightening limits on pollutants in vehicle emissions over consecutive Euro Norms. In 2015, the U.S Environmental Protection Agency revealed that Volkswagen had installed "manipulation devices"[31] in their vehicles that significantly lowered the NOx emissions during the official lab-based emissions test.[32,33] Following the Volkswagen scandal, numerous other automakers were exposed for using similar methods to cheat the emissions test.[32] In response to the emissions test fraud, polluting vehicles have been recalled and the EU has introduced laws to improve emissions control validation testing.[34] Although 10 million vehicles have since then been recalled and a mandatory on-road component to the official emissions test was added in 2018, it may take years for the air quality in city centers to improve since many polluting cars remain on the roads.[31,35] The EU cautions that "the effectiveness of market surveillance will depend on how the Member States implement it."[31] The emission scandals demonstrate that there is great uncertainty about pollutant levels in vehicle emissions, which drives the need to ensure that testing and validation of emissions is robust.

Unfortunately, Denmark does not regulate emissions testing of passenger vehicles beyond a basic EU-regulated test for carbon monoxide.[19,28] Passenger cars are required to have general inspections every other year once each car has reached 5 years since production.[26] The inspection does include the EU emissions test,[26] however the procedure and required testing instruments have not been specified or standardized. The emissions test consists of a smoke-based opacity test to measure carbon monoxide levels and sometimes to approximate particle mass levels.[36] The opacity testing devices quantify how much light is displaced by smoke from the exhaust and is commonly used in inspections due to its low-cost.[36] However, opacity testing is a method from the 1990s that was developed when diesel vehicles emitted large amounts of smoke and soot.[19] Moreover, the opacity test cannot accurately test the emissions of most current on-road passenger diesel vehicles (Euro 4/5/6) that emit smokeless exhaust.[36] The opacity test is even less useful for testing the effectiveness of DPFs since the testing devices are insensitive to particles smaller than 50 nm (or 0.05 μm) resulting in underestimations of PM emissions.[36] Some inspection facilities even offer to provide "environmental certificates" to vehicles that pass the opacity test, even though the technique is inadequate for properly evaluating vehicle emissions.[36,37] As an alternative to outdated opacity-based emissions testing equipment, the TSI PET (shown in Figure 11) device used for emissions tests in Dubendorf, Switzerland, can quickly and precisely evaluate the effectiveness of DPFs during low idle of the vehicle.[38] "The devices cost around 8,000 euros ($9,060 [or 59,700 DKK]), making them affordable for police and garages that do emissions inspections."[38] However, without additional regulation on Danish emissions testing, inspection facilities can continue to use outdated and unreliable testing techniques/ equipment simply because they are the cheapest option.[36]

Figure 11: TSI PET being used in an emissions test

Diesel Buses

Emissions from diesel buses are tested using the On-Board Diagnostic (OBD) technique in periodic vehicle inspections, as regulated by the EU.[28] OBD tests monitor the "performance of major engine components," using light indications if a component malfunctions (e.g. check engine light).[39] In addition to periodic OBD testing, traffic companies may also develop supplementary testing procedures since current OBD tests do not always clearly indicate whether the emissions filtration technology is working.[19,28] The OBD test uses the backpressure sensor to determine proper DPF operation: If the backpressure sensor reports values within the expected threshold, then it is assumed that there are no problems with the filter.[28] If the sensor value is above the threshold, the filter is clogged and needs to be regenerated/cleaned.[19] If the sensor value is below the threshold, the filter is broken (cracked open) and needs to be replaced.[19] However, the backpressure sensor does not detect all cases of DPF malfunction.[19,28] For example, small cracks on the filter allow large numbers of particles to escape, but are not large enough to affect the backpressure.[28] Another undetected DPF malfunction can occur if there is a combination of holes and clogged filter channels; the impact of each flaw on the backpressure sensor counteracts the other, for a combined neutral effect.[19] Ultimately, a number measurement is required to determine whether the filter continues to effectively filter particulates while in use.[19]

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Movia has chosen to supplement the OBD emissions validation technique with their own in-field emissions test, Miljøsyn.[28] The protocol for the in-field testing of Movia buses provides a better means of evaluating exhaust pollution using actual measurements of particle number, particle mass and nitrous oxide concentrations (PN, PM, and NOx).[28] The strategy of the Miljøsyn test is to compare emissions performance between "new, well-operating buses"[28] and other buses in the field.[28] Frantz Bræstrup, Specialist at FORCE Technology and author of Movia's in-field testing manual, summarized the procedure as follows:

Emission measurement instruments are placed on the new buses; when the bus accelerates, the peaks in the PM, PN, and NOx concentrations are recorded. The peak values from the new buses are used as baselines for properly functioning emissions systems (this is only done once on a number of buses to determine the limit values). The same process is completed for another busX.

The peak values for busX are compared with the threshold baseline of the "new, well-operating buses." If the peak values are below the threshold value, then the emissions technology is assumed to be functioning properly.

Ideally, Movia could validate the emissions of their contracted buses against the Euro emission standards by periodically bringing each bus to a special Euro Norms test bed.[28] However, the Euro Norms test, which uses a portable emissions measurement system (PEMS), is extremely expensive ($50,000 USD / 342,700 DKK per bus) and thus is not viable for testing.[17] Instead, OBD and in-field testing of the Movia buses is a more feasible alternative.[28] Nonetheless, OBD is not always a reliable technique for evaluating filter performance and Movia's in-field tests cannot measure the engine effect under the same conditions as the Euro Norm test.[19,28] Furthermore, Movia's third-party in-field emissions testing on Euro 4, 5, EEV, and 6 has been hindered due to recent problems with the measurement devices.[17] Movia expects to start testing these buses again in October 2019, using a new emissions testing manual.[17] Meanwhile, another third-party company has been conducting tests on the buses on a smaller scale.[17]

Table 6: Particle number concentrations for various Euro 6 buses

Euro Norm	License Plate Number	Particle Count (Number/cm³)
Euro 6	AL 94007	8,400*
	AL 94021	42,900*
	AL 94003	55,100
	AL 94013	208,100
	AL 94017	265,600

*Indicates the measurement was the result of combined emissions (Euro 5 bus also present at bus stop)

The complications of emissions testing for the Movia bus fleet has allowed buses with malfunctioning DPFs to continue driving. Table 6 displays the particle concentrations emitted from each Euro 6 bus that was measured at the Tietgensgade bus stop over a 20 minute observation period. Euro 6 DPFs are expected to be the most effective retroactive technology for reducing particle pollution from diesel vehicles, since they can remove ~99% of all particulate matter, including ultrafine particles.[4] However, the significant variation in particle numbers measured during the presence of each Euro 6 bus shows that many of the DPFs are not functioning effectively. A single Euro 6 bus (Plate AL94017) produced 265,600 particles, which is more than 30 times the number of particles produced by the combined emissions (8,400 particles) of a Euro 5 and Euro 6 bus idling at the bus stop. The drastic difference in particle numbers emitted by buses of the same Euro 6 emission standard indicates that new, effective bus filters can malfunction without proper maintenance. Regardless of extensive effort to retrofit all buses with Euro 6 DPFs, ultrafine particle pollution will continue to threaten the health of Copenhagen's citizens unless the filters are properly maintained.

Prospect of Emissions-Free Vehicles

The variation in emission testing techniques, equipment, and reliability points to a greater issue: It is extremely difficult to monitor vehicle emissions, and even more challenging to understand how emissions from a single vehicle contribute to ambient particle pollution levels and impact the health of the city population. In fact, determining the relationship between traffic emissions, ambient particle pollution, and health impacts is currently at the leading edge of science.[11] **Rather than focusing long-term efforts on the varying technologies, unstandardized maintenance, and complicated emissions restrictions in an attempt to reduce the harmful health effects of polluting vehicles, it is important to consider the overall shift to zero-emission vehicles.** Copenhagen has ambitious climate goals to become carbon-neutral (emissions are still produced) by 2025 and fossil-free by 2030.[19] Traffic companies can contribute significantly to the achievement of the 2025 and 2030 climate goals by increasing the electric vehicle share within their fleet. Different municipalities can support climate goals by allocating funding for a diesel-free bus fleet.[17] In 2019, Movia added 76 electric buses (~5% of the entire Movia fleet), primarily to run on bus routes in Roskilde, Copenhagen, Frederiksberg, Egedal, and Ballerup.[17] Tests in Copenhagen and Roskilde have also shown that shifts to electric buses so far have been successful and are economically viable.[17] Movia is focused on running most buses on biodiesel, biogas or electricity by 2025,[28] and will move towards an HVO (Hydotreated Vegetable Oil, ie. biodiesel), biogas, electric, and hydrogen fleet by 2030.[17] However, biofuels are not clean fuels since they still produce air pollutants (although less than conventional fossil fuels) and contribute to CO_2 emissions when combusted.[19] Emissions-free vehicles simplify the discussion for traffic-related air pollution since exhaust pipe pollutants are eliminated at the source.[11] Before vehicle fleets are shifted, however, the city must focus on the health costs of particle pollution and seriously consider the present opportunities for controlling emissions from diesel vehicles; "It is a matter of will, not technical challenges."[19]

Copenhagen Can Enhance Strategies to Reduce UFPs

For cities to significantly reduce levels of particulate pollution and to continue making reductions over consecutive years, systematic change is required. Such large-scale change requires extensive coordination between political initiatives, technological solutions, and social transformations. As a leader in sustainability, Copenhagen has thus far engaged in a variety of political, technological, and social efforts to decrease levels of particulate pollution within the city. However, several opportunities for further particle reduction in Copenhagen can be identified using strategies from successful practices in other European cities.

Copenhagen has utilized some economic incentives to encourage the citizens to engage with particulate reduction efforts. The high Danish registration tax on purchasing new cars has discouraged car ownership, and resulted in significantly lower car ownership levels compared to those of neighboring countries.[6] The annual green car owner's tax has encouraged the purchase of small, energy-efficient cars.[6] Electric vehicle owners benefit from additional economic incentives, such as free parking and charging in many places in the city.[19] However, a tax-change in 2007 made small diesel cars without particulate filters more economical, which consequently increased levels of particle pollution.[6] Copenhagen responded in 2010 with a new tax law, still in practice today, that requires owners of diesel cars without particulate filters to pay an annual fee of 1,000 DKK.[40] However, some DPF retrofits can cost upwards of 10,000 DKK,[40] which may indicate that the tax is not high enough to apply sufficient economic leverage.[6] In fact, the calculations included in the financial law assumed that an average consumer would pay the fine instead of installing a filter.[19] Furthermore, the former Danish government reduced the registration tax for fossil-fueled cars in 2018, which resulted in an increase in car ownership and greater exhaust pollution.[19]

In other cities, economic incentives have proven more effective for facilitating ambitious green vehicle transformations. In Norway, the national government has made electric vehicles (EVs) more affordable through large tax exemptions.[41] Furthermore, the City of Oslo exempts EV owners from road tolls, ferry fees, and city emission charges, and gives EVs access to HOV-lanes, free parking, and free charging.[41,42] Due to the impressive political support, as of December 2018, 45% of all new car sales in Oslo were battery electric. Presently, Copenhagen is electrifying part of its public bus fleet, and will have added 41 more electric buses by the end of

2019.[43] The switch to zero-emissions electric buses will eliminate 350 pounds (160 kg) of diesel particulate matter emissions per bus over a 12-year period.[44] However, the city can use Oslo as an example and take action to incentivize private adoption of zero-emission vehicles.

Before large scale transitions to electric vehicles can be made, Copenhagen should focus on limiting harmful emissions from its current fleet of diesel vehicles as much as possible. It is imperative that DPFs effectively filter all sizes of particulates, notably the smallest particles, otherwise diesel exhaust will retain high amounts of toxicity.[11] The Euro emission standards began to regulate the emissions of smaller particles in Euro 5 for diesel passenger cars and in Euro 6 for heavy-duty diesel trucks/buses with limits on the number of emitted particles, in addition to limits on particle mass.[6] Cities can enforce the Euro emission standards via environmental zones (also called low emission zones, LEZ). The Danish low emission zones (Miljøzone) target heavy-duty diesel trucks and buses that weigh over 3.5 tons; only Euro 4 - Euro 6 vehicles and Euro 0 - Euro 3 vehicles with installed closed particulate filters are permitted to enter the zone.[6] As a result of the environmental zone in Copenhagen (map shown in Figure 12), "particle emissions from trucks and buses on H.C. Andersens Boulevard in 2010 have been reduced by 60% ... [which] corresponds to 16% of the total particle emissions from all vehicles."[45] The reductions of particulate pollution are expected to result in 150 fewer premature deaths and 8000 fewer cases of asthma, annually.[45]

However, the Danish low emission zones could increase restrictions to resemble other zones internationally and further limit exhaust pollutants. Since 2010, the German low emission zones required all sizes of diesel vehicles (passenger cars, vans, trucks, and buses) to be at least Euro 4 vehicles or Euro 3 vehicles with installed diesel particulate filters, as seen in Table 7.[6] Due to tight restrictions, diesel particle emissions have been reduced by an estimated

Table 7: Comparison of Danish and German Low Emissions Zones[6]

		German low emission zones		Danish low emission zones	
		Technology requirement	Age requirement a)	Technology requirement	Age requirement a)
Trucks and buses	Diesel	Euro 3 with closed particulate filter	Euro 4	Euro 0, 1, 2 and 3 with closed particulate filters	Euro 4
Vans	Diesel	Euro 3, with open (or closed) particulate filter	Euro 4	No Requirement	No Requirement
	Gasoline	Euro 0 with new catalytic converter	Euro 1	No Requirement	No Requirement
Passenger cars	Diesel	Euro 3, with open (or closed) particulate filter	Euro 4	No Requirement	No Requirement
	Gasoline	Euro 0 with new catalytic converter	Euro 1	No Requirement	No Requirement

Figure 12: Copenhagen's Environmental Zone (Miljøzone)[6]

63% in Berlin, compared to a non-zone scenario.[46] Increasing restrictions in the Danish low emission zones is an opportunity for lowering particle concentrations further, and also for targeting reductions to harmful smaller particulates. If Euro 5/6 are enforced in the zone, then the city could begin controlling particle number emissions. The former Danish government passed tighter restrictions for the low emission zones, which will be implemented after 2025.[19] The zone will only permit Euro 6 heavy-duty vehicles/vans and require older heavy-duty vehicles/vans to be retrofitted with Euro 6 emissions-equivalent filters.[19] Furthermore, "the new majority in the Danish Parliament has promised to tighten the environmental zone law [soon],"[47] but debate continues about how far the new regulations should extend.[48] Many are urging the new government to include filter requirements for passenger cars.[19]

Increasing studies on traffic patterns within cities across the globe have found that the unnecessary idling of vehicles contributes heavily to the production of air pollutants. Since March of 1990, Copenhagen has prohibited idling of a vehicle for more than one minute if not required (the conditions for 'required' are unspecified).[49] The police are responsible for enforcing the idling regulation, but citizens are first required to contact the offending company and send a complaint form to the municipality before the police are contacted.[49] The cumbersome process has been ineffective in successfully targeting and reducing idling. However, there are both technological and social solutions for mitigating idling. Electric auxiliary power units (APUs) installed on heavy-duty trucks and buses can provide climate control, lighting, and other electronic components to eliminate the need for the vehicle to idle to retain these features.[50] A study on mitigating excessive idling of Chicago Transit Authority buses found that retrofitting just one bus with an APU could result in approximately $12,400 - $14,700 (84,100 - 99,700 DKK) of fuel savings each year.[51] Modifying the entire transit fleet could prevent over 3 tons (2720 kg) of particulates from being produced from idling each year.[51] Education programs about idling and implementing anti-idling operations in business can also significantly reduce idle time and emitted exhaust pollution. For example, a cotton linen delivery company tested an anti-idling education/ monitoring program that ultimately decreased average daily idle time from 70 minutes to 7 minutes and saved approximately 1 gallon (3.8 liters) of fuel per vehicle each day.[52] Copenhagen could consider such strategies to reduce idling behavior instead of relying on police enforcement of the idling regulation.

Cycling is a popular mode of transportation within the City of Copenhagen and has been a significant part of the Danish Culture. The city has made extensive effort to support cycling as emissions-free transportation by constructing bicycle paths along all major roads that are separated from the driving lanes to ensure safe travel. The cycling lanes are cleaned regularly and snow plowed during the winter so they can be used year-round. Approximately 75% of Copenhagen citizens use cycling for daily travel and the population owns 5 times more bicycles than cars.[6] Because of the popularity of biking, the street level UFP concentration on H.C. Andersens Blvd. has been reduced by an estimated 18%.[6] However, the busiest streets are where the highest concentrations of particle pollution are found. Cyclists, pedestrians, and other soft-road users are directly subjected to the high levels of PM pollution as they travel alongside the street. While the promotion of pollution free forms of transportation should be a major focus, it is also important to reduce citizen exposure to street level particle pollution wherever possible. Helsinki, Finland has implemented a comprehensive monitoring system that addresses the localization issue of particle concentration measurements.[53] The system consists of numerous monitoring stations placed in close proximity across the metropolitan part of the city to inform citizens about what areas to avoid, which also promotes general awareness about air pollution.[53] In fact, monitoring programs evoke behavioral changes, including increased use of public transportation/car share programs, which has contributed to reducing overall particle emissions by 5% to 15%.[54]

Addressing Harmful Diesel Emissions

Balancing Immediate Concerns with Long Term Goals

Based on the investigation of particle pollution in Copenhagen, the overall lack of regulation on emissions technology has contributed to a myriad of pollution problems with current on-road diesel vehicles. Copenhagen's ambitious climate goals and proclaimed focus on sustainability is not reflected by how the local or national government has addressed polluting transportation. Although the transportation sector will move in the direction of emissions-free technology over the next couple decades, short term efforts are necessary to address present levels of traffic-related particle pollution. The threat posed by remaining particle pollution is clear when described in terms of health effects and health costs instead of limit values:

- Exposure to high levels of toxic, traffic-produced UFPs contributes to the exacerbation of asthma, pneumonia, COPD, chronic bronchitis, and lung cancer, and creates cell mutations that are transmitted to future generations.[7,8,9]
- Over 3,500 premature deaths in Denmark between 2016 and 2018 can be attributed to $PM_{2.5}$ pollution.[19,55]
- The external costs related to air pollution in Denmark between 2016 and 2018 is about 75 billion DKK ($11 billion USD).[55]

It is essential that every effort is made to eliminate preventable particle pollution from diesel vehicles during the transition to emissions-free transportation.

Near Term Efforts

[approximate timeline: 1-3 years]

Near term efforts should focus on solutions that can address the immanent problems with diesel particle pollution.

1. Shift to Effective UFP Filtration Technology

Currently, technology exists that eliminates both particle mass and particle number concentrations from diesel exhaust with 99% removal efficiency. Traffic companies and private diesel vehicle owners should retrofit all diesel vehicles (cars, vans, trucks, and buses) with Euro 6 emission control technology. New DPF retrofits are a less costly alternative to purchasing new vehicles and substantially reduces the harmful health effects of particulates produced by diesel fuel combustion. Furthermore, the Euro 6 DPF effectiveness is not hindered by idling behavior. As the contractor for Copenhagen's public bus fleet, Movia should retrofit the remainder of diesel vehicles with Euro 6 filters to prevent citizens from continuing to inhale high concentrations of pollutants as the bus passes the cycling lanes and sidewalks. Furthermore, Movia should also ensure that their biodiesel buses, which will comprise the majority of the 2025 fleet, are outfitted with effective Euro 6 DPF technology. All DPF retrofits should also consist of active regeneration systems since city driving conditions are unfavorable for passive regeneration and may lead to filter failure. Private adoption of more effective emission control technology is vital to reduce PM and UFP pollution before Environmental Zone restrictions are increased.

2. Regulation of Proper Emission Tests for Diesel Vehicles

The Danish government should regulate emissions testing to mandate the replacement of outdated testing techniques/equipment with the appropriate alternatives. The smoke-based opacity test is an outdated/unreliable method for determining proper filter function and should not be permitted in official inspections for any type of diesel vehicle (cars, vans, trucks, and buses). Diesel passenger vehicle emission tests should be performed using the affordable TSI PET device which can accurately evaluate the effectiveness of DPFs and includes a PN measurement. In emissions tests for heavy-duty diesel vehicles, traffic companies should also be required to use a PN measurement device (eg. P-Trak) to detect small cracks that may not be identified during OBD emission tests. Modern emission testing is needed to properly assess the function of more effective DPF technology, and requires new regulation of the techniques/instruments.

Long Term Efforts

[approximate timeline: 3-5 years]

Long term efforts should focus on supporting the eventual transition to emission-free transportation.

3. Discourage Ownership of Diesel Vehicles

To promote private adoption of electric and zero-emissions vehicles, the national government needs to concurrently discourage traditional diesel vehicles. The Danish government should increase the registration tax for new diesel cars by 2-3x and keep the present tax rate for emission -free vehicles. Additionally, the tax on diesel vehicles without adequate (Euro 6) filter technology should be increased, since it is currently too low to create any changes. By adjusting taxes in this manner, the national government can maintain its sources of funding, discourage car ownership (for especially diesel), and incentivize zero-emission vehicles. Finally, the new Danish government should extend the Euro 6 requirements in the 2025 low emission zone to all diesel vehicles, including passenger cars. Once the new restrictions take effect, all private diesel vehicle owners will need to make the choice between retrofitting their old vehicle to Euro 6 emission standards, purchasing a new Euro 6 diesel vehicle, or purchasing a zero-emissions vehicle.

4. Encourage Adoption of Zero Emission Vehicles

While diesel vehicles are discouraged at the national level, the city should incentivize emission-free vehicles. While biodiesel and biogas are more sustainable alternatives to conventional fossil diesel and natural gas, they still produce carbon dioxide and harmful pollutants when combusted. Thus, emissions-free transportation needs to be prioritized. The city should introduce an annual carbon tax or emission charges for combustion vehicles, and exempt electric vehicle owners from paying the additional pollution fees. Movia has plans to manage a primarily biodiesel and biogas bus fleet by 2025, but the city should prioritize more funding for electric buses. Movia should inform the municipality about how Roskilde successfully obtained a fully electric bus fleet so that Copenhagen may also electrify more of their buses.

Direct Citizen Action

[approximate timeline: immediately]

Immediate efforts should focus on engaging citizens in the issue while the national and local government pass legislation.

5. Public Awareness Events hosted by Miljøpunkt Indre By & Christianshavn

5.To fix the lack of awareness surrounding ultrafine particle pollution, our sponsor, Miljøpunkt Indre By & Christianshavn should collaborate with Local Committees and other environmental groups in the municipality to host events aimed at spreading knowledge about the health effects of PM pollution. Our health flyer should be used to inform citizens of the dangers of UFP pollution, but not in a way that instills fear, rather one that empowers them with knowledge. Local awareness events should also be used to teach citizens how to perform their own emissions tests and how to advocate for cleaner air within the local government.

Providing citizens with PM mitigation strategies and health information will help make UFP pollution a higher priority for the national government and help facilitate large scale change.

6. Engaging Citizens in Diesel Emission Tests

Another way to raise awareness about particulate pollution is by encouraging citizens to test their own vehicle emissions using the handkerchief test, shown in Figure 13. Learning how to perform the handkerchief emissions test will help motivate citizens to monitor their DPFs since the current inspections do not effectively test filter function. Although the handkerchief test is not a reliable method for determining if the filter is removing UFPs, it can detect if the filter has a major malfunction. Ultimately, engaging citizens in efforts to monitor function of DPFs is important for spreading awareness about the lack of effective emission reduction efforts, unreliability of current emissions testing, and dire need for new testing regulations.

Figure 13: Steps of the Handkerchief test[6]

Sponsor Deliverables

Our booklet report included crucial information about the importance of reducing all sizes of particulates and key outcomes from the investigation of current strategies and technology within the city, in addition to our recommendations. The report was designed for our sponsor to distribute to political leaders, taxi/bus companies, and other local committee chairmen to inform them of our findings and ultimately, prompt legislation. Furthermore, the team created a citizens' flyer to communicate the most important health risks related to PM pollution and a few ways citizens can take action to reduce traffic-related particle pollution in their city. The additional materials can be found in the supplementary materials file.

We believe that our project work and deliverables will increase awareness about UFP pollution, highlight the shortcomings of present political and technological efforts to reduce particulate emissions, and encourage legislative action to improve air quality in Copenhagen.

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Supplemental Materials for this project can be found at https://wpicpc.org

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