Effects of Vegetation on Traffic-Related Particulate Matter

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30 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Environment and Natural Resources

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Abstract

Traffic-related air pollution has been shown to have detrimental effects on health and the environment. One of the components of such pollution is particulate matter smaller than 10 µm in aerodynamic diameter (PM_{10}), which increases the risk of cardiopulmonary symptoms and diseases when inhaled or absorbed.

Since the amount of traffic has steadily been increasing around the globe, mitigation measures to combat traffic-related air pollution have been researched. As plants are already known for their sequestration properties, research has been put forth in order to investigate other potential amenities they might offer.

This thesis focuses on the effects vegetation barriers have on particulate matter (PM) emitted by road traffic. Through a comparison in PM distribution with and without a vegetation barrier, as well as a comparison between two different kinds of barriers, an attempt was made to determine the effectiveness of these barriers, and potentially offer a suggestion to the city officials in an attempt to improve near-road air quality in Reykjavik.

The results of the study indicate that the smallest fraction of measured particles (ultrafine particles up to 1 µm) responds well to a dense barrier made up of plants of various species, both coniferous and deciduous, and of varying heights.

The results for other sizes and for the coniferous barrier in general were less conclusive.

Dedication

Za moju mamu koju volim najvise na svetu!

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Abbreviations

CO_2 - carbon-dioxide

EC - European Commission

EEA - European Economic Area

EFA - the Environment and Food Agency of Iceland

EHPO - Environmental Health and Protection Office

EU - European Union

LRTAP Convention - Convention on Long-range Transboundary Air Pollution

m/s - meters per second

µm – micrometer

$µg/m^3$ - microgram per cubic meter

MFA - Ministry for Foreign Affairs

nm – nanometer

No – Number

PM - Particulate matter

PM_X - particles with a diameter $< X$ µm

UST - Umhverfisstofnun (the Environment Agency of Iceland)

VOCs - volatile organic compounds

Acknowledgements

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사랑하자!

1 Introduction

In recent years the need to regulate human activities for the benefit of our health and the environment has become more apparent. In this regard, air pollution is one of the most urgent issues that needs to be addressed for various reasons, most notably the emission of greenhouse gasses that impact the climate, and the effects that inhaling or otherwise absorbing, particulate matter has on our health.

While technological improvements and stricter emission regulations in recent years have contributed to the decrease in transport-related particulate matter (PM) emissions, this decrease has been offset by an increase in the number of vehicles (many of which are diesel powered and emit a significantly higher amount of particulate matter than gasoline vehicles), as well as an increase in the number of short trips and traffic congestion (Krzyzanowski *et al.*, 2005; Palmgren *et al.*, 2003; Kelly & Fussell, 2012).

Therefore it has become increasingly difficult to reach policy objectives of reduced air pollution in many countries. One such objective has been stated by the European Union (EU) in its 6th Environment Action Programme: "… to achieve levels of air quality that do not give rise to significant negative impacts on, and risks to, human health and the environment" (European Commission, 2002).

In order to achieve this, it is necessary to employ as many methods as possible including both prevention and mitigation of air pollution.

Since plants are known to bind carbon-dioxide (CO_2) through their process of photosynthesis, they have become an invaluable tool in attempts to minimise air pollution and as such, their effects on other pollutants have been researched as well. Particulate matter is one such pollutant and will be the focus of this research.

1.1 Particulate Matter

Particulate matter (PM) is the name used for a complex mixture of liquid droplets and solid particles suspended in the atmosphere such as dust, soot, black smoke, volcanic ash and the like (Kelly & Fussell, 2012; Environmental Protection Agency, 2013).

Particulate matter varies greatly in composition, and is for this reason usually classified by size. The most common way to refer to particles is by classifying them into ultrafine, fine and coarse particles, or by attaching the number in the subscript of the abbreviation (PM) that refers to the upper limit of the particle size taken into account. For example, PM_{10} encompasses all particles up to the size of 10 micrometers (μm).

Coarse particulate matter includes particles sized 2.5–10 μm in aerodynamic diameter or, as they are commonly referred to, $PM_{2.5} - PM_{10}$. Fine particles are those with aerodynamic diameter smaller than 2.5 μm ($PM_{2.5}$) (Fig. 1.1). Ultrafine particles are particles less than 100 nanometers (nm) in diameter ($PM_{0.1}$). It should be noted that ultrafine particles are not as yet regulated, unlike their larger counterparts, and that sometimes their definitions vary. Certain papers classify all particles smaller than 1000 nm as ultrafine (PM_1). For the purpose of this study, any PM smaller than 1 μm (PM_1) will be referred to as ultrafine (Krzyzanowski *et al.*, 2005; California Air Resources Board, 2006).
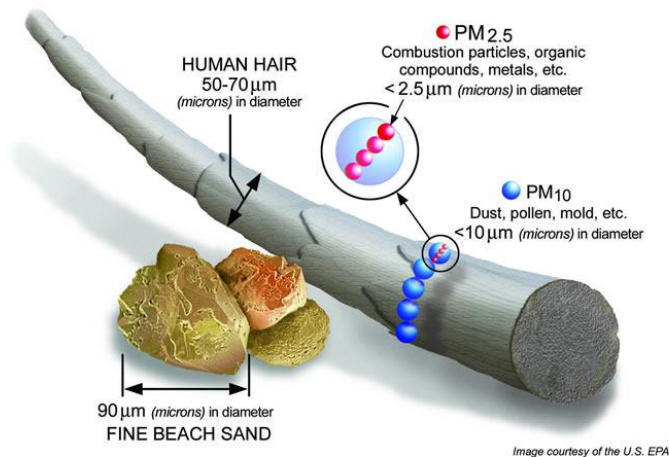
Figure 1.1 Size of PM_{10} and $PM_{2.5}$ particles relative to human hair and beach sand (Environmental Protection Agency, 2013)

Depending on their origin, different sources result in different types of particulate matter with regards to their chemical composition. It should also be noted that while transported in the atmosphere, their chemical and physical characteristics may change as they encounter and react with other particles (Palmgren *et al.*, 2003; Krzyzanowski *et al.*, 2005).

1.2 Origins of Particulate Matter

Particulate matter can stem from natural sources such as soil, sea spray, pollen, spores, volcanic ash and emissions of biogenic and organic compounds, as well as from anthropogenic sources. These include traffic emissions, both from burning fossil fuels and from wear and tear of roads and vehicle components (such as brake and clutch linings and pads, tyres and fuel tanks), as well as mining, agriculture, electricity production and other industries (Kelly & Fussell, 2012). It was estimated that before May 2004, road transport was the most important source of ambient air concentrations of PM_1 in most urban areas of European Union (EU) countries at the time. In these areas, tailpipe emissions of primary particles by road transport contributed up to 30% of $PM_{2.5}$, and non-tailpipe pollutants

(such as resuspended road dust and brake-lining wear) were the most important source of coarse particulate matter (Krzyzanowski *et al.*, 2005).

In the European Economic Area (EEA, which includes Iceland), the most important source for anthropogenic PM emissions is the "commercial, institutional and households" sector, which includes combustion-related emissions from sources such as heating of residential and commercial properties. This is followed by the "industrial processes" sector and "road transport" sector (Figure 1.2) (EEA, 2014a). Although Iceland is included in these calculations, the fact that around 90% of homes in Iceland are heated using geothermal energy sources should be noted (Ministry for the Environment in Iceland, 2006), considering that domestic-coal burning is one of the the main sources of PM from stationary combustion (Kelly & Fussell, 2012). Emissions of particulate matter in Iceland will be covered specifically in the following section.

Figure 1.2 contents:

	Agriculture	Commercial, institutional and households	Energy production and distribution	Energy use in industry	Industrial processes	Non-road transport	Other	Road transport	Solvent and product use	Waste
PM10	13.3	38.0	6.8	7.7	14.7	1.8 / 0.3	14.1	1.0		2.3
PM2.5	4.4	48.5	5.6	9.2	10.5	2.4 / 0.4	15.3	1.1		2.6
SOx	0.1	9.4	70.2	13.4	4.3	2.0	0.1			
NOx	1.8	14.8	22.1	13.4	2.1	7.1	0 / 0	38.4	0.0 / 0.3	
NH3	93.9		0.2 / 0.2 / 0.2	1.0 / 0.0 / 0.3	0.0	1.9 / 0.1 / 2.2				

Figure 1.2 The contribution made by different sectors to emissions of primary PM$_{2.5}$ and PM$_{10}$, and to emissions of the secondary particulate matter precursors in the European Economic Area (EEA) in 2010 (EEA, 2014a)

PM can be emitted directly (primary emission) or formed in the atmosphere through chemical reactions of gaseous precursors, such as nitrogen oxides, sulphur dioxide, ammonia and volatile organic compounds (VOCs) (secondary emission) (Krzyzanowski *et al.*, 2005; Kelly & Fussell, 2012).

Generally speaking, especially in urban environments, coarse particles are most often of natural origin, while fine particles seem to predominantly have anthropogenic origin (DoE, 1995; Donaldson *et al.*, 2001; Thorsteinsson *et al.*, 2011a).

Primary PM emissions from road traffic come from exhaust pipes, brake linings, tyre wear, as well as road wear and resuspension of road dust (Krzyzanowski *et al.*, 2005; Kelly & Fussell, 2012). Resuspension, which is the renewed suspension of particles after their deposition, is affected by factors such as the road surface and traffic intensity, and weather conditions like humidity, wind speed and precipitation.

Ships and boats should also be taken into consideration, especially in Iceland. In coastal areas of Western Europe it is estimated that ship emissions account for 10–20% of the overall PM_{10} concentrations (Fagerli & Tarrasson, 2001). With soot comprising 40–80% of the primary PM mass, emissions from ships might give rise to elevated ambient soot concentrations (Krzyzanowski *et al.*, 2005).

1.3 Particulate Matter in Iceland

As stated before, particulate matter can stem from natural and anthropogenic sources. Since the focus of this research is specifically particulate matter emitted from anthropogenic sources, it is important to distinguish between these two origins.

1.3.1 Natural Sources

Iceland's unique landscape provides for several natural sources of particulate matter. One of these sources are Iceland's sandy deserts which cover over 20 000 km^2 (~20%) of Iceland. The sand in these deserts is often dominated by volcanic glass following volcanic eruptions which are common in Iceland (Arnalds *et al.*, 2001). Glaciers are also a significant source of particulate matter as the ice grinds over subglacial sediment and bedrock. The sediment released through such grinding frequently ends up suspended in glacial meltwater and gets distributed throughout the country. While a lot of the sediments are transported directly to the ocean, glacial floods (known in Iceland as *jökulhlaups*) deposit the fine sediment in layers across proglacial floodplains (*sandur*) (Thorseinsson *et al.*, 2011a). Lack of vegetation in these areas combined with strong Icelandic winds causes a redistribution of particles across vast areas (Ovadnevaite *et al.*, 2009). Sometimes the dust plumes can be caught on satellite images (Figure 1.3)

Figure 1.3 MODIS Aqua image 13:45 (local time) showing dust blowing from Landeyjasandur and Markarfljót towards Reykjavík on April 28, 2007. Image courtesy of MODIS Rapid Response System at NASA/GSFC.

With the melting of glaciers due to climate change, more subglacial sediment gets exposed and becomes available for eventual airborne redistribution (Thorseinsson *et al.*, 2011a). Similar is true of sandy deserts if they keep spreading and causing erosion and desertification (Arnalds *et al.*, 2001).

With Iceland lying right on top of the mid-Atlantic Ridge, volcanic activity is common. Iceland has 30 active volcanic systems, of which 13 have erupted since the first settlement in year 874 (Smithsonian Institution, 2013). Volcanic eruptions can be a massive source of particulate matter of various sizes. Depending on the amount of material disgorged from the volcano, the effects of this matter can have negative consequences on local population's health (Carlsen *et al.*, 2010). Ash resuspension after an eruption has ended can also be a significant source of particulate matter, even across great distances. An example of this is the ash storm that hit Reykjavík on 4 June 2010, two weeks after the eruption of Eyjafjallajökull had ended. This was the first major effect of the eruption that was felt in Reykjavík and was caused entirely by resuspension of ash (Thorsteinsson *et al.*, 2011b).

1.3.2 Anthropogenic Sources

According to the Environment Agency of Iceland (Umhverfisstofnun, or UST), road traffic and fishing boats are the highest source of local, anthropogenic air pollution (2014).

Iceland is one of the countries with the highest number of motor vehicles per capita (almost 750 vehicles per 1000 people between 2009 – 2013) (World Bank, 2013) which more than likely contributes to the fact that Iceland is the country with the highest ecological footprint per capita in the world (Johannesson, 2010). Despite Iceland's ecological footprint being this high, which is mainly due to its position as one of world's largest consumers, Iceland's carbon output per capita is much lower than of the countries in the same income group (World Bank, 2010). This seemingly incompatible data simply serves to illustrate Iceland's unique socio-economic and geographical position. However, data from the European Economic Area (EEA) website shows a trend whereby total emissions of PM_{10} and $PM_{2.5}$ have increased in Iceland between 1990 and 2011 (Figure 1.4). The increase in emissions is second only to Finland in all of the EEA (EEA, 2014b).
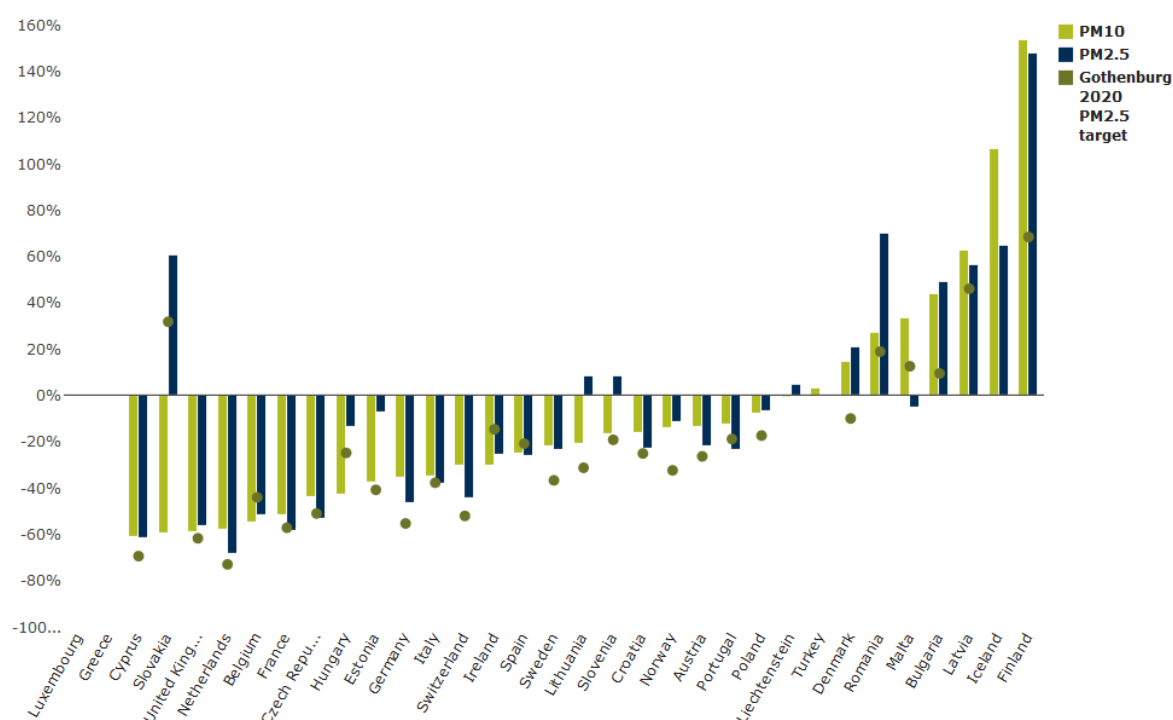
Figure 1.4 Percentage change in $PM_{2.5}$ and PM_{10} emissions within the EEA in the period between 1990 and 2011 (EEA, 2014b); Note that Iceland is not a party to the Gothenburg Protocol of the LRTAP Convention and therefore no ceiling exists for Iceland

The large number of vehicles per capita in Iceland does not only contribute to PM emissions through the burning of fossil fuel. In a northern country where snow and ice are common throughout the year, such as Iceland, the use of studded tires is quite common. In 2002, approximately 60% of the vehicles in Iceland in the winter were equipped with studded tyres (Ingason and Johannesson, 2002). According to a research by Skuladottir *et al.* (2003) non-studded tyres cause only 7% of asphalt erosion that studded tyres cause. The study suggests that asphalt was responsible for around 55% of the ambient air particulate pollution in winter time in Iceland at the time of this research, which took place in 2003 (Figure 1.5a)(Skuladottir *et al.*, 2003). However, due to research like this and better overall environmental awareness, the use of studded tyres is becoming discouraged

in Iceland, at least when not absolutely needed, and as a result, their use is slowly dwindling and has decreased to around 35% in 2011/2012 (Kienle, 2013).

A more recent study by an Icelandic engineering and consulting company, EFLA, aimed to compare the contents of Icelandic particulate matter with that of Skuladottir *et al.*'s findings. The asphalt content has dropped drastically in the span of 10 years between the two researches, from 55% down to 17%. However, the soot and break lining content has increased dramatically, from 7% soot content to 30%, and from 2% break lining content to 14%. This keeps the PM content predominantly of anthropogenic origin (EFLA, 2013).

Another major difference between the two researches is the ash content which was not apparent in 2003, but now makes up 18% of the PM. This is probably another consequence of recent volcano eruptions.

Figure 1.5 Contents of combined particulate matter (coarse and fine) represented in average percentages from the samples taken during the winter in Iceland presented in 2003(a) and in 2013 (b) (Skuladottir et al., 2003; EFLA, 2013)

Skuladottir *et al.* also presented a difference in content depending on particle size. When broken down into coarse and fine particles, the content percentage changes slightly. The two figures below show PM content of separate samples (presented as bars). It is apparent that the coarse fraction is dominated by asphalt, followed by soil (Figure 1.6) while soot seems more prevalent in the fine fraction, followed by asphalt (Figure 1.7).

Figure 1.6 Contents of coarse particulate matter represented in average percentages from the samples taken during the winter in Iceland (Skuladottir et al., 2003)

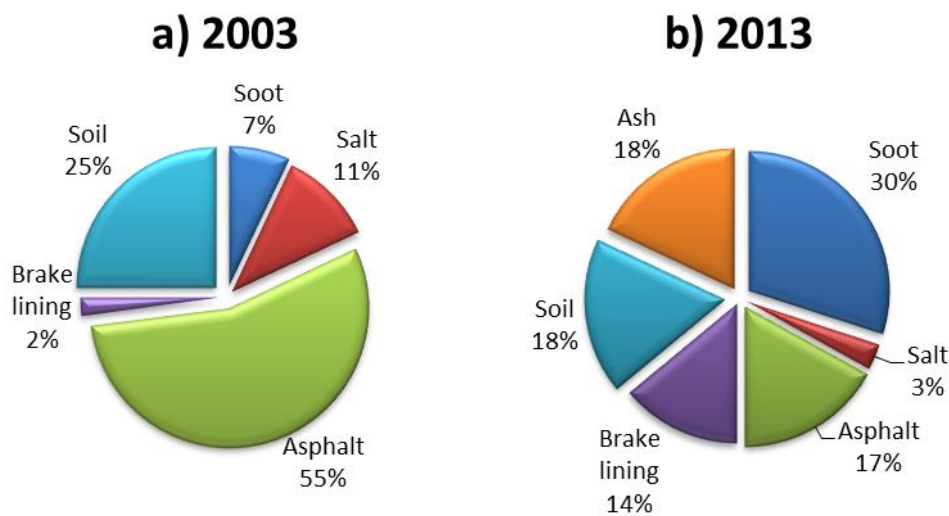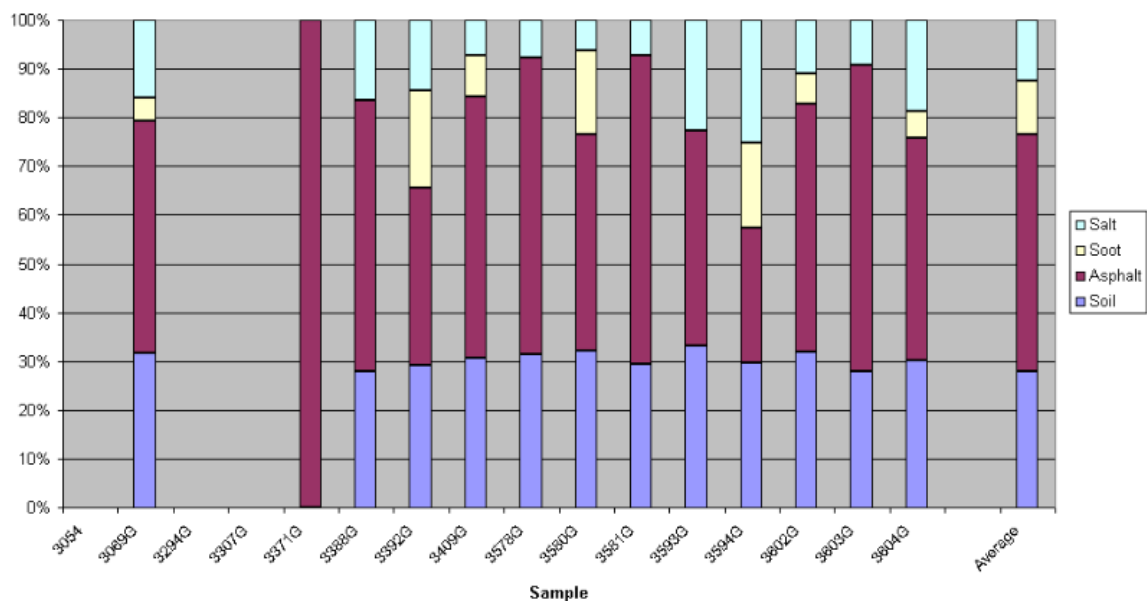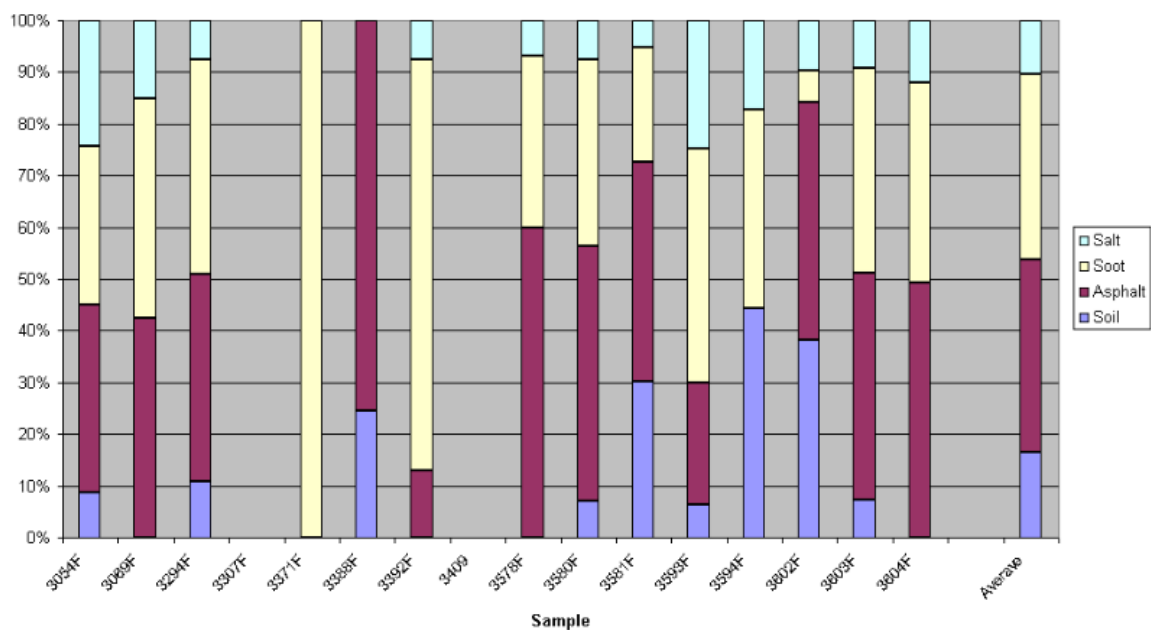*Figure 1.7 Contents of fine particulate matter represented in average percentages from the samples taken during the winter in Iceland (Skuladottir et al., 2003)*

Another noteworthy observation is that PM content was also weather-dependant, with samples taken on dry days showing a higher amount of asphalt while soot is dominating on wet days.

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1.3.3 Monitoring

Monitoring of air quality has been done in Iceland since 1985 when the Environment and Food Agency of Iceland (EFA) started a measuring station at Miklatorg, Reykjavik, where airborne dust and heavy metals were measured. The city of Reykjavik Environmental Health and Protection Office (EHPO) set up another monitoring station at Grensás in 1990, where nitrogen dioxide, carbon monoxide, ozone, sulphur dioxide, benzene and dust ($PM_{2.5}$ and PM_{10}) have been measured. Today there are several monitoring stations in Iceland (mainly Reykjavik) but main urban traffic station remains the Grensás station (UST, 2014).

1.4 Regulations Concerning Particulate Matter

Since the effects particulate matter and other airborne pollutants can have on health and the environment were recognised, governments and organisations have slowly started putting forth efforts to minimise air pollution, mainly through setting emission limit values.

1.4.1 European Union

The European Union Air Quality Directive 2008/50/EC was adopted on 21st May 2008 and entered into force on 11th June 2008, and is the current directive regulating the ambient air concentrations of PM and other air pollutants within the European Union.

The Directive aims to merge most of the previous air-pollution related legislation into a single directive (except for the fourth daughter directive). Previous limit values for PM_{10}, nitrogen dioxide, nitrogen oxides, sulphur dioxide, benzene, carbon monoxide and lead were kept and in addition limit values and exposure related objectives were established for $PM_{2.5}$ (Kienle, 2013; EC, 2014). Ultrafine particles, however, remain unregulated as of September 2014.

1.4.2 Iceland

Icelandic environmental legislation is based heavily on that of the European Union. This applies to air quality regulations as well. Pollutant limit values are based on EU directives with a few exceptions where Icelandic rules are usually stricter (Table 1.1) (MFA, 2013). For example, Iceland has set stricter limits for PM_{10} emissions. The average daily PM_{10} concentration limit in Iceland is 50 $\mu g/m^3$ and this limit is not to be exceeded more than 7 times during the year. The average yearly PM_{10} concentration limit is 20 $\mu g/m^3$ (Icelandic regulation No 251/2002). $PM_{2.5}$ is regulated in Iceland since 2014 (Icelandic regulation No 245/2014).

The implementation and monitoring of these rules and regulations is done by The Environment Agency along with local health inspection authorities.

Table 1.1 Icelandic regulations and relevant EU directives regarding air quality (MFA, 2013).

Icelandic Regulation No	EU Directive
787/1999	96/62/EC
251/2002	1999/30/EC
251/2002 + 245/2014	2000/69/EC
745/2003	2002/3/EC
410/2008	2004/107/EC

Directive 2008/50/EC on ambient air quality and cleaner air for Europe has not yet been adopted in Iceland although it has been discussed and is considered EEA relevant (MFA, 2013).

2 Distribution and Behaviour of Particulate Matter

The varying composition of particulate matter has a great effect on its physical and chemical characteristics. There is a significant difference, depending on particle size, with regards to deposition processes and distribution from the source.

2.1 Distribution Mechanisms

The distance particulate matter travels after its emission depends on many factors. While some particles get deposited right after their emission, other particles are able to travel for kilometers aided by some of the mechanisms discussed below.

2.1.1 Deposition

Deposition is defined as a combination of processes that removes the particles from the atmosphere. Three types of deposition are discussed here – wet deposition, dry deposition and occult deposition.

Wet deposition occurs when rain, snow or mist removes particles from the atmosphere and deposits them to the ground. The removal of particles from the atmosphere by gravity, impaction and Brownian motion, is known as dry deposition. Brownian motion occurs when a particle gets randomly displaced by other particles hitting it or by an external force (Figure 2.1.1) (Mörters & Peres, 2008). Due to this spatial migration, particles are more likely to get deposited after they stick to a surface they encounter. Wind-driven cloud and mist water deposition is known as occult deposition and while similar to wet deposition, it is generally less efficient.
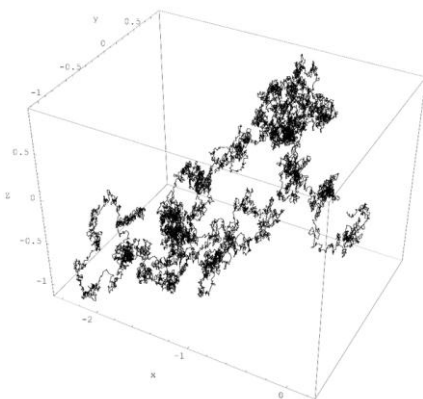
Figure 2.1.1 A single realisation of three-dimensional Brownian motion for times $0 \leq t \leq 2$

Dry deposition is mostly limited to the Earth's surface while wet deposition accounts for the deposition of particles at higher altitudes as well (Beckett *et al.*, 1998).

As a rule, the concentration of particles decreases as a function of distance from the source due to the various processes mentioned earlier, as well as dispersion and coagulation. All these mechanisms are particle size sensitive and affect particles of different sizes in different ways (Reponen *et al.*, 2003). For example, Brownian motion (one of the processes of dry deposition) accounts for the removal and deposition of most ultrafine particles (smaller than 100 nm). Impaction and direct interception have a greater effect on particles in the 0.1 – 2.0 µm size range. Impaction is a process where the flow path of a particle is curved in such a way that the particles collide with the obstacle while following the airflow that would normally take it around the obstacle. Interception is a type of impaction where the flow path of a particle is too near to the obstacle (Lee & Ramamurthi, 1993). Particles larger than that, especially those larger than 8.0 µm, depend on gravity for sedimentation (Beckett *et al.*, 1998).

Coagulation processes should also be taken into account, where aerosol particles collide with each other and merge to create larger particles. As a result of this, there will be a continuous decrease in number concentration but an increase in particle size (Figure 2.1.2). This might also cause concentrations of larger particles to decrease more gradually with distance while for smaller particles (particles smaller than 0.1 µm), the combination of coagulation and dilution results in a rapid decrease in concentration with the distance (Zhou & Levy, 2007).

Figure 2.1.2 A typical size distribution of diesel exhaust particles showing the relationship between particle count vs particle mass (Dieselnet, 2002)

In areas where mist and fog are fairly common, occult deposition has an effect on pollutant removal from the air (Fowler *et al*., 1989).

2.1.2 Meteorology

Meteorology, especially wind speed and direction, play an important role in pollution distribution and should be considered as key factors in most measurements.
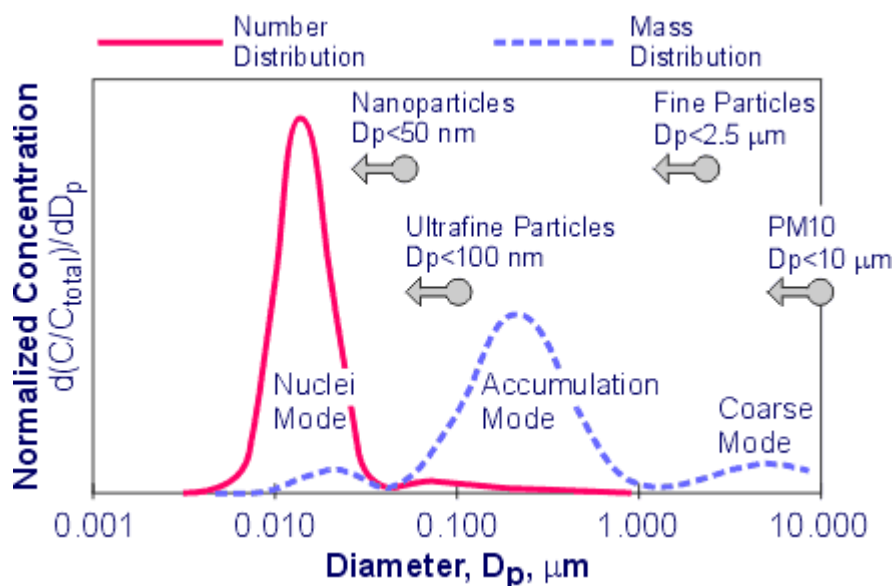
When the wind blows directly from the source towards the receptor, the concentration gradient is more pronounced and extends further away than when the wind blows parallel to the road, or away from it. According to some research, the concentration of fine and ultrafine particles dropps by half at a distance of 100–150 m from the source when measurements are taken downwind (Karner *et al*., 2010). The reduction to half the concentration happens 50–100 m from the road when the wind is blowing parallel to the line source (Reponen *et al.,* 2003). The study by Hitchins *et al.* (2000) showed that the lower the wind speed, the higher the particle concentration is closer to the source. This is due to higher dilution and faster mixing of air at higher wind speeds when the wind blows from the road.

Different wind speeds were also found to have different effects on PM_{10} concentrations in Iceland. Strong winds (above 6 m/s) lead to higher PM concentrations due to resuspension and erosion from the ground. Slower winds (under 2 m/s) also tend to show higher concentrations due to PM accumulation, while winds between 2–6 m/s show lower concentrations due to dilution of PM by the wind (Kienle, 2013).

2.2 Difference in Distribution Depending on Particle Size

Research has found that PM_1 tends to show heavy concentrations at $200 - 500$ m distance from the road after which its concentrations drop dramatically. In fact, exposures of people living close to busy main roads might be expected to be about 25% higher than background exposures for PM_{10} or $PM_{2.5}$, while the excess is likely to be at least 50% for elemental carbon (Krzyzanowski *et al*, 2005; Reponen *et al.*, 2003). Coarse particles ($PM_{2.5} - PM_{10}$) settle more quickly after emission than fine particles ($PM_{2.5}$), but their amount is still significantly higher than background concentration up to 150 m away from urban highways (Krzyzanowski *et al.*, 2005; Reponen *et al.*, 2003).

2.2.1 Coarse Particles

According to the synthesized measurement data from 1978 to June 2008 (Karner *et al.*, 2010), PM_{10} shows a steady decline from the source and would even out with the background concentrations at approximately 176 m away from the road. Using the background normalization technique[1] it was determined that PM_{10} concentrations are on

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[1] Background Normalization Technique can identify whether and where measured concentrations fall to background levels. The normalization divides observed near-road concentrations by the reported

average 1.42 times higher than background concentrations in the first 80 m from the road, after which point they decline by about 28% beyond 120 m. Similarly, in a study by Reponen *et al.*(2003) the particles in the 0.3 – 20 µm range showed minimal gradient with concentrations only decreasing to 85% 400 m away from the road (compared to 30% for ultrafine particles), and to about 80% at the 1600 m location. These measurements take into account wind direction that was perpendicular to the line source.

Reponen *et al.* (2003) theorize that the lack of gradient for coarse particles might be due to them being heavier and settling at a faster rate than ultrafine particles, within the first 50 m of their emission. Hitchins *et al.* (2000) found that in the case of coarse particles, concentrations near a busy road were not significantly higher than average values for the urban environment although they did still decrease to around 60% at 150 m from a road, when the wind is blowing from the road.

2.2.2 Fine Particles

Measurements of $PM_{2.5}$ show a lot of variation in behaviour in various studies, but the trend seems to indicate that their concentration drops with distance (Reponen *et al.*, 2003). Karner *et al.* (2010) compared $PM_{2.5}$ and fine particle numbers (beginning at 300 nm) at the source and at background levels and their results seem to indicate that the numbers hovered at the background concentration levels throughout and didn't show variation by distance.

However, Hitchins *et al.* (2000) conducted measurements at distances ranging from 15 – 375 m from a busy road which show that the concentrations of fine and ultrafine particles declined to about half their maximum (as measured at 15 m from the road) when they reach a distance of approximately 100 – 150 m from the road when the wind is perpendicular to the road. An approximation of $PM_{2.5}$ fraction was also conducted and showed a decrease with distance from the road – to 75% with the wind blowing from the road and 65% for wind parallel to the road, at the distance of 375 m. However, no such gradient was found for PM_{10} and $PM_{2.5}$ in the research conducted by Roorda-Knape *et al.* (1998).

2.2.3 Ultrafine Particles

Ultrafine particles up to 1 µm in diameter showed the most dramatic gradient. The smallest particles (3 – 15 nm) show a fairly rapid decline and drop by half at a distance of 100 – 150 m from the source and subsequently reach their background levels at approximately 190 m away from the road, with the concentration at the source being 4 times higher than at the background level (Karner *et al.*. 2010; Hitchins *et al.*, 2000). Reponen *et al.* (2003) also found that ultrafine particle (0.02 – 1 µm) concentrations decrease to half between the sampling points located at 50 m and 150 m downwind from the source. The concentration

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background value and as values approach one, near-road concentrations approach background (Karner *et al.*, 2010).

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decreased to 30% at the 400 m location and to 10% at the farthest sampling location (1600 m) compared to the concentration measured at the location closest to the source (50 m). Steeper gradient was observed when the wind was perpendicular to the highway than when it was parallel to it.

In a repeated sampling period concentrations at 400 m and 1600 m were about 60% lower than those measured at 80 m and in another, the concentrations at the 800 m and 1600 m locations were about 85% of the concentration measured at the 400 m location. This shows a consistency in gradient for ultrafine particles.

2.3 Spatial Extent of Particulate Matter Impact

Zhou and Levy (2007) looked at the "spatial extent" of the impacts of certain pollutants. Spatial extent is the distance from the source in which individuals or population groups might suffer adverse effects to their health due to pollution. Their research encompassed publications between 1997–2005 that dealt with air pollution related to mobile sources, focusing on certain pollutants including particulate matter.

As metrological conditions, such as wind speed and direction, play a major role in pollutant distribution, Zhou and Levy (2007) used the following equation for estimating pollutant concentrations downwind from the source for relatively inert pollutants:

$$C = \frac{2Q}{\sqrt{2\pi}U\sigma_z}$$

Where:

C is the downwind concentration ($\mu g/m^3$),

Q is the source strength per unit distance ($\mu g/(m \cdot s)$),

U is the average wind speed (m/s) and

σ_z is the vertical dispersion coefficient (m).

Since wind speed also affects travel time between the source and the measurement location, this can have an impact on the amount of coagulation for ultrafine particles, in addition to the aforementioned effects wind can have on dilution and vertical dispersion.

According to the equation above, a higher vertical dispersion coefficient (σ_z) corresponds to lower downwind concentrations. Since the coefficient is a function of downward distance and atmospheric stability, it follows that at the same downwind distance, unstable atmospheric conditions correspond to higher dispersion coefficients. This means that if all other conditions are the same, the spatial extent of influence for the same pollutant is smaller under unstable conditions. Because smaller particles (especially those smaller than 0.1 μm) are susceptible to coagulation, which is when particles collide with one another

and adhere to form larger particles, it is important to note that while the particle count might drop drastically with the distance, the PM mass might show a slower decrease.

The results of Zhou and Levy's study (2007) show that inert (non-reactive) pollutants with high background concentrations, such as PM mass without background removed in the analysis, show little discernable gradient in their distribution from the source. However, the spatial extent for elemental carbon and PM mass concentration with background removed in the analysis is at approximately 100 – 400 m, and 100 – 300 m for ultrafine particle count.

3 Effects on Health

Since particulate matter is found in the form of aerosols, its impact on human health, through inhalation, has been noted in epidemiological findings. Particularly dangerous are fine ($PM_{2.5}$) and ultrafine (PM_1) particles which, when inhaled, can travel deep into the human bronchi and lungs which causes various health issues including chronic lung tissue inflammation (Pekkanen *et al.*, 1997; Donaldson *et al.*; Calderon-Graciduenas *et al.*, 2004; Noor *et al.*, 2011). Some research even indicates that ultrafine particles might be the primary culprit of lung tissue inflammation, but such studies are still relatively few (Donaldson *et al.*, 2001, Knibbs *et al.*. 2011).

Particles larger than 10 μm are generally not considered dangerous to health as they are not as likely to enter human respiratory tract as smaller particles (Krzyzanowski *et al.*, 2005).

In most urban areas, transportation is one of the most significant sources of suspended particulate matter, which has led to concerns about those living close to big and active roads. Locations where emissions from specific sources may expose individuals and population groups to elevated risks of adverse health effects are known as „hot spots" (Zhou & Levy, 2007). For example, people living in street canyons, which are areas where the source of pollution (usually a big road) is flanked (most commonly by buildings) in such a way that traps pollution (Krzyzanowski *et al.*, 2005), are especially vulnerable to the effects of traffic-caused PM pollution. While there are no street canyons to speak of in Iceland, they exist in most big cities elsewhere and they have been a source of much research. In fact, the effect on health of transport-related air pollution is one of the leading concerns about transport and the need for its regulation with regards to air quality. Several studies show higher rates of respiratory symptoms and reduced lung capacity in people living close to major roadways (Krzyzanowski *et al.*, 2005)

Another target of research are groups of people that are particularly vulnerable to airborne pollutants, such as children, the elderly, people suffering from asthma and similar respiratory issues, as well as certain occupational groups (such as professional drivers and railway workers) (Krzyzanowski *et al.*, 2005).

Krzyzanowski *et al.* (2005) have reviewed various research on health effects of transport-related air pollution and their research indicates that transport-related air pollution contributes to an increased risk of death, mainly from cardiopulmonary causes. In addition, it increases the risk of pulmonary symptoms and diseases. According to a few studies, there is a significant increase in the risk of myocardial infarction after exposure to air pollution. Some studies also point to an increased risk of lung cancer in people with long term exposure to transport-related air pollution, mainly through their occupation (Brueske-Hohlfeld *et al.*, 1999).

Calderon-Graciduenas *et al* (2004) have linked chronic respiratory tract inflammation, caused by PM presence in the lung tissue (mainly bacterial lipopolysaccharide and combustion-derived metals), to chronic inflammations of the brain. Their research has shown that the pathology of people chronically exposed to air pollution has a number of similarities to the pathology of people afflicted by Alzheimer's disease.

Particulate matter has been linked to allergic responses and fine PM is associated with increased risk of mortality and respiratory morbidity (Krzyzanowski *et al.*, 2005).

It is also known that ambient air pollution can have adverse effects on pregnancy, including an increase in post neo-natal infant mortality (WHO Regional Office for Europe, 2004) as foetuses are considered to be more vulnerable to environmental effects due to higher rates of cell growth (Perera *et al.*, 1999).

There have been attempts to identify specifically which component of particulate matter plays the biggest role in causing adverse effect on health, but this has not been accomplished yet. It is known however that Polycyclic Aromatic Hydrocarbons (PAHs) have the ability to cause DNA damage and that they are carcinogenic (Krzyzanowski *et al.*, 2005) but beyond that, no specific culprits have been identified for other ailments.

4 Effects of Vegetation on Particulate Matter

Effects of vegetation on mitigating air pollution have become increasingly interesting for researchers as well as urban planners since trees, besides being known for their carbon sequestration, are noted to be effective in removing other pollutants, especially particulate matter (e.g. PM_{10}), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and ozone (O_3), from the air (Powe and Willis, 2004). Research shows that due to overall greater leaf surface and more turbulent mixing of air, trees are more efficient in capturing pollutants than shorter vegetation (Fowler *et al.*, 1989). Hewitt *et al.* (2005) found that mature, mixed woodland is around 3 times more effective in capturing particles than grassland. This indicates that increasing the tree cover in urban areas helps mitigate traffic-related air pollution through dry deposition (Nowak *et al*., 1998).

4.1 Mechanisms

Airborne pollution is usually removed from the air by the leaf stomata where, once inside the leaf, gasses get absorbed to form acids or react with inner-leaf surfaces (Figure 4.1.1). Often, the trees simply act as a barrier by intercepting airborne particulate matter and while some particles get absorbed, most intercepted particles remain stuck to the surface of the tree whence they most often get washed away by precipitation or fall to the ground with leaves and twigs (Nowak *et al..* 1998). However, it is possible for the plants to reach a saturation point after long periods without precipitation, when the particles don't get washed away, but are in stead left clogging the stomata. This renders the plants less effective in capturing particles (Shackleton *et al.*, 2011)
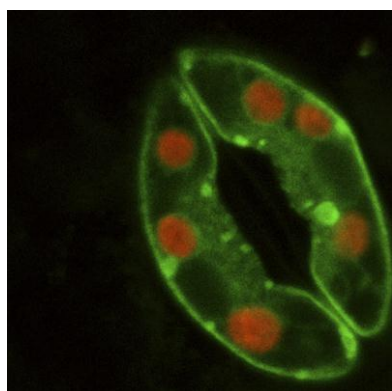

Figure 4.1.1 Plant stomata dyed with fluorescent dye (Creative Commons Licence)

The efficiency of trees in catching and absorbing PM depends on various factors, most notably tree type and meteorological conditions (Powe and Willis, 2004). Even when trees are placed next to a road, the paricles were found to be deposited both on the side closer to

the road, and on the side facing away from it, as the pollutants get caught by the hairy surface of leaves (Figure 4.1.2) (Maher *et al.*, 2013).

Due to finer and more complex structure of their foliage, conifers (and other evergreen trees) seem to have a higher trapping efficiency ($C_p{}^2$) than their deciduous counterparts. Amongst broadleaved trees, it is the ones with coarse and hairy leaves that have higher C_p as the increased stickiness of surface facilitates greater coarser particle capture, while surface roughness has a greater influence on the uptake of finer particles (Beckett *et al.*, 1998; Rasanen *et al.*, 2013). Shackleton *et al.* (2011) found that amongst the lower growth plants they were researching, the ones with very high hair density captured $PM_{2.5} - PM_{10}$ with double the efficiency of plants with hairless leaves.
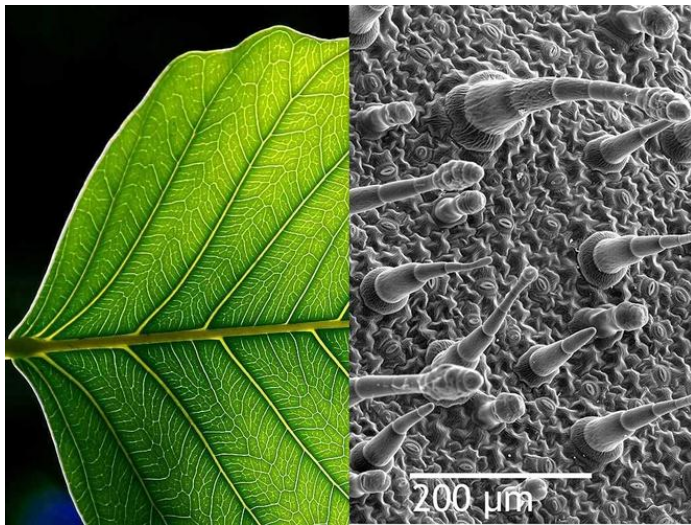
Figure 4.1.2 Magnified surface of a leaf from a deciduous tree (Creative Commons Licence)

Trees capture particulate matter through deposition on bark and leaf surfaces, which is to say, through dry deposition. Dry deposition could be represented by the following formula:

$$\frac{dC_i}{dt} = -\frac{V_{d,i}}{z} * C_i$$

where:

C_i is pollutant concentration

$V_{d,i}$ is the deposition velocity

z is the height through which the pollutant is well mixed

$V_{d,i}$ depends on the type of pollutant, i, and the nature of the surface and is generally higher for vegetation than for other urban surfaces. Some of the reasons behind this are the

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[2] C_p is a unitless ratio (or percentage) that depends on the trapping efficiency quotient. If all impacted particles are captured, then the impaction efficiency would equal the trapping efficiency, indicating that no bounce-off was occurring. Cp is used to describe uptake by impaction and direct interception.

metabolic uptake by plants, the "stickiness" of the leaf surface, the surface area of plants and their aerodynamic properties (Pugh *et al.*, 2012).

Wind speed (*u*) also influences the efficiency of capture, with greater speeds giving larger particle inertia and thus, more effective impaction (Table 4.1.1) (Beckett, Freer-Smith & Taylor, 2000). The deposition of particles on tree surfaces happens mainly through turbulent flow and associated impaction. Namely, the inertia of a particle travelling through an air stream as it curves around an object (such as a leaf or a stem) forces it through the boundary layer and onto the object's surface (Gregory, 1973). This is what makes trees more efficient in capturing particles than low growth flora.

Table 4.1.1 Published deposition velocities (v_d), depending on plant species, particle size (d_p) und wind speed (u) (from Freer-Smith et al.,2005; Sehmel, 1980)

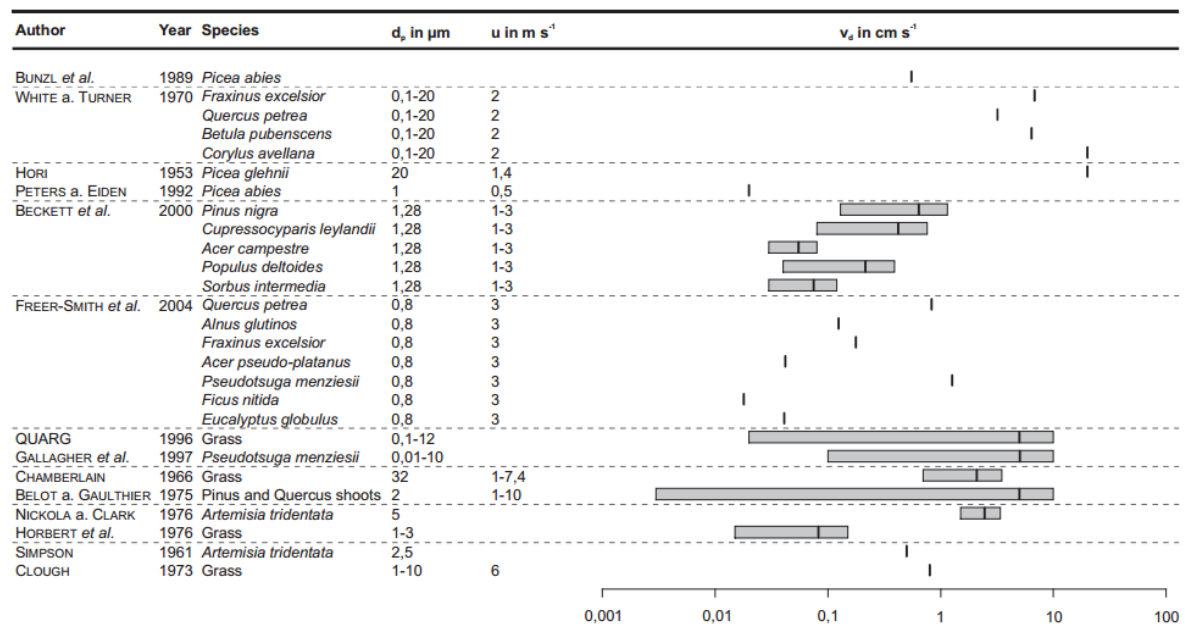| Author	Year	Species	d_p in µm	u in m s^{-1}	v_d in cm s^{-1}
Bunzl *et al.*	1989	Picea abies			
White a. Turner	1970	Fraxinus excelsior	0,1-20	2	
		Quercus petrea	0,1-20	2	
		Betula pubenscens	0,1-20	2	
		Corylus avellana	0,1-20	2	
Hori	1953	Picea glehnii	20	1,4	
Peters a. Eiden	1992	Picea abies	1	0,5	
Beckett *et al.*	2000	Pinus nigra	1,28	1-3	
		Cupressocyparis leylandii	1,28	1-3	
		Acer campestre	1,28	1-3	
		Populus deltoides	1,28	1-3	
		Sorbus intermedia	1,28	1-3	
Freer-Smith *et al.*	2004	Quercus petrea	0,8	3	
		Alnus glutinos	0,8	3	
		Fraxinus excelsior	0,8	3	
		Acer pseudo-platanus	0,8	3	
		Pseudotsuga menziesii	0,8	3	
		Ficus nitida	0,8	3	
		Eucalyptus globulus	0,8	3	
QUARG	1996	Grass	0,1-12		
Gallagher *et al.*	1997	Pseudotsuga menziesii	0,01-10		
Chamberlain	1966	Grass	32	1-7,4	
Belot a. Gaulthier	1975	Pinus and Quercus shoots	2	1-10	
Nickola a. Clark	1976	Artemisia tridentata	5		
Horbert *et al.*	1976	Grass	1-3		
Simpson	1961	Artemisia tridentata	2,5		
Clough	1973	Grass	1-10	6	

Table 4.1.1 shows a synthesis of previous research regarding deposition velocities (v_d) for particles of various sizes and for different species of plants. Litschke & Kuttler (2008) were slightly sceptical regarding the results that included particles up to 20 µm, as their deposition velocity is faster simply due to their weight and the effect of gravity. Table 4.1.2 shows deposition velocities of particles by size group in two different research locations in England, United Kingdom – one in an urban area and one in the surrounding countryside, taking into consideration some of the most common local tree species (Litschke & Kuttler, 2008). These results were found to be somewhat surprising because, based on previous research, the expected v_d was less than 1 cm s^{-1}, which is much lower than results showed.

Another factor to take into consideration is the subsequent resuspension of particles after they were deposited onto the plant surface. Witherspoon & Taylor (1969) found that after one hour, the resuspension rate of an oak is 91% while for a pine, this rate is only 10% which is thought to be one of the factors making pine-trees (and other conifers) more effective in PM filtration.

Table 4.1.2 Deposition velocities of PM_{10}, PM_2 and PM_1 on the foliage of various tree species (modified after Freer-Smith et al., 2005)

Particle size fraction	Deposition velocity in cm s^{-1}				
	Pine	Cypress	Maple	Poplar	Whitebeam
Sussex field site					
PM_{10}	2,8	3,4	3,6	0,6	5,4
PM_2	1,8	4,6	9,2	0,8	11,0
PM_1	36,2	33,7	31,7	25,4	27,2
Withdean Park					
PM_{10}	4,7	6,2	1,8	0,4	3,3
PM_2	6,1	3,7	2,5	0,8	4,5
PM_1	29,9	19,5	11,6	12,3	16,9

4.2 Known Effects

Several studies have tried to model the benefits of trees in urban areas. McPherson *et al.* (1994) estimated that in Chicago trees removed approximately 234 tonnes of PM_{10} in 1991, improving average hourly air quality by 0.4% (2.1% in heavily wooded areas), and Nowak *et al.* (1998) calculated that trees in Philadelphia improved air quality by 0.72% through removal of PM_{10} by dry deposition. These results were acquired by designating randomly located plots within the study area. An estimate of leaf-surface area was then conducted and average removal rates of pollutants were applied to get an estimation on the amount removed from the air by plants.

Maher *et al.* (2013) found that the presence of trees (young birch) in front of a row of roadside houses lead to a drastic decrease (around 50%) of PM found inside the houses screened by the trees, as opposed to the houses that were directly exposed to the road.

5 Methods

The measurements were made with two identical TSI Optical Particle Sizers (model 3330) labelled UI-1 and UI-2 (University of Iceland 1 and 2, respectively) (Figure 5.1). Measurements were taken next to one of the busiest roads in Iceland, Miklabraut, which runs east – west connecting Reykjavik's downtown with the road leading north into the so-called "ring road", Iceland's main highway. Because Iceland is so sparsely populated, one of the major challenges of this research was choosing the time when the amount of traffic would be high enough to provide meaningful results. During regular work days two traffic peaks were determined, one in the morning hours from 7:30 to 9:00 and one in the afternoon from 16:00 to 18:00. On week-ends and holidays, measurements were aimed at noon to 13:00.

Figure 5.1 Setting up a TSI Optical Particle Sizer, Model 3330 at the Klambratún location, behind vegetation barrier (left and middle); Average traffic conditions on Location 1 (right).

TSI Optical Particle Sizers (model 3330) were designed to count the number of particles of a certain size per cubic centimeter (cm^3) for the duration that was set by the user. In this research, samples were one minute long. The particle sizes that the instruments accounted for were as follows:

Ultrafine particles - particles up to 1000 nm ($PM_{1.0}$): 0.300 µm, 0.374 µm, 0.465 µm, 0.579 µm, 0.721 µm and 0.897 µm;

Fine particles – particles up to ~2.5 µm ($PM_{2.5}$): 1.117 µm, 1.391 µm. 1.732 µm, 2.156 µm and 2.685 µm;

Coarse particles – particles up to 10 µm (PM_{10}): 3.343 µm, 4.162 µm, 5.182 µm, 6.451 µm, 8.031 µm and 10 µm.

In order to achieve best results and allow the instruments to capture as many particles as possible, the measurements were taken during periods without precipitation that would

lead to wet deposition. This meant that there was a minimum of 24 hours without precipitation before the measurements were taken and with a prognosis of dry weather on the measuring day. Strong winds were also avoided as much as possible.

Since the goal of the study was to determine if vegetation barriers have an impact on the distribution of particulate matter emitted from road traffic, it was necessary to collect data both with a barrier between the two instruments, and without one, for comparison.

For each set of measurements, one of the two instruments was placed next to the Miklabraut road (within 1 meter of the road) with the goal of providing the information on the emission of particles at the source. The other instrument was placed at a distance of 20-35 meters from the first instrument, in a line perpendicular to the road.

Three locations along the Miklabraut road were chosen for this research (Figure 5.2).
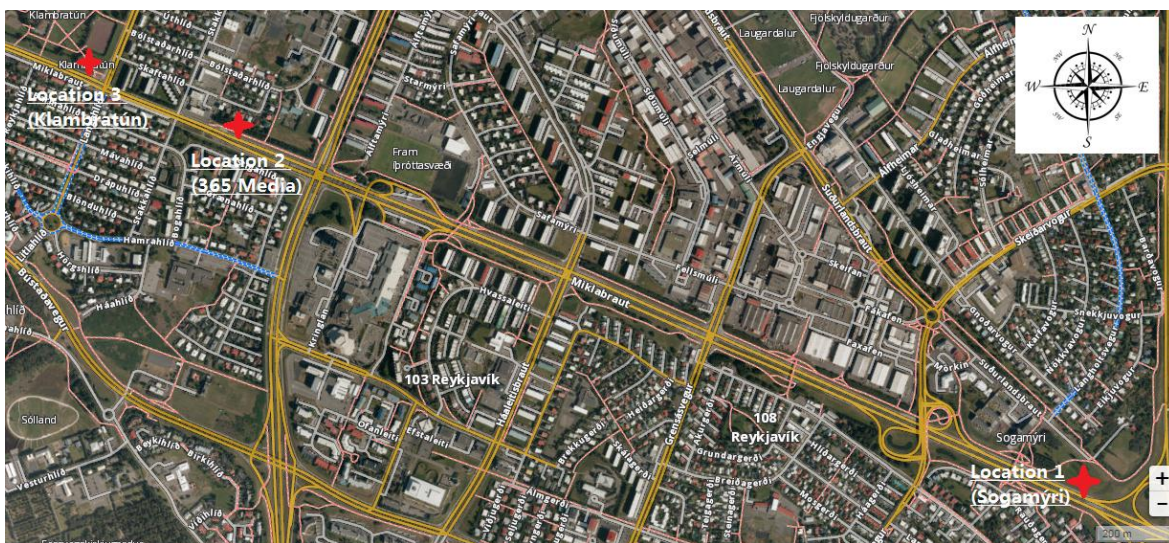

Figure 5.2 Sampling locations along the Miklabraut road, Reykjavík, Iceland marked as red stars.

5.1 Location 1 - Sogamýri

Measurements from the 4th of July 2013 were taken on a clearing by the side of Miklabraut road at Sogamýri (Location 1). The instrument labeled UI-1 was placed next to the road and set to take one minute samples every minute for the duration of one hour (from 12:00 – 13:00). The other instrument (UI-2) was initially placed right next to UI-1 in order to check if the instruments show consistent numbers (which they did) and was afterwards placed further and further away from UI-1 (in a line perpendicular to the road) with no barrier between them. The goal was to determine the natural rate of deposition for particulate matter of varying sizes (Figure 5.1.1).

Figure 5.1.1 Location 1 next to Miklabraut road at Sogamýri, Reykjavik, Iceland, showing the two instruments at various distances from each other

5.2 Location 2 – 365 Media

Data collected in May 2014 was taken at a location which provided a vegetation barrier. The UI-1 device was placed within one meter of Miklabraut road, close to the 365 Media building (Skaftahlíð 24, 105 Reykjavík), to collect data at the source. The UI-2 device was set to take measurements in two spots (at different times) that were located 25 meters away from UI-1, in the direction perpendicular to the road and away from it. One location was behind a vegetation barrier which will be described shortly (Figures 5.2.1 and 5.2.2), while the other was a close-by location with no barrier between UI-2 and the road (Figure 5.2.3). The goal was to compare the results from these two places and see if the vegetation barrier makes any difference.

The barrier at this location consisted of a 1 m high hill that runs parallel to the road separating the trees from it, as well as a 5 m wide belt of coniferous trees. The trees (pines) were in poor health at the time measurements were taken and were devoid of much of their foliage.

Figure 5.2.1 Location 2 close to the 365 Media building on the Miklabraut road, Reykjavik, Iceland showing a device placed next to the road, and a device placed behind a barrier of coniferous trees

Figure 5.2.2 Barrier made of coniferous trees and a 1m tall grass-covered hill

Figure 5.2.3 Location close to the 365 Media building on the Miklabraut road, Reykjavik, Iceland showing a device placed next to the road, and a device placed on a path perpendicular to the road and directly exposed to it

5.3 Location 3 – Klambratún

The third sampling location was also positioned along Miklabraut road, in front of, and within the Klambratún park. Samples were taken on 30th, 31st July and 1st of August 2014. As before, one of the samplers was placed within one meter of Miklabraut road while the other was placed 25 – 30 m perpendicular to it, sometimes behind a vegetation barrier and sometimes in a clearing. Here the UI-1 device was sometimes used as a rover, while UI-2 was stationary. This was done due to there being some doubts regarding certain particle sizes (0.7 μm and 0.8 μm) being measured properly by the two instruments.

Figure 5.3.1 Barrier made of trees and shrubs of varying species, heights and leaf types

The vegetation barrier in the park was chosen due to it being fairly different from the coniferous barrier from the second location. The park barrier was significantly denser and consisted of various trees, bushes and shrubs, of varying heights (Figure 5.3.1). The trees were both deciduous and coniferous. The lower growth plants were up to 2 m high and deciduous. Density of the barrier was such that it was impossible to see through it and its width was roughly 2 m (Figure 5.3.2).

Figure 5.3.2 Klambratún location with the barrier with one instrument placed next to the road, and the other placed behind the vegetation barrier in the park.

A nereby location was chosen where the instruments could be placed at same distances from one another and the road, but with no barrier between them, for comparison purposes (Figure 5.3.3).

Figure 5.3.3 Klambratún location without the barrier with one instrument placed next to the road, and the other placed ~25 m behind it, perpendicular to the road with no barrier between them

6 Results

The raw data that was extracted from the instruments and analysed, was separated according to the location where it was collected, and presented below in order to get a better overview of the effects different types of barriers have on particulate matter.

6.1 Location 1, Sogamýri – No Barrier

Data gathered at Location 1 was collected to give an idea of how particulate matter spreads with distance within the first ~35 meters from emission, which is the range where all the other data was collected. In this case there was no barrier present between the two instruments and the wind speed was minimal so the only factor in changes in concentration should be the distance from the road source.

The concentrations of coarse particles ($PM_{2.5}$ to PM_{10}) were so low (less than 20 particles/cm^3 on average) that it was difficult to come to a conclusion regarding their behavior since even the slightest fluctuation in their numbers accounts for a big change in percentage (Figure 6.1.1).
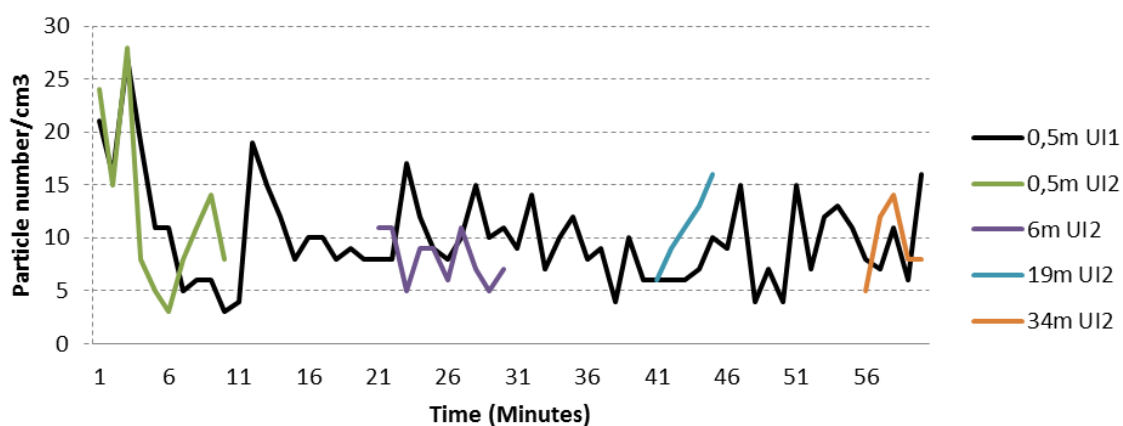

*Figure 6.1.1 A representative size from the coarse particle fraction – concentrations of particles **4.162 µm** in diameter as measured by UI-1 (black line) and UI-2 at various distances over the course of one hour on 04.07.2013.*

Fine particles and ultrafine particles larger than 0.5 µm showed no decline in concentration with distance and their concentrations at 6, 19 and 34 meters coincided with those taken within a meter of the road (Figure 6.1.2).
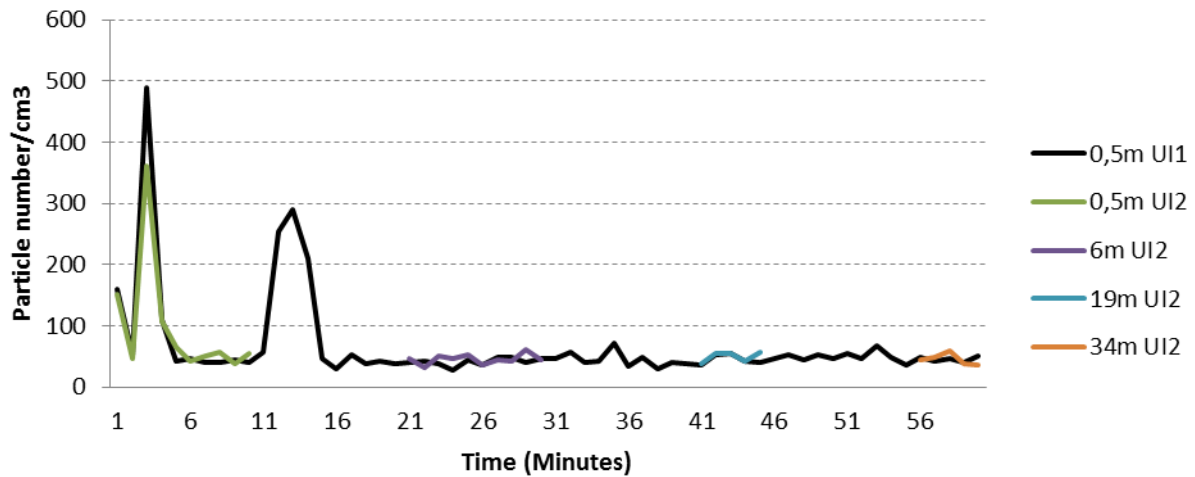
*Figure 6.1.2 A representative size from the fine particle fraction – concentrations of particles **1.117 μm** in diameter as measured by UI-1 (black line) and UI-2 at various distances over the course of one hour on 04.07.2013.*

Ultrafine particles, smaller than 0.5 μm (Figure 6.1.3), showed a lack of sensitivity to concentration peaks the further they were from the road. Their behaviour seems to be the same at 6 m from the road as at 34 m.
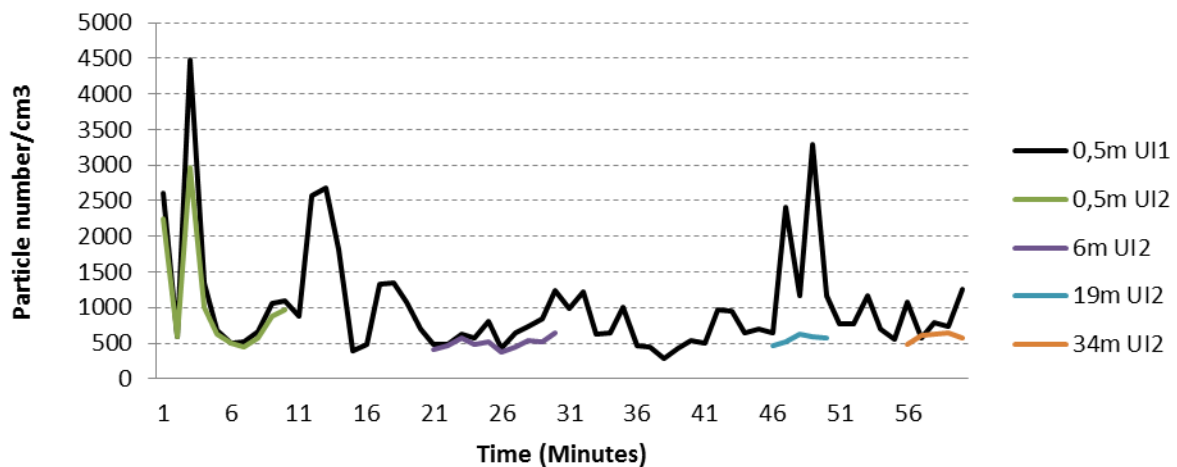

*Figure 6.1.3 A representative size from the ultrafine particle group (up to 0.5 μm in diameter) – concentrations of particles **0.374 μm** in diameter as measured by UI-1 (black line) and UI-2 at various distances over the course of one hour on 04.07.2013.*

6.2 Location 2, 365 Media – Coniferous Barrier

The data collected at Location 2 (365 Media), which included a barrier that is made of coniferous trees (pines), approximately 12 m tall, seems to indicate that this barrier doesn't have much impact on the distribution of particulate matter. Namely, the results acquired

when measuring with and without a barrier seem quite similar. The smallest particles (up to 0.6 µm), show very similar tendencies regardless of the presence of a barrier (Figure 6.2.1)

The columns represent the decrease in particle count, for given particle sizes, between the instrument placed next to the road, and the instrument placed 25 m perpendicular to the road. Ultrafine particles up to the size of 0.6 µm unanimously show a decrease with the distance, however, they show incinsistency when it comes to the presence of the barrier. While the smallest particles (0.3 µm) show a more significant decrease behind a barrier, the other sizes show either equal or greater decrease when there is no barrier.
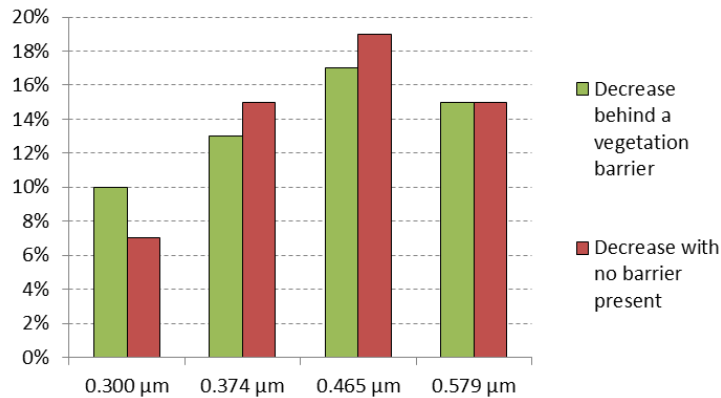

Figure 6.2.1 Decrease in fine particle concentration between the instrument placed next to the road and the instrument placed 25 m perpendicular to the road as measured on 22.05.2014 and 23.05.2014. at Location 2

When broken down per sampling session, it would seem that the barrier has some effect on taking out the concentration peaks on certain occasions (Figures 6.2.2 and 6.2.3).
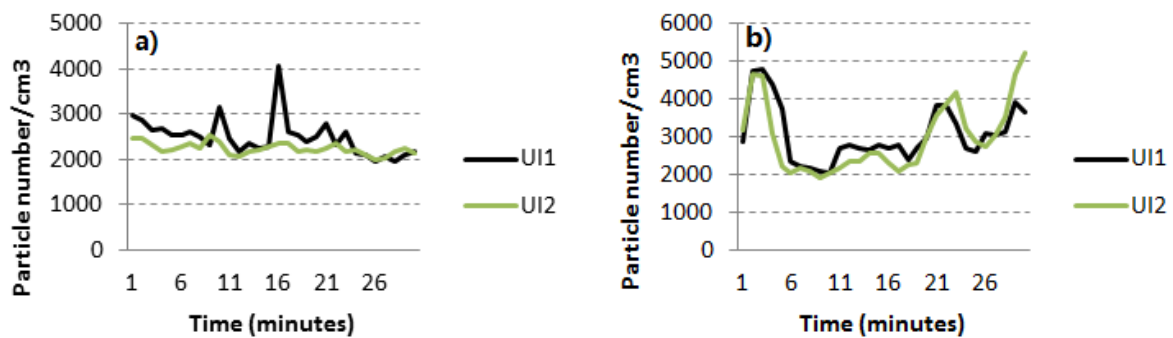

*Figure 6.2.2 Concentrations of **0.374 µm** particles as measured next to the road (black line, UI-1) and behind a vegetation barrier (green line, UI-2) at 16:45 (a) and 18:05 (b) in May 2014.*
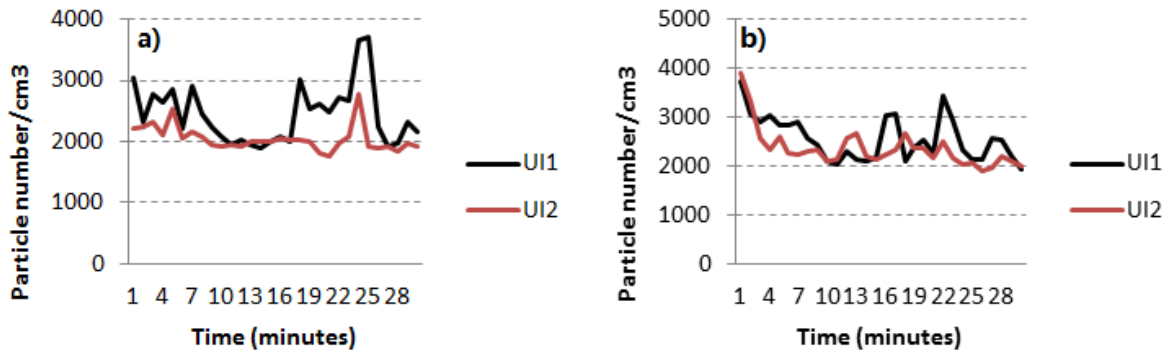
*Figure 6.2.3 Concentrations of **0.374 μm** particles as measured next to the road (black line, UI-1) and 25 m away from the road with no barrier (red line, UI-2) at 17:25 (a) and 18:45 (b) in May 2014.*

Similarly, fine particles paint much the same picture as other size groups regarding the vegetation barrier, namely, there doesn't seem to be any detectable difference in particle behaviour. One notable thing is that the decrease with the distance seems to be minimal (or not present) in this size fraction (Figure 6.2.4)
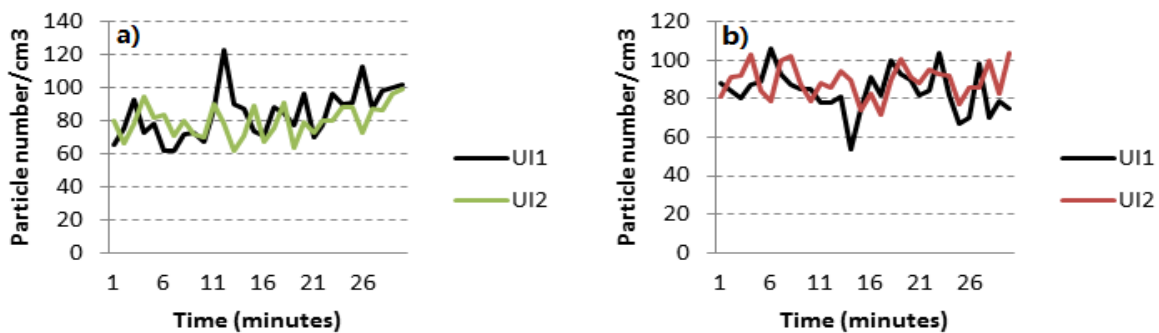

*Figure 6.2.4 Concentrations of **1.117 μm** particles as measured next to the road (black line, UI-1) and 25 m away from the road behind a vegetation barrier (green line, UI-2) (a) and with no barrier (red line, UI-2) (b) in May 2014.*

Coarse particles were scarce again and could be counted in dozens per cubic centimetre for the most part. This renders the results less reliable than is optimal, but even so, the tendency seems to be that while the concentrations do decrease with the distance, the decrease is about the same regardless of the presence of this particular coniferous barrier (Figures 6.2.5 and 6.2.6).
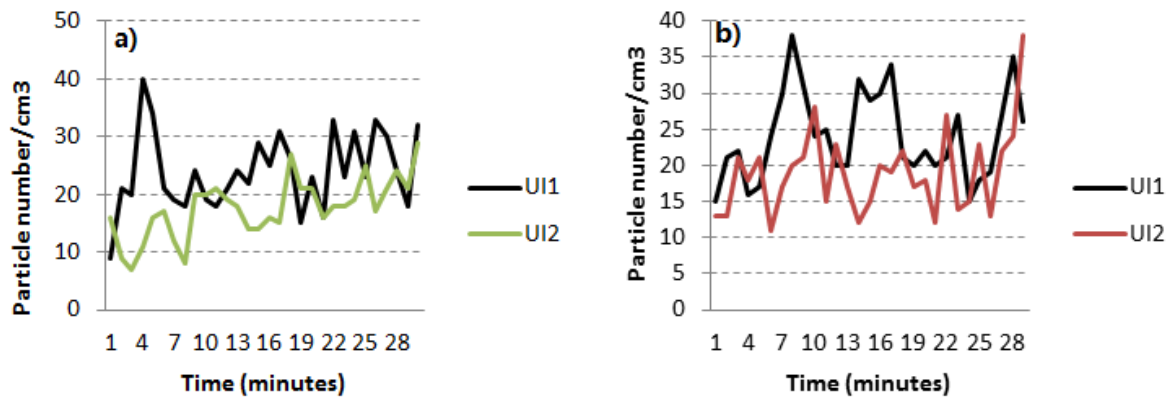
*Figure 6.2.4 Concentrations of **3.343 μm** particles as measured next to the road (black line, UI-1) and 25 m away from the road behind a vegetation barrier (green line, UI2) (a) and with no barrier (red line, UI-2) (b) in May 2014.*

Like in Figure 6.2.1, the columns represent the decrease in particle count between the two instruments. In majority of cases the presence of a barrier seems to result in a greater decrease of particles at 25 meters, however, most of the times that difference is marginal.
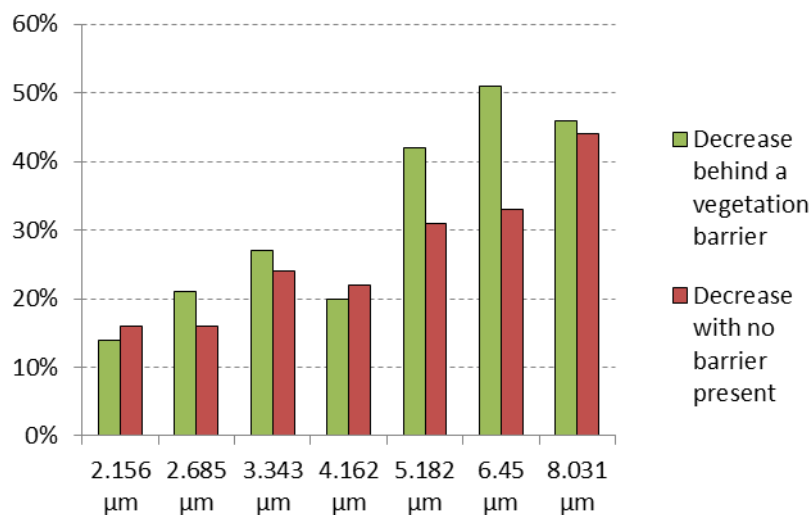

Figure 6.2.5 decrease in larger particle concentration between the instrument placed next to the road and the instrument placed 25 m perpendicular to the road as measured on 22.05.2014 and 23.05.2014. at the 365 Media building location

Most of the time, while sampling on this location, the wind was minimal, but there were a few occasions when it could be felt, and in those situations, the wind was blowing from the road towards the sampling instruments.

6.3 Location 3, Klambratún – Mixed Barrier

Measurements taken on the afternoon of 30th of July at Location 3 (Klambratún) seem somewhat intriguing in that they don't seem to follow the expected trend. Namely, the results for almost all particle sizes show an increase in concentrations behind the barrier (Figures 6.3.1 – 6.3.3). This is not in line with the results taken at the same location on other days, nor is it in line with the results from other locations. This discrepancy could be explained by the new tarmac that was was laid on Miklabraut just in front of the sampling location within 24h before the measurements were done. It is possible that the particles released from the roadwork got caught behind the barrier where they stayed even after they were dispersed from the road. The wind on this day was fairly weak and was blowing parallel to the road.
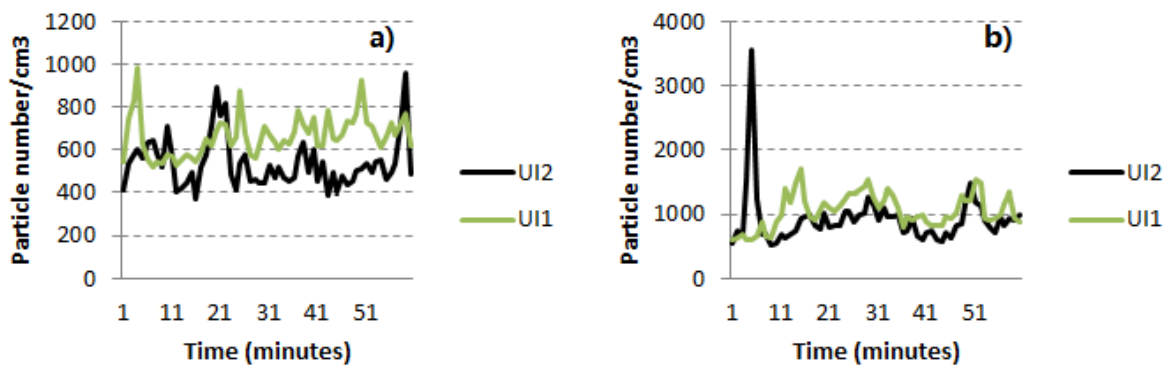

*Figure 6.3.1 Concentrations of **0.374 μm** particles as measured next to the road (black line, UI2) and 25 m away from the road behind a barrier (green line, UI-1) at 17:40 (a) and 18:05 (b) on 30.07.2014.*

*Figure 6.3.2 Concentrations of **1.117 μm** particles as measured next to the road (black line, UI-2) and 25 m away from the road behind a barrier (green line, UI-1) at 17:40 (a) and 18:05 (b) on 30.07.2014.*
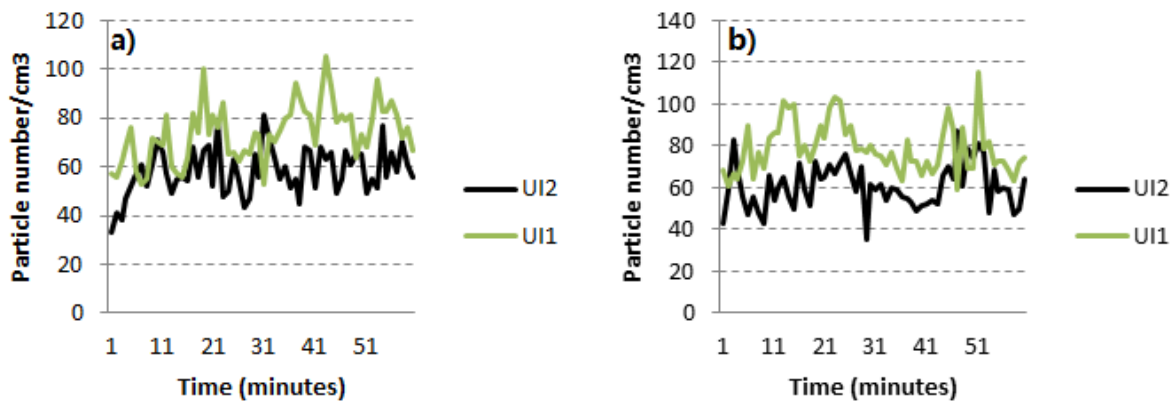
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*Figure 6.3.3 Concentrations of **3.343 μm** particles as measured next to the road (black line, UI2) and 25 m away from the road behind a barrier (green line, UI-1) at 17:40 (a) and 18:55 (b) on 30.07.2014.*
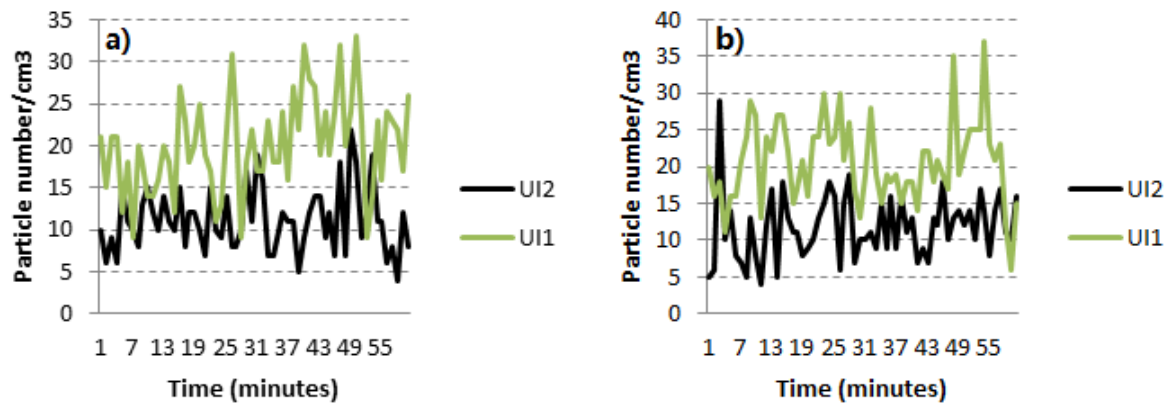
The only particles in this set that showed a decrease behind the barrier were the 0.3 μm sized ones, and they showed a decrease of only 4% (Figure 6.3.4). It was apparent that the sudden peaks of concentration did not penetrate the barrier.
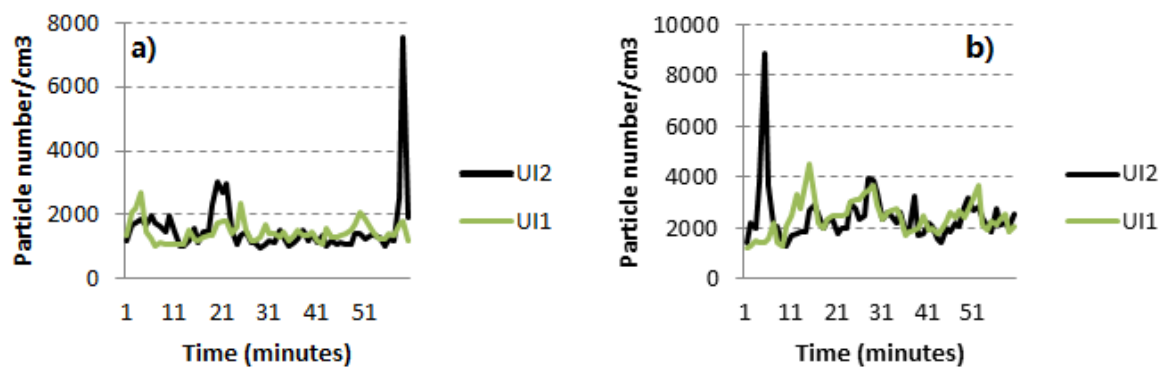

*Figure 6.3.4 Concentrations of **0.3 μm** particles as measured next to the road (black line, UI-2) and 25 m away from the road behind a barrier (green line, UI-1) at 17:40 (a) and 18:55 (b) on 30.07.2014.*

Because this set of data seems quite atypical considering general trends measured on all locations, it will not be included in the percentages given below.

Results taken on the morning of 31st of July show an interesting pattern as well. Namely, the concentration levels behind the barrier seemed consistently very low (Figure 6.3.5). This could be due to high levels of humidity in the morning, as dew made the ground and plants wet which could lead to deposition with particles sticking to wet grass and leaves. The wind was barely present during the hours the measurements were taken. The traffic itself was of low intensity which resulted in an accordingly low level of emissions even next to the road. After consulting the PM_{10} and $PM_{2.5}$ concentrations measured by the two monitoring stations in Reykjavik - an urban traffic station at Grensás (GRE) and a background station at Fjölskyldu og Húsdýragarðurinn (FHG), it was apparent that on these days PM concentrations were very low, even as measured by GRE station (which is situated next to a big road), this early in the morning, and would show an increase after 9h.
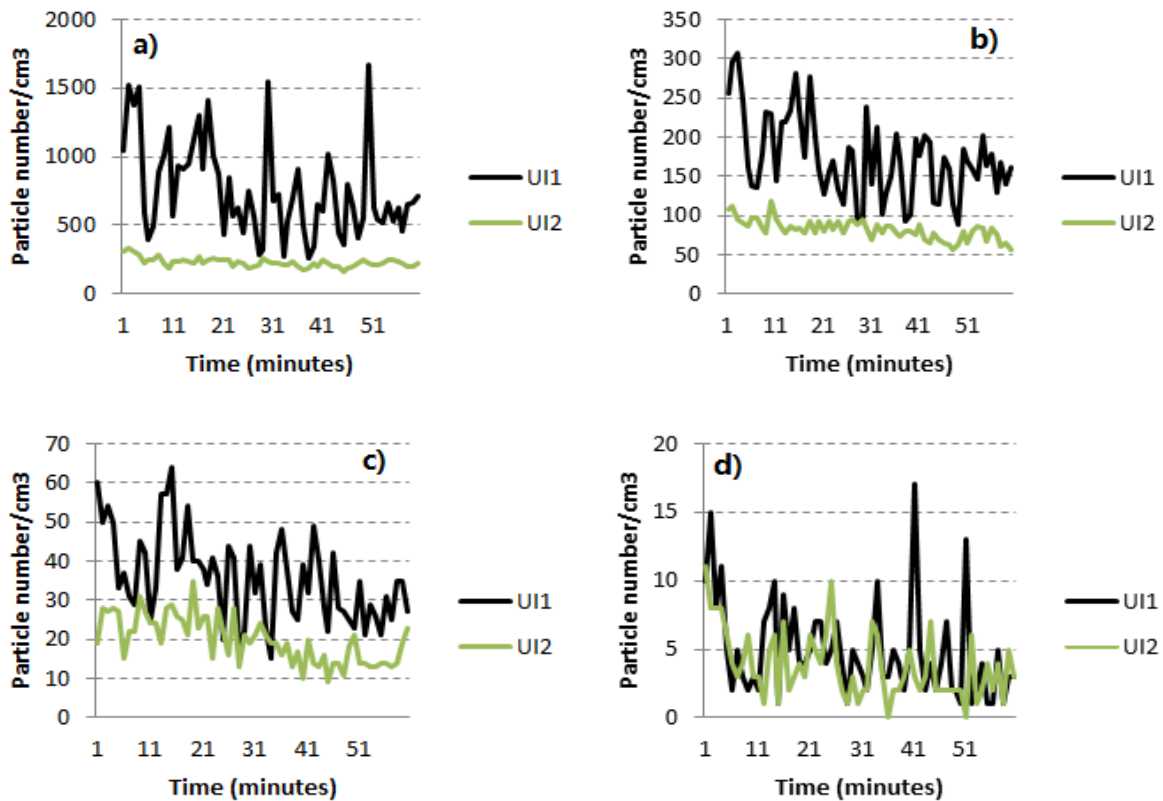
*Figure 6.3.5 Concentrations of **0.374 μm** (a), **0.579 μm** (b), **1.391 μm** (c) and **4.162 μm** (d) particles as measured next to the road (black line, UI-2) and 25 m away from the road behind a barrier (green line, UI-1) at 08:35 on 31.07.2014.*

Overall, the results at this location showed a fairly big difference in particle concentrations depending on the presence of a vegetation barrier. For 0.3 μm particles the decrease in concentration is roughly double behind the barrier than in its absence (Figures 6.3.6 and 6.3.7). Namely, the average decrease in the particle concentration measured 25 m perpendicular to the road, compared to those taken within the first meter of the road, is, on average, 23% when there is no barrier and 47% with the vegetation barrier between the two instruments.
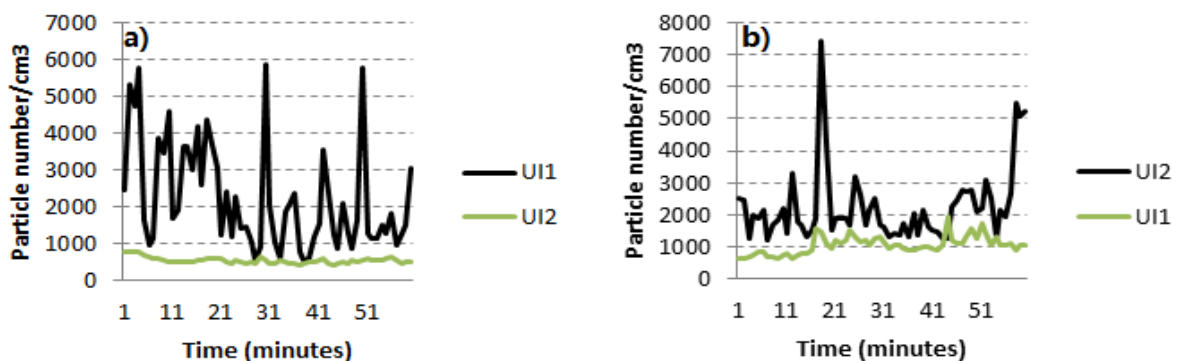

*Figure 6.3.6 Concentrations of **0.3 μm** particles as measured next to the road (black line) and 25 m away from the road behind a barrier (green line) at 08:35 (a) and 17:30 (b) on 31.07.2014.*

*Figure 6.3.7 Concentrations of **0.3 μm** particles as measured next to the road (black line) and 25 m away from the road without a barrier (red line) at 18:50 (a) on 31.07.2014. and 12:05 (b) and 13:15 (c) on 01.08.2014.*

Similarly, this trend seems consistent among ultrafine particles up to 0.6 μm in diameter (Figure 6.3.10). For example, for 0.374 μm particles, the decrease behind a barrier is around 50% greater than without it (48% decrease behind a barrier and 25% decrease without it) (Figure 6.3.8 amd 6.3.9).

*Figure 6.3.8 Concentrations of **0.374 μm** particles as measured next to the road (black line) and 25 m away from the road behind a barrier (green line) at 08:35 (a) and 17:30 (b) on 31.07.2014.*
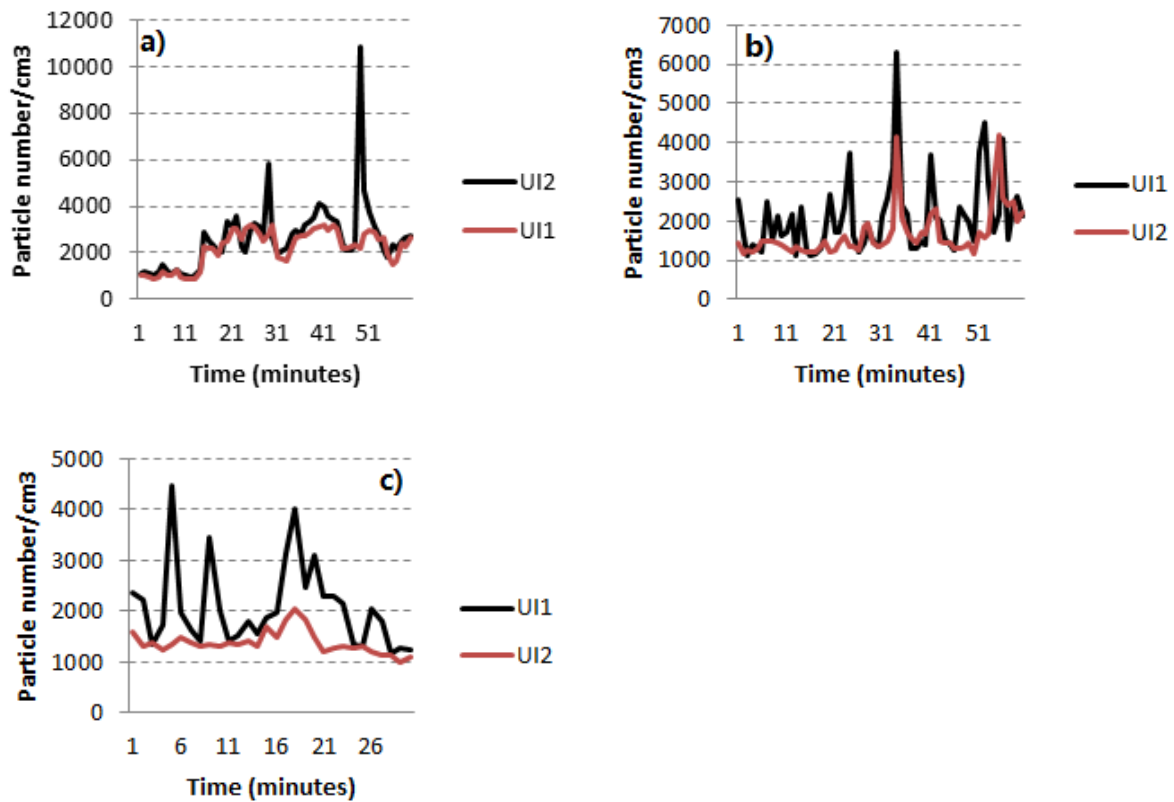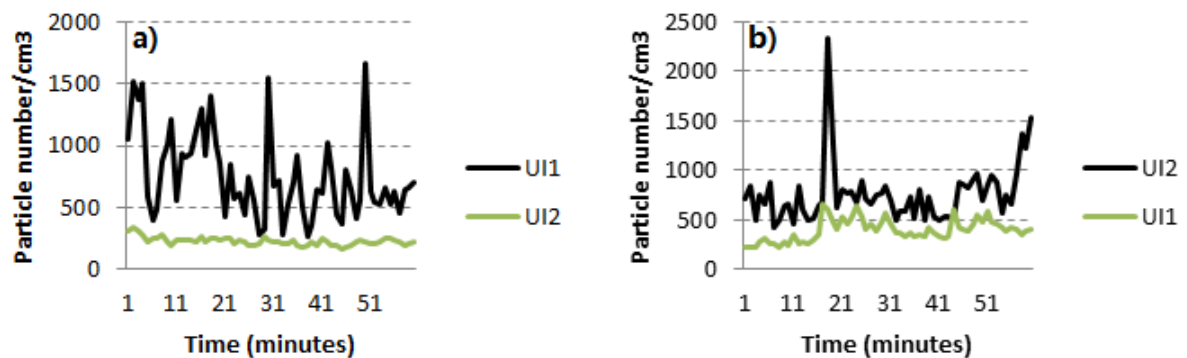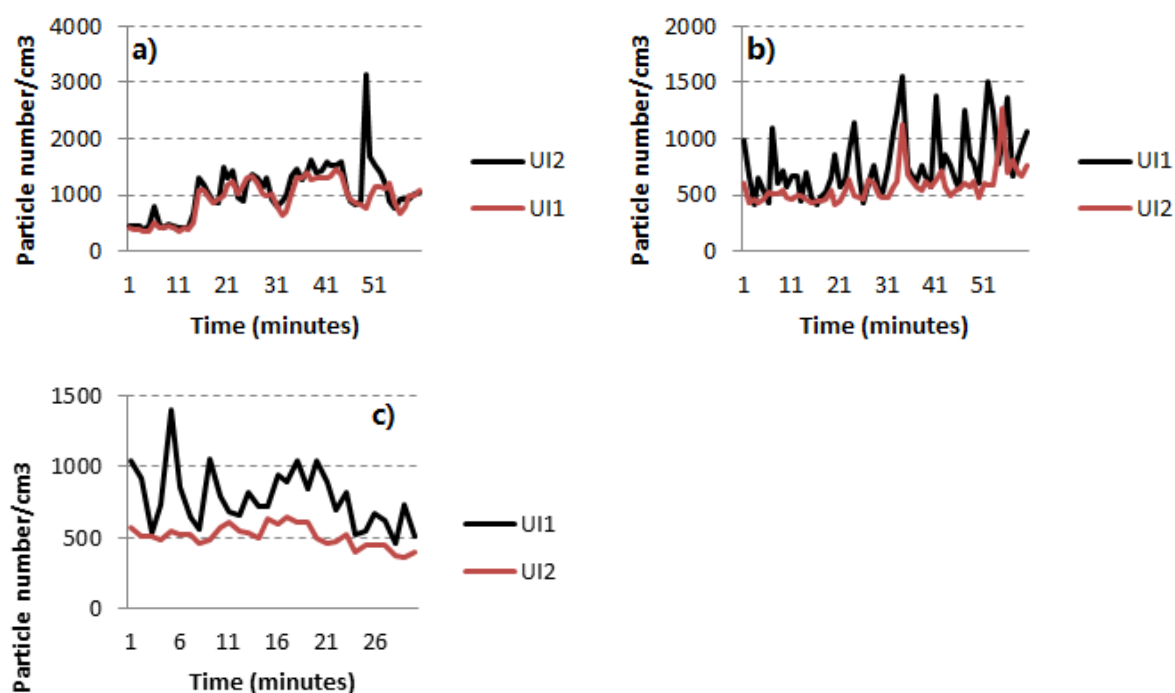
*Figure 6.3.9 Concentrations of **0.374 μm** particles as measured next to the road (black line) and 25 m away from the road without a barrier (red line) at 18:50 (a) on 31.07.2014. and 12:05 (b) and 13:15 (c) on 01.08.2014.*
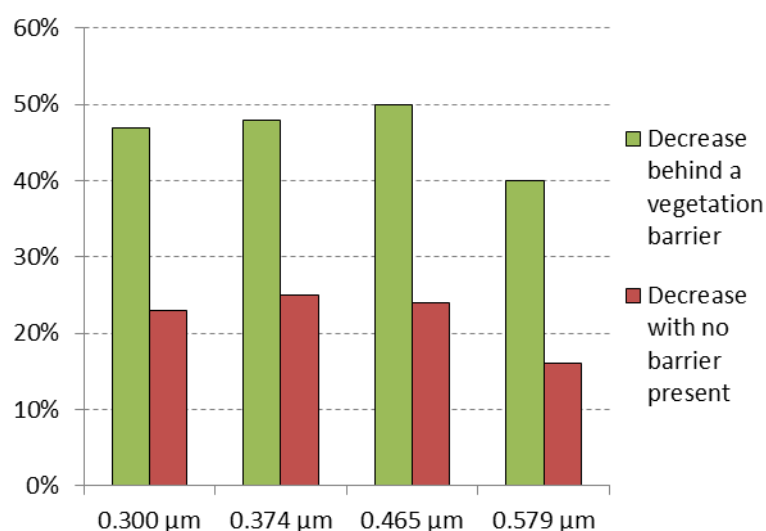
Figure 6.3.10 decrease in particle concentration between the instrument placed next to the road and the instrument placed 25 m perpendicular to the road as measured on 31.07.2014 and 01.08.2014. at Location 2 (Klambratún)

The situation with larger particles is less consistent. Particles 1-2 μm in size show a consistent decrease in concentration behind a barrier (around 30% on average), while without a barrier this decrease is roughly 14%, but in some cases a slight increase in concentrations has been seen (Figure 6.3.11).

*Figure 6.3.11 Concentrations of **1.117 µm** particles as measured next to the road (black line) and 25 m away from the road behind a barrier (green line) at 08:35 (a) and 17:30 (b) on 31.07.2014. and without a barrier (red line) at 18:50 (c) on 31.07.2014. and 12:05 (d)*

Coarse particles (larger than 2 µm) show a wide range of behaviour, from significant decrease to noticeable increase in concentration both with and without a barrier. Overall, the particle counts for this size group were quite low which probably amplified this inconsistency (Figure 6.3.12).

*Figure 6.3.12 Concentrations of **4.162 μm** particles as measured next to the road (black line) and 25 m away from the road behind a ba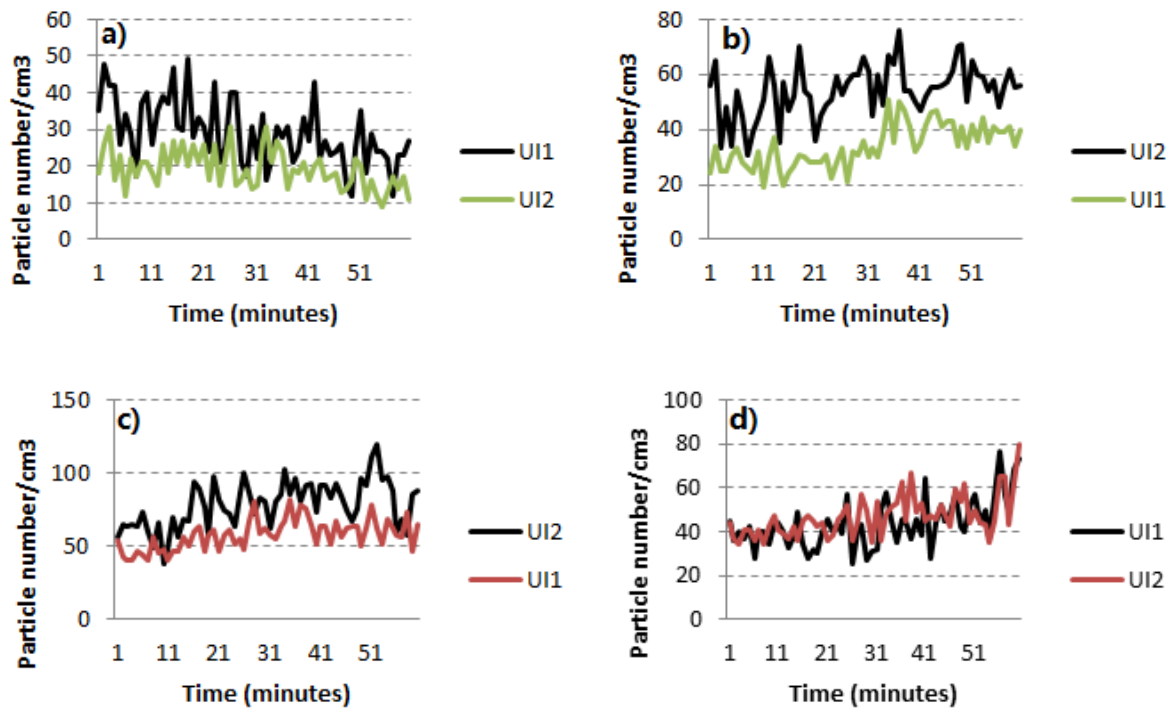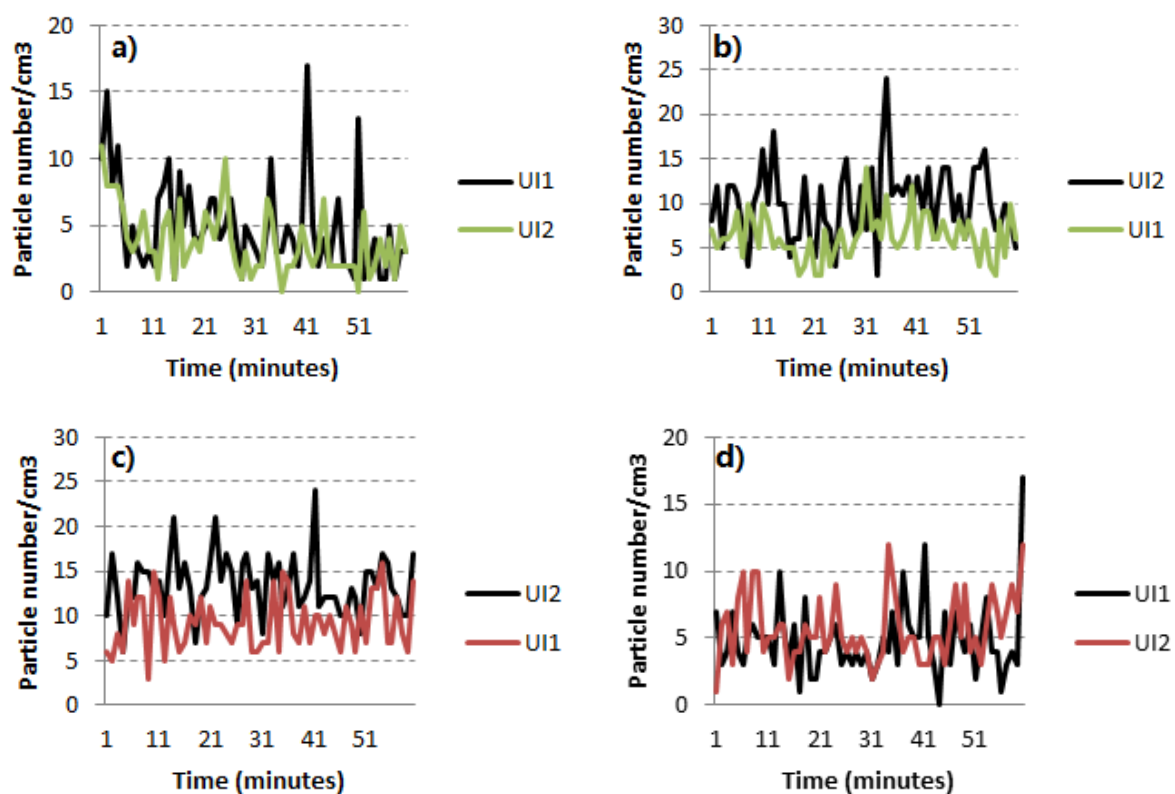rrier (green line) at 08:35 (a) and 17:30 (b) on 31.07.2014. and without a barrier (red line) at 18:50 (c) on 31.07.2014. and 12:05 (d)*

7 Discussion

It is hard to say if a clear-cut conclusion can be deduced from this research. While Iceland is one of the countries with the highest amount of vehicles per 1000 people (World Bank, 2013), the reality is that the population of Iceland doesn't even number 350 000 inhabitants, and as such, the traffic volume in the capital, even during the busiest hours, can not be compared to the traffic in other major cities where most of the similar research has been conducted. Because of this, and the high number of days with precipitation, especially in the last two years, the amount of pollution, especially the coarse particle count, was quite low in some samples.

By including the samples taken by two measuring stations in Reykjavik at the time of this research, it was evident that during the night and early morning the PM_{10} and $PM_{2.5}$ concentrations were negligible. This notion was strengthened by some of the results gathered in the early morning through this research. This could be due to an extremely low volume of transport during the night in Reykjavik, or due to mist and dew collecting close to the ground during the dawn, or, which is most likely, it is a combination of both these factors.

Despite this, some clear tendencies could be spotted when comparing the results from the two locations with barriers, as well as when comparing them to previously done research on the topic of PM distribution and filtration.

The two researched barriers show distinct differences in their impact on particular matter, especially on the ultrafine fraction. Particles smaller than 0.6 µm in diameter showed almost the same decrease in concentration 25 meters perpendicular to the road with the coniferous barrier and without it. This decrease was approximately 14% for both. On the other hand, the mixed vegetation barrier proved to make a big difference in concentration for this same size group. The concentration decrease for particles < 0.6 µm behind the mixed barrier was 46% on average, while this decrease was 22% without it. From this it can be concluded that the mixed barrier is much more effective in filtering the ultrafine particles than the coniferous barrier.

The difference between the effectiveness of the two barriers brings up some interesting questions. As previous research unanimously showed, conifers are more effective in particle capture than deciduous trees. However, the trees in the coniferous barrier in this research where affected by an ailment that left them devoid of most of their needless. This seems to confirm that it is the foliage of coniferous trees that plays the major role in their effectiveness, rather than simply their presence as a physical barrier. It would be interesting to include healthy conifers in any similar future study.

Particles between 0.6 – 1 µm showed very inconsistent results. The particles in this size group often showed an increase in concentration with distance, but not often enough to call it a trend. Their behaviour with regards to the presence of either barrier was also inconsistent. A question was raised if perhaps the plants themselves emitted some of the PM in that range which could lead to these inconsistencies, however, no conclusive answer was found. Plant pollen was discounted as it is normally larger than 10 µm in diameter (Litschke & Kuttler, 2008) and as such falls out of the scope of the instruments that were used to take samples.

Slightly larger particles, between $1 - 2$ μm, did show a notable decrease behind the mixed barrier, around 30% (while the decrease was 14% without a barrier on the same location) on average, however, in some cases both with and without a barrier, an increase in concentration was detected 25 m away from the road.

Coarse particles (> 2 μm) were generally too few in number to show a reliable trend. The situation is such that a difference of 10 particles per cubic centimeter sometimes made a significant difference in percentages. With this in mind, the calculations, such as they are, show that the coniferous barrier had a very slight impact on this size group. The decrease for coarse particles behind the barrier was approximately 32% while it was approximately 27% with no barrier present. No trend was detected on the location with the mixed barrier.

8 Conclusion

It is clear that in order to present more conclusive and meaningful results, especially for particles larger than 0.6 µm, a larger scope of samples and locations is needed. Despite the timeframe of this research being over a year, the actual days on which the measurements could be taken were very few. This is a limitation of Icelandic climate which does not lend itself to outdoor research that requires dry weather conditions.

After analysing the results, the ineffectiveness of leafless conifers was quite striking and the inclusion of a barrier composed of healthy conifers would have been invaluable. However, the lack of foliage and the subsequent ineffectiveness of the barrier did serve to strengthen the conclusions from previous research on the topic, that it is the leaves and needles of trees that play the biggest role in PM capture, rather than twigs and bark.

The mixed barrier, however, proved to be very effective in filtering particles smaller than 0.6 µm. The exact reason behind the effectiveness of the mixed barrier on ultrafine particles should be researched more. Plant health seems to be one of the prerequisites of an effective barrier. A comparison of a healthy coniferous, mixed and deciduous barrier would help identify the best composition in order to maximise its effectiveness.

As ultrafine particles are the ones that are most detrimental to health, a next-to-the-road vegetation barrier that would prevent at least this fraction from spreading far from its source, and impacting those living or working close to busy roads, seems like a worthwhile investment.

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