ΠΑΝΕΠΙΣΤΗΜΙΟ ΔΥΤΙΚΗΣ ΑΤΤΙΚΗΣ
ΣΧΟΛΗ ΜΗΧΑΝΙΚΩΝ
ΤΜΗΜΑ ΜΗΧΑΝΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ

**Διπλωματική Εργασία**

# Μελέτη των συγκεντρώσεων αιωρούμενων σωματιδίων εντός των σταθμών και των συρμών του μετρό στην Αθήνα

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**FACULTY OF ENGINEERING**
**DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING**

**Diploma Thesis**

# Investigation of suspended particles levels inside the stations and trains of Athens Metro

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Η Διπλωματική Εργασία έγινε αποδεκτή και βαθμολογήθηκε από την εξής τριμελή επιτροπή:

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## ΔΗΛΩΣΗ ΣΥΓΓΡΑΦΕΑ ΔΙΠΛΩΜΑΤΙΚΗΣ ΕΡΓΑΣΙΑΣ

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«Είμαι συγγραφέας αυτής της διπλωματικής εργασίας και ότι κάθε βοήθεια την οποία είχα για την προετοιμασία της είναι πλήρως αναγνωρισμένη και αναφέρεται στην εργασία. Επίσης, οι όποιες πηγές από τις οποίες έκανα χρήση δεδομένων, ιδεών ή λέξεων, είτε ακριβώς είτε παραφρασμένες, αναφέρονται στο σύνολό τους, με πλήρη αναφορά στους συγγραφείς, τον εκδοτικό οίκο ή το περιοδικό, συμπεριλαμβανομένων και των πηγών που ενδεχομένως χρησιμοποιήθηκαν από το διαδίκτυο. Επίσης, βεβαιώνω ότι αυτή η εργασία έχει συγγραφεί από μένα αποκλειστικά και αποτελεί προϊόν πνευματικής ιδιοκτησίας τόσο δικής μου, όσο και του Ιδρύματος.
Παράβαση της ανωτέρω ακαδημαϊκής μου ευθύνης αποτελεί ουσιώδη λόγο για την ανάκληση του διπλώματός μου.»

Ο/Η Δηλών/ούσα
Ροδάνας Δημήτριος-Μιχαήλ

(Υπογραφή φοιτητή/ήτριας)

## Περίληψη

Στην μέρες μας, το ζήτημα της μόλυνσης του αέρα είναι ένα ζήτημα που καθημερινά λαμβάνει περισσότερη προσοχή από παγκόσμιους φορείς υγείας και πολιτικών οργανώσεων, κατά επέκταση το ζήτημα της συλλογής αξιόπιστης και ποιοτικής πληροφορίας για την παρακολούθηση και την αντιμετώπιση της αέριας ρύπανσης εμφανιστεί. Ένα σύνολο επιστημονικών άρθρων και ερευνών έχουν αρχίσει να μελετάνε τα οικονομικά και τα τεχνικά χαρακτηριστικά της συλλογής πληροφοριών και την καταμέτρηση της ποιότητας του αέρα με την χρήση του χαμηλού κόστους καταγραφικών. Η χρήση αυτής της τεχνολογίας καλείται να λύσει το πρόβλημα της διαθεσιμότητας, της μεταφοράς και της οικονομικής προσιτότητας στις διαθέσιμες τεχνολογίες για την καταγραφή της αέριας ρύπανσης με μικρό κόστος στην ακρίβεια και την αξιοπιστία των πληροφοριών.

Σε αυτήν την διπλωματική μελέτη σκοπός είναι, μέσω ενός εμπειρικού πειράματος να αναδείξουμε τις δυνατότητες των χαμηλού κόστους καταγραφικών και να αναφέρουμε τυχών μειονεκτήματα κατά την χρήση τους. Για να επιτύχουμε αυτόν τον σκοπό η διπλωματική μελέτη χωρίστηκε σε δύο μέλη, στο πρώτο μέλος της μελέτης κάνουμε την αξιολόγηση και την σύγκριση των χαμηλού κόστους καταγραφικών με καταγραφικά υψηλών προδιαγραφών υπό συνθήκες ανοιχτού πεδίου, το δεύτερο μέλος είναι η αξιοποίηση του καταγραφικού για την καταγραφή της αέριας ρύπανσης για διαδρομή της προαστιακή περιοχή της Βάρκιζας μέχρι την κεντρική περιοχή του Αιγαλέω, με την χρήση μέσων μαζικής μεταφοράς και πιο συγκεκριμένα με την χρήση των δημόσιων λεωφορείων και του μετρό. Ο αέριος ρύπος υπό μελέτη ήταν τα μικροσωματίδια μεγέθους 2.5. Η διπλωματική μελετά κατά κύρια βάση την συγκέντρωση των μικροσωματιδίων σε κυβικά μέτρα αέρα και στον δείκτη AQI (Air Quality Index). Η διαδικασία κατά την οποία έγινε η συλλογή των μετρήσεων έγινε με την λογική της προσομοίωσης της έκθεσης σε ρύπους κατά την χρήση Μ.Μ.Μ. κατά την διάρκεια της εβδομαδιαίας ρουτίνας ενός φοιτητή ή ενός πλήρους εργαζομένου με κυλιόμενο ωράριο. Κατά την επεξεργασία των δεδομένων λήφθηκαν υπόψιν οι συνθήκες θερμοκρασίας, υγρασίας και πίεσης που καταγράφηκαν από την καταγραφική συσκευή. Τα αποτελέσματα ανάδειξαν ότι το μετρό έχει την μεγαλύτερη συγκέντρωση μικροσωματιδίων σε σύγκριση με τα λεωφορεία και της διαδρομές ως πεζός και ότι τα λεωφορεία είχαν την μικρότερη συγκέντρωση του επιβάτη καθόλη την υπό μελέτη διαδρομή. Το καταγραφικό ήταν επίσης σε θέση να καταγράψει φαινόμενα που καταγράφουν ραγδαία αυξομείωση της συγκέντρωσης κατά την διάρκεια του μετρό (τα ρεύματα αέρα που δημιουργούν οι συρμοί, ο παράγοντας της ηλικίας των συρμών κ.ο.κ.). Στην συνέχεια έγινε μια σύγκριση των δεδομένων που συλλέχθηκαν στα προάστια και στο κέντρο. Το καταγραφικό επίσης κατάφερε να καταγράψει την επιρροή που έχουν τα αυτοκίνητα στην συγκέντρωση των μικροσωματιδίων. Τέλος τα δεδομένα από το καταγραφικό χαμηλού κόστους ήταν σε θέση να αναδείξει την αξία που έχει η κινητικότητα των επιβατών σε κάθε στάση παρά η αυξομείωση των συνολικών επιβατών που έχει το κάθε βαγόνι, και ότι ακόμα και αν το σύνολο δεν αυξήθηκε αν η κίνηση ήταν μεγάλη επηρεάζει σημαντικά την συγκέντρωση των μικροσωματιδίων.

## Λέξεις – κλειδιά

Αέρια ρύπανση, ποιότητα αέρα, χαμηλού κόστους καταγραφικά, συλλογή πληροφοριών, επεξεργασία πληροφοριών, καταγραφή ρύπανσης, υγεία, μέσα μαζικής μεταφοράς, PurpleAir.

## Abstract

In recent years, where Air Pollution issues are continuously growing and are receiving more attention from both worldwide health and political organisations, the issue of collecting data sustainably and efficiently for the observation and treatment of Air Pollution has been arose. A multitude of papers and studies have been conducted that dig further on the technical and economical aspects of data collecting and Air Quality monitoring with Low-Cost sensors showcasing a promising solution. Low-Cost sensors are called to solve the problem of portability, accessibility and budget friendly option for monitoring of Air Quality with a seemingly minor loss on reliability and precision.

In this thesis the goal is to showcase, through a real-case scenario study, the capabilities of low-cost sensors as well as to pinpoint what are the drawbacks of using such devices. To achieve such goal the thesis was separated in two individual parts, the first part was the calibration and comparison of the Low-Cost sensor to a reference instrument of high accuracy over observatory "open field" conditions and the second part, where the sensor was used to monitor a route from a suburb area of Athens, Varkiza, to a central area of Athens, Aigaleo, through the use of public transportation and more in specific public buses and metro. The studied pollutant was particulate matters of sizes of 2.5. The thesis studied the mass concentration of particulate matter within the air (μm/m3) as well the value of the particular matter (PM) concentration in AQI (Air Quality Index). The sequence in which the monitoring took place was modelled in such way of recreating the weekly routine of a student resident or a full time working resident, simulating the average exposure of a public transportation user. In the phase of processing data for the formation of graphs and conclusions temperature, humidity and pressure were taken into consideration, provided by the Low-Cost sensor used for the monitoring of PM. The results showcase that the metro station has the highest concentration of PM in comparison of public buses and walking routes and public buses have the lowest exposure to the passengers of PMs. The Low-Cost sensor also provided data for tracking phenomenons of intense production/concentration of PM in the air, while in the metro subway (the air created during the slowing down of a metro wagon etc.). Furthermore a comparison of the concentration of PM was showcased in the suburb area (Varkiza) and central area (Aigaleo) of Athens and once again the Low-Cost sensor was able to track down the correlation between the car activity and phenomenons of PM concentration intense increase. Finally during the monitoring sessions and through the graphs provided from the data collected it seems that the density of passenger play minor role in the increase of PM concentration and instead a major factor is the intensity of the activity of the passengers (the amount of passengers boarding and disembarking the wagon), even if the total amount of passengers is relatively low.



## Keywords

Air Pollution, Air Quality, Low-Cost Sensors, Data collection, Data management, Air Pollution monitoring, Health, Public Transportation, PurpleAir.

## Περιεχόμενα

**Αλφαβητικό Ευρετήριο**

IEEE: The Institute for Electrical and Electronics Engineers

# INTRODUCTION

This thesis is studying the possible value of a low cost sensor of Purple Air can offer in a proper investigation of the Air Quality of an average student's route within the centre of Athens and more specifically within the Metro system of Athens. After an evaluation of the sensor, there will be a study of a sample gathered of the route and the presentation of the results of the monitored Air Quality levels from the Purple Air device.

## Subject of the Thesis

The subject of this thesis is to delve deeper into the possible use of low cost sensors considering their "imperfections" to showcase a validated case study of Pollution Monitoring in Public Transportation and to further investigate future usages these sensors may offer in the subject of data collection of Air Pollution and Air Quality.

## Goal and Purpose

The purpose of this thesis is to showcase the true potential of low cost sensors in data collection of Air Pollution monitoring and the goal is to further understand the limitations and the workarounds through an empirical study of these Low Cost sensors.

## Methodology

For the completion of the purpose of this thesis, the methodology that was followed was to first evaluate the reliability and the accuracy of the sensors compared to and up to standards sensor as well as the repeatability of their performance compared to the same sensor (comparison of data collected from identical copies of the same device). Next step was to collect data from the route of study and evaluate the data collected from that route.

## Innovation

The innovation in this thesis is the visualisation of the concentration of Air Quality within the Attica Metro Subway with the use of a low-cost sensor.

## Structure

The structure of this thesis is based on Chapter and Subchapters.

# 1 Chapter 1$^{o}$ : Introduction to Air pollution.

Within the past few years a subject that started picking up awareness is the issue of Air Pollution and its influence on the Environment. Environmental degradation and Pollution has shown to be a consistent subject of debate at a high political state and showcases the severity it holds, since such issue has been proven to affect the society, the economical state of a country as well as the worldwide quality of life.

Since the beginning of the century all over the world many countries faced severe damages from natural disasters and environmental phenomenons that had a direct link to Environmental Pollution and more specifically Air Pollution. Some of those issues were the photochemical fog that threatened many capitals throughout central Europe [1] and US[2] as well as China[3], the Ozone layer depletion, the raise of worldwide temperature and many natural disasters that are caused indirectly by those issues like the increasing rate of ice melting on the Antarctic Peninsula[4].

As an emergency reaction to all of the above many countries decided on an emergency call on monitoring and maintaining their environmental imprints with ultimate goal to gradually decrease them to the ideal zero-emission policy.

Some of the most important monitoring steps that countries have agreed upon is the monitoring of their Air Pollutants and Air Pollutant Emissions, their garbage wastes as well as their toxic and nuclear wastes produced by energy and heavy industries.

The subject of this thesis is to delve deeper into the subject of monitoring of Air Pollution and Air Pollutants as well as suggesting and evaluating alternative solutions on means of monitoring.

## 1.1 Air pollution and effects on health and life quality.

Air is considered Polluted if living beings that come in contact with it have a direct or indirect negative effect on their health[5]. Air Pollution existed before the human activity took place, but most ecosystem do have a well-thought sophisticated system of maintaining the quality of Air at the highest possible. It is important to make the distinction between different categories of Air Pollutants on their effects and on what group of living beings it affects the most, as well as what's their impact individually to humans specifically, directly or indirectly.

*Toxic Air Pollutants*, are pollutants that have a direct negative effect on our health in the long-term or even in some cases or under specific scenarios in the short-term. Some of them have a more toxic nature towards animals and humans some have a more toxic effect on plants and soil. Some of those toxic Pollutants are the CO, $NO_x$, $O_3$, $SO_3$, $PM_{2.5}$ etc.

*Greenhouse Gases* are also Air Pollutants but they mostly influence the Greenhouse effect which affects our ecosystem and has caused many indirect issues to specific groups of people, but mostly on animals and plants. Some of the toxic Air Pollutants are also part of the Greenhouse Gases category but there are also some Greenhouse Gases like $CO_2$ that have little to no negative impact to our health directly.

Most of the issues that Air Pollutants are causing directly to our health is the fact that they significantly worsen existing breathing and lung diseases like Asthma, as well as greatly effecting possible cancer types. Furthermore Air Pollution exposure has been directly connected with many heart issues like heart failures and heart attack episodes. Finally many of the Air Pollutants are known to cause many irritations on the eyes and the skin.

## 1.2 Introduction to Air Pollutants.

Air Pollutants are first of all categorized by their nature in the atmosphere, more specifically we divide Air Pollutants between primary and secondary[6].

Primary are the Air Pollutants that are emitted from the source directly to the atmosphere and they have a relatively more simplistic nature. Some of them are the Particular Matter (PM), CO, $SO_x$ etc.

Secondary Air Pollutants are Pollutants that require a chemical reaction to be formed and they have a more complex nature due to the more complex formations they have. Due to the lack of understanding towards their formations it is harder to fight them and control them. Some of them are $O_3$, peroxy nitrates (PAN), Photocemical oxidants etc.

### 1.2.1 Carbon Dioxide ($CO_2$)

Carbon Dioxide is a Gas that was naturally on the atmosphere. It is produced mostly as a product of any combustion reaction and it is created during the breathing process by most of living beings (plants included) [7]. Carbon Dioxide is a Primary Air Pollutant that is non toxic to humans nor animal and plants, it is considered as an Air Pollutant mostly because it is the main Greenhouse Gas and it is the one Air Pollutant that it is impossible to minimize its production to zero. The concentration of $CO_2$ has a lot of significance because it is an easy way to showcase the human imprint and because it is also one of the relatively easy Air Pollutants to maintain at lower levels.

### 1.2.2 Carbon Monoxide (CO)

Carbon Monoxide similarly to Carbon Dioxide is created by chemical reaction but Carbon Monoxide is produced by incomplete chemical reactions due to lack of Oxygen. Carbon Monoxide is significantly toxic and can cause poisoning in high concentrations. It is mostly produced by fossil fuel combustion engines, a tiny amount is also produced by numerous living organism but not in a notable amount. Carbon Monoxide is particularly dangerous because of the combination of its toxicity and its untraceable nature, it is colourless, tasteless and odorless [7]. Carbon Monoxide also has a notable contribution to the Greenhouse Effect as well as the production of $O_3$ [8].

### 1.2.3 Nitrogen Oxides ($NO_X$)

Nitrogen Oxides consists of multiple different forms of Nitrogen and Oxygen which most of them are poisonous, some of the more common ones are the Nitric Oxide (NO), Nitrogen Dioxide ($NO_2$), Nitrous Oxide ($N_2O$), Nitrogen Trioxide ($NO_3$), Dinitrogen Dioxide ($N_2O_2$) and Oxatetrazole ($N_4O$).

Nitrogen Oxides are mostly created due to combustion of fossil fuels and even though every Nitrogen Oxide has different effects and target groups, for the most part they all have some poisonous effects at high concentrations and they all do damage the soil and the plants. They also contribute to the formation of $O_3$ [8].

### 1.2.4 Sulphur Dioxide ($SO_2$)

Sulphur Dioxide is one of the Pollutants that have little direct effect on the environmental issues, but because it strongly damages the flora as well as the animals and humans. Sulphur Dioxide is also one of the Pollutants that are seen more commonly in nature. Sulphur Dioxide is commonly observed at dangerous amounts during volcano eruptions and in some cases there is a limited amount of emissions from inactive volcanos. Sulphur Dioxide is also produced by human activity, mostly by the burning of sulphur-bearing fossil fuels as well as copper extractions [8].

### 1.2.5 Ozone ($O_3$)

Ozone is one of the most complex Air Pollutants because it requires really specific and conditions for its formation. Ozone in ground level is significantly harmful for both the environment and health. Ozone requires a set of Air Pollutants and high concentration of sunlight, some of the Pollutants that are greatly contributing on Ozone formation is $NO_X$ and VOC, other pollutants contribute too but in a lesser extend. Ozone is particularly toxic for humans but most importantly it is extremely toxic for flora and in specific vegetation [8]. The reason Ozone is complex to treat is because it is a Secondary Air Pollutant which we cannot directly decrease its concentration instead we must decrease possible Pollutants that can be contributing in forming Ozone.

Fortunately Ozone requires a constant amount of UV rays for the Ozone formation to take place, which means that for Ozone to be formed constant sunlight is required and thus countries with inconsistent and/or cold weather are relatively safe from ground level Ozone emissions.

### 1.2.6 Hydrocarbons (CH)

Hydrocarbons are different forms of Carbon and Hydrogen combinations, some of them are Propane ($C_3H_8$), Methane ($CH_4$), Ethane ($C_2H_6$) etc. Some of the Hydrocarbons have significant contribution on the Greenhouse Effect but mostly they were contributing at the creation of VOCs which furthermore created issues like Ozone Layer Depletion and Urban Smog, which both issues greatly concerned many governments. Hydrocarbons are also considered to contribute to Sea Pollution as well. Hydrocarbons are found naturally in the atmosphere but human activity has increased their production, mostly through livestock activity and agriculture [9].

### 1.2.7 Particulate matters ($PM_1$, $PM_{2.5}$, $PM_{10}$)

Particulate matters have no specific chemical structure, instead it is a variety of matters that showcase a similar effect and similar characteristics. The main way we categorise them is by their size with a number next to the PM indicating their size, for example when we are referring to $PM_{2.5}$ we are talking for particles of 2.5μm. Due to the somewhat complex nature that PM can have we can't pinpoint exactly their effect in the environment since in some cases some PM can be harmless, in some cases the PM can even be consisted of heavy metals, which they are extremely harmful to soil and living beings [10]. PM are harmful for humans and they have strong correlation with lung cancers and many other breathing issues. PM can also be poisonous and toxic depending on their nature and initial formation, usually PM concentrations from heavy industry is considered to be toxic or even hazardous [11]. PM are created from combustion of fossil fuel but most importantly from fires and industrial activity.

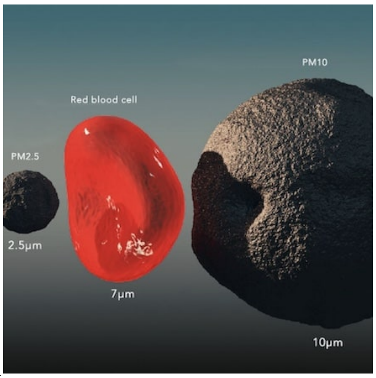


**Illustration 1: Visual represantation of the size of PM2.5**

### 1.2.8 Volatile Organic Compounds (VOC)

Volatile Organic Compounds are some of those Air Pollutants that are not found naturally in the atmosphere. They are created through chemical processes and they were used in the early 90s for various chemical products [9]. Even though they can be harmful to humans the main danger they oppose is their complex chemical structure that can cause a set of reactions to form various different Air Pollutants. Most importantly VOCs were known to be the main cause of the Ozone reaction in the Ozone Layer furthermore causing Depletion of Ozone on many places on Ozone Layer. There was a strong movement towards the banning of most VOC, thus VOCs has been replaced as refrigerants and greatly decreased over the years.

### 1.2.9 Lead (PB)

Lead was a highly toxic element in many high-performance fuels. It was banned from commercial fuels during the 90s due to its low necessity, high toxicity and easy replaceability. It is still used sometime in aircraft gasoline, in metal industry (smelting) and oil and gas extraction. Lead has been connected to many issues and effects on children, like learning disabilities due to lead exposure as well as lead poisoning [12]. Even though Lead has been greatly decreased since the nineties, it is still strongly observed with concern for any possible increase on its emissions.

## 1.3 Urban air pollution (/Urban Heat Island)

Urban Pollution is mostly referred the Pollution inside cities and on suburb areas of cities, with urban European areas holding 83% of the $PM_{2.5}$ concentration [13]. Overall the main Pollutants in most countries usually are the industrial sector and the transportation sector (including both commercial and private use of transportation means), cities and urban areas tend to have the highest concentration of transportation activity [14].

According to the above in cities it is highly likely that the overall emission productivity and thus the emission concentration will be located to capital city or high-density cities. On top of that an effect called Urban Heat Island adds up to the long-term situation of urban pollution and its effect on its residents.

Urban Heat Island is an effect caused by the highly concentrated activities that have thermal losses as effect, of which it creates a theoretical bubble around the city (sometimes consisting of suburb areas as well) of which the temperature is higher than the actual temperature of the geographical area the city is located in. The UHI effect worsen the conditions needed for the dispersion of many Air Pollutants as well it creates ideal conditions for the creation (/concentration) of many Air Pollutants (Ozone is the most notable one). UHI can be measured in two different categories, the atmospheric UHI (AUHI) effect, of which it calculates the air temperature difference caused by this effect, and the surface UHI (SUHI) effect which it calculates the overall increase temperature of surfaces within the city. The surface UHI effect is significant because based on the SUHI effect we can best calculate the night temperature difference that will be observed during night time [15].

Considering all of the above we can agree that in Urban areas the Air Pollution is not only increased but much more difficult to be decreased through natural means requiring dedicated solutions considering all these factors.

## 1.4 Environmental issues caused/reinforced by air pollution

Air Pollution was first look upon after some significant issues caused by Air Pollution. Some of the most significant were the photochemical smog and the ozone layer hole.

<u>Photochemical smog</u> was a phenomenon that strongly appeared in capital cities, it was an ultraviolet layer of smog that had the characteristic of absorbing a big amount of sunlight. This smog was created mostly by Volatile Organic Compound (VOC), Nitroden Oxide and Dioxide (NO & $NO_2$) and hydrocarbons. It also created ideal conditions for an increasing rate of Ozone ($O_3$) production due to the high solar energy absorbed in combination with NO and $NO_2$.[3] The Photochemical Smog was quite aggressive toward people with existing health issues and it was highly toxic due to the high concentration of $O_3$, it was also particularly unpleasant due to both the smell, the lack of sunlight as well as the effect it had on air causing a great discomfort. Photochemical Smog had also a significant effect on building and more crucially historic monuments since the chemicals released by the Photochemical Smog cause great corrosion.

The Ozone Layer Hole (or Ozone Layer Depletion) was a significant environmental concern in the start of the century. The Ozone Layer Depletion was the phenomenon of the natural Ozone Layer in the stratosphere showcasing a significant decrease over specific geographical places (most notably Antarctica). The Ozone Layer is a Layer of Ozone which filters and protects the earth from Ultraviolet radiation from sunlight. Due to the increased use of Chlorofluorocarbons which once they reach the Ozone Layer they have a tendency of degrading Ozone particle and causing a decrease of the Ozone concentration and thus the decrease in the Ozone Layer [9]. This had further effect on both the increase of heat in the world as well as the increased rate of health issues and most notably skin cancers. This phenomenon forced many countries to create a law system that would prevent future scenarios like that.

Greenhouse Effect is a natural phenomenon on which a group of gases are reflecting back to earth some of the solar beams as well as they garner some of the solar energy, maintaining the temperature of earth at a viable state [16]. The issue caused by human activity is that the production of these gases was rapidly increased and it increased their concentration in the air and thus the percentages of the beams reflected back to earth as well as the amount of solar energy they garner, as a result it causes an increase of temperature worldwide. Some of the most notable Greenhouse Gases is $CO_2$ and $CH_4$.

Acid Rain is the effect where $SO_X$ and $NO_X$ react with water and oxygen to form Sulfuric Acid and Nitric Acid, either through evaporation or strong winds these acids are spread to the soil and water on which they increase the toxicity of the soil and water making them incapable to host plant life and extremely harmful to existing plant and animals [17]. Acid Rain also makes rain water non drinkable and requires heavy processing to make it drinkable. Acid Rain has effects on buildings too and it can cause immeasurable damages to monuments and more specifically marble based constructions.

Permafrost is a thick underground layer which consists of many materials and chemical elements that is at a frost state and was first formed during the last ice age. The Permafrost is bellow approximately 25% of the total surface of our planet and is covered by a relatively thin layer of dirt which is called active layer and unlike permafrost its state changes up to the season. Permafrost layer as mentioned before is consisted of multiple materials and chemical elements of whom many are heavy metal elements, of which usually they are really toxic for the nearby ecosystem but due to the low temperature these heavy metals are either neutral to the ecosystem or in some cases even contributing. Due to the heat increase worldwide caused by the Greenhouse effect and many other factors, permafrost is steadily melting causing many morphological changes on the surface of the area as well as many natural distractions. Another side effect of this phenomenon of the melting of Permafrost is the release of a big quantity of heavy metals that were part of the frozen layer, causing irreversible damages to the ecosystem and more specifically to the plant capabilities of the soil [18].

## 1.5 Monitoring and evaluating Air Pollution and Air Quality

Historically due to the presence of some of the above issues a set of worldwide actions were taken. Some of them was the Clean Air Act in 1970 further creating the Environmental Protection Agency, in this legislation for the first time a set of standards is created setting limitations on the Air Pollutants Emissions the National Ambient Air Quality Standards (NAAQS) in which both the industry and mobile sources are required to decrease the emission levels. A later update of the Clean Air Act took place at 1977 adding additional preventing laws in the legislation. Another update took place in the 1990 with the Clean Air Act increasing the responsibility for reinforcing their authority accordingly to attain the updated standards that also took into consideration factors such as acid rain and toxic pollutants [51].

Similarly in 1997 the Kyoto protocol is first discussed, discussing for trading options that could reduce methodically the increase of Air Pollution, but also for the first time a set of Air Pollution monitoring goals is also suggested. At 2005 the protocol is agreed and signed from 192 parties [52].

Clean Air Act created for the first time a set of legislations that was based on the evaluation of the Air Quality and Kyoto's protocol set for the first time the first standards for Air Quality monitoring. Similarly 5 years prior to the discussion of Kyoto protocol the United Nations Framework Convention on Climate Change (UNFCCC) took place that for the first time discussed the subject of Greenhouse Effect and on how to control it [53]. To this day actions like that are taking place and all these legislations are getting tighter and more strict every year, the Paris agreement that was signed in 2016 sets the most strict standards for 2030 and a goal of reducing the world temperature by 1.5ºC.

For all these legislation a widely adapted evaluation system had to be used. The creation of many Air Quality indexes was followed with many regional indexes seeing use throughout. These indexes were created with two major things in mind, the public health and the environment, with some indexes focusing on the first one and some on the second one. With the passing of time only a handful of the indexes are still used to this day. Monitoring methods to this day are vague and as long as they deliver to the standards that each country has set it is used. There are some models that help into installing a proper monitoring station and there are some proven methods of collecting data through the use of maps and sensors.

## 1.6 Air Quality Indicators

Air Quality Indicators are scales of calculations of each Pollutant individually through an algorithm consisting of the toxicity and how harmful the studied Pollutant is considered and its concentration in a certain mass of Air.

Every country around the world has different criteria on evaluating the toxicity and harmfulness of each Pollutant, meaning that a variety of different Indexes were created based on the needs of each country or region.

Indexes overall are needed for the comprehensive reading of the Air Quality and the toxicity levels of the Air we are exposed to. Even though throughout the years many countries have created their own Indexes nowadays only a set of Indexes are still used. Some of the most influential Indexes that are not used anymore are Pollution Standards Index (PSI) that was created from United States Environmental Protection Agency (U.S.E.P.A.) due to a worrying increase of patients with health issues that were most likely caused by Air Pollution. It was designed to only calculate a certain set of Air Pollutants of which it consisted of CO, $NO_2$, $SO_2$, $O_3$ and the Total Suspended Particulate (TSP).

| PSI | Descriptor | General Health Effects |
|---|---|---|
| 0–50 | Good | None |
| 51–100 | Moderate | Few or none for the general population |
| 101–200 | Unhealthy | Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects. To stay indoors. |
| 201–300 | Very unhealthy | Health warnings of emergency conditions. The entire population is more likely to be affected. |
| 301+ | Hazardous | Health alert: everyone may experience more serious health effects |

**Table 1: Health scale of PSI Index**

## Air Quality Index (AQI)

Air Quality Index is one of the most prominent index due to its simplicity. AQI was created by U.S.E.P.A. based on their standards for Air Quality and their standards on what levels of each Pollutant is considered toxic or not and it replaced PSI since AQI was an overall more complete and accurate Index scale. In the case of AQI each Pollutant is evaluated individually through this equation [19]:

$$AQI = \frac{(AQI_{Hi}) - (AQI_{Lo})}{(Conc_{Hi}) - (Conc_{Lo})} \times \left((\mathbf{Conc_i}) - (Conc_{Lo})\right) + (AQI_{Lo})$$

Where:

$Conc_i$= Input concentration for a given pollutant
$Conc_{Lo}$= The concentration breakpoint that is less than or equal to $Conc_i$
$Conc_{Hi}$= The concentration breakpoint that is greater than or equal to $Conc_i$
$AQI_{Lo}$= The AQI value/breakpoint corresponding to $Conc_{Lo}$
$AQI_{Hi}$= The AQI value/breakpoint corresponding to $Conc_{Hi}$

**AQI and Concentration Breakpoints by Pollutant (2015)**

| Ozone | $Conc_{Lo}$ (PPM) | $Conc_{Hi}$ (PPM) | $AQI_{Lo}$ | $AQI_{Hi}$ |
|---|---|---|---|---|
| Good | 0.000 | 0.054 | 0 | 50 |
| Moderate | 0.055 | 0.070 | 51 | 100 |
| Unhealthy For Sensitive Groups | 0.071 | 0.085 | 101 | 150 |
| Unhealthy | 0.086 | 0.105 | 151 | 200 |
| Very Unhealthy | 0.106 | 0.200 | 201 | 300 |

AQI values >300 are calculated using 1-hour $O_3$ breakpoints.

| $PM_{2.5}$ | $Conc_{Lo}$ (μg/m$^3$) | $Conc_{Hi}$ (μg/m$^3$) | $AQI_{Lo}$ | $AQI_{Hi}$ |
|---|---|---|---|---|
| Good | 0.0 | 12.0 | 0 | 50 |
| Moderate | 12.1 | 35.4 | 51 | 100 |
| Unhealthy For Sensitive Groups | 35.5 | 55.4 | 101 | 150 |
| Unhealthy | 55.5 | 150.4 | 151 | 200 |
| Very Unhealthy | 150.5 | 250.4 | 201 | 300 |
| Hazardous | 250.5 | 500.4 | 301 | 500 |

| $PM_{10}$ | $Conc_{Lo}$ (μg/m$^3$) | $Conc_{Hi}$ (μg/m$^3$) | $AQI_{Lo}$ | $AQI_{Hi}$ |
|---|---|---|---|---|
| Good | 0 | 54 | 0 | 50 |
| Moderate | 55 | 154 | 51 | 100 |
| Unhealthy For Sensitive Groups | 155 | 254 | 101 | 150 |
| Unhealthy | 255 | 354 | 151 | 200 |
| Very Unhealthy | 355 | 424 | 201 | 300 |
| Hazardous | 425 | 604 | 301 | 500 |

**Table 2: AQI health scale for each pollutant individually.**

| AQI | Air Pollution Level | Health Implications | Cautionary Statement (for PM2.5) |
|---|---|---|---|
| 0 - 50 | Good | Air quality is considered satisfactory, and air pollution poses little or no risk | None |
| 51 -100 | Moderate | Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution. | Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion. |
| 101-150 | Unhealthy for Sensitive Groups | Members of sensitive groups may experience health effects. The general public is not likely to be affected. | Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion. |
| 151-200 | Unhealthy | Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects | Active children and adults, and people with respiratory disease, such as asthma, should avoid prolonged outdoor exertion; everyone else, especially children, should limit prolonged outdoor exertion |
| 201-300 | Very Unhealthy | Health warnings of emergency conditions. The entire population is more likely to be affected. | Active children and adults, and people with respiratory disease, such as asthma, should avoid all outdoor exertion; everyone else, especially children, should limit outdoor exertion. |
| 300+ | Hazardous | Health alert: everyone may experience more serious health effects | Everyone should avoid all outdoor exertion |

**Table 3: AQI health scale for the overall pollution.**

## Regional Pollution Index (RPI)

Regional Pollution Index (RPI) is originated by Australia, of which was used daily since the early 60s with a double daily report of the RPI results during the morning and the afternoon report having a complete coverage of the whole day with relatively high reliability.

Just like AQI, Regional Pollution Index is also calculated for every Pollutant individualy. The equation used for the calculation of RPI is the following [20]:

$$RPI = \frac{Pollution\ concentration}{Pollutant\ standard\ level\ or\ goal} \times 50$$

| RPI VALUE | RPI Level | Air Quality |
|---|---|---|
| 0 ≤ x RPI ≤ 25 | Low | Healthy |
| 26 ≤ x RPI ≤ 50 | Intermediate | Intermediate |
| 50 ≤ x RPI | High | Unhealthy (risky) |

**Table 4: Health scale of RPI Index.**

**European Regional Pollution Index (ERPI)**

European Regional Pollution Index (ERPI) is the European index based on the calculation of RPI but considering the European regulations on Air Pollutants and Air Quality.

Every Pollutant is also calculated individually in ERPI and the equation used is the following [21]:

$$ERPI = \frac{Pollution\ concentration}{Pollutant\ standard\ level\ or\ goal} \times 50$$

| Ατμοσφαιρικός Ρύπος | Οριακή Τιμή Συγκέντρωσης |
|---|---|
| $NO_2$ | Ωριαία τιμή: 200 μg/m$^3$ |
| $SO_2$ | Ωριαία τιμή: 350 μg/m$^3$ |
| CO | Μέγιστη μέση τιμή οκταώρου: 10 mg/m$^3$ |
| $O_3$ | Μέγιστη μέση τιμή οκταώρου: 120 μg/m$^3$ |
| $PM_{10}$ | Μέση ημερήσια τιμή : 50 μg/m$^3$ |

**Table 5: Table of pollutant limitation set by the European Union**

| Τιμή ERPI | Τάξη ERPI | Ταξινόμηση ποιότητας αέρα |
|---|---|---|
| 0 – 2 | **1** | Πολύ καλή |
| 2 – 21 | **2** | Καλή |
| 21 – 40 | **3** | Ικανοποιητική |
| 40 – 60 | **4** | Επαρκής |
| 60 – 79 | **5** | Κακή |
| ≥79 | **6** | Πολύ κακή |

**Table 6: ERPI scale**

# 2 Chapter 2$^o$: Air Pollution Monitoring Stations

Monitoring standards are mostly set by the regulations stated by the European Union for Europe and they require a set amount of reported days within a year as well as a set amount of “valid” data from the overall data collected, which means that the data collected needs to be of high accuracy. More specifically the monitoring stations require 90% of reporting data within a year and 75% of such being considered as valid data [22]. Thus the monitoring sensors that have been preferred over the years are systems that can deliver that needs reliability with minimal corrections and that can be reliability operating within the minimum given by the legislations.

**Illustration 2: An example of an enstablished and validated monitoring station.**

## 2.1 Traditional Monitoring Stations and Sensors

A traditional monitoring station usually consists of a complete system of sensors which they provide data for everything the station is responsible at monitoring. A traditional monitoring station usually consists of a data archiving server where the raw data from the sensors are stored and evaluated in the Air Quality Index of choice (in some cases multiple indexes are uses). The data archiving server in some station also does corrections and processing of the initial data. Finally there is a computer processing unit (CPU) of which draws the corrected data for the data archiving server which will do the final processing and conduction of the data and will post or print the final report of the monitoring station [23]. European commission also requires for the station to also report on the climatological and meteorological data provided from equally reliable equipment, meaning that usually monitoring stations are also equipped with wind sensors (direction and speed), solarimeters as well as temperature and humidity sensors [27].

Monitoring Stations are categorised by the different locations they are in and the type of environments they are set to monitor. The main three categories are [24]:

- Traffic stations, of which they are located nearby a traffic road.
- Industrial stations, of which they are located either close to a factory or a space of industrial activity or is located to position which it can monitor the total activity of an industrial area.
- Background stations, of which their location is supposed to be exposed to a quality of air that is representative of the average quality of air the average individual or vegetations is exposed to.

The stations can also be categorised over the type of area they are located onto by the density of residents of the area. These categories are [24]:

- Urban area, highly building dense area with lots of human activity.
- Suburban area, moderate or highly dense area with moderate human activity.
- Rural area, sparsely populated area with minimal human activity.

These different categories do play role in the later "correction" of the data which many high end devices usually provide alongside with a software. During the last ten years the main difference that made monitoring systems to increase their precision is mostly the option of considering possible errors and correcting possible imperfections in the architecture of the monitoring stations design, such as the limitation they have when they are responsible for a wide area, with the samplings giving accurate data for just a portion of that area. But with the given software technology we have and in combination of a multitude of GIS (Geological Information System) softwares the data are much more accurate to the area the station is responsible for, or monitoring stations are able to cover a much larger area with the same level of accuracy and reliability [23].

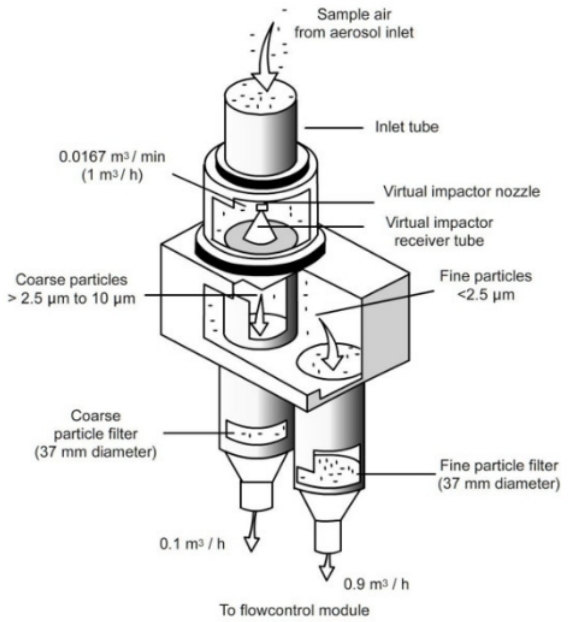



**Illustration 3: Detailed showcase of a common PM sensor.**

## 2.2 The state of technology of monitoring air pollution and air quality

Throughout the years a multitude of technologies have been used for the accurate monitoring of Air Pollution, but nowadays mostly three technologies are still used in commercial level, for reporting up to standards data. The main three technologies are optical laser sensors (non-dispersive infrared/ NDIR), the electrochemical sensors and finally to some extend for sound reactive pollutants there is the electroacoustic sensors (mostly used in $CO_2$). There are also some highly specialised sensors that are used under specific occasions and are meant to deliver above the standards data for specific scenarios (reliable data in extreme weather conditions, reliable monitoring of smaller scales than the set by the standards etc.), some of them are **biochemical sensors** (mostly used in hospitals and industrial sectors), **thermal sensors** (are used in experiments and science labs for scientific applications), **gas ionization sensors** (are used for the monitoring of mostly illegal or heavily constricted heavy metals in heavy industry) and finally catalytic sensors (which they were used for centuries in industries for the detection of flammable and explosive gasses, they are still used to this day but not for Air Pollution monitoring, since their accuracy is relatively low, but they are effective enough to prevent possible risks of fire or explosion within small spaces) [28].

The main characteristics that determine the usability and the reliability of a sensors are:

- ***Sensitivity.*** Sensitivity is the level of concentration of which the sensor will react and will respond with the corresponding indication. The lowest the level of the concentration needed for a proper response from the sensor the highest the sensitivity of the sensor. High sensitivity is required in most sensors used for the monitoring of AQ (Air Quality), as well as the monitoring of health-risking pollutants (like PB, CO etc.) in industrial sector or hospitals.
- ***Selectivity.*** Selectivity is a complex parameter of sensors, it defines how effective the sensor is at monitoring selectively the gas the sensor is programmed to monitor, due to the common characteristics of many pollutants some pollutants can cross-interfere, $NO_2$ for example can

interfere with an SO sensor, selectivity is also referred to as gas cross-interference. Gas cross-interference is a distinct issue in electrochemical sensors and a common way to determine the effectiveness of a sensor overall. Due to how common this issue is and how complex it can be to effectively increase the selectivity of a sensor, especially on low-cost sensors.

In the case of most sensors that are using a complimentary software system to correct their data, usually selectivity is the main characteristic that is "corrected" and the most significant one. Selectivity performance changes drastically in most sensors with the increase of temperature, humidity and atmospheric pressure.

- ***Stability/Consistency.*** Consistency of data collecting is the parameter of which the sensor under controlled conditions can provide consistently the same results over long periods of time. Stability heavily influences the reliability of the sensor.
- ***Responsiveness.*** Responsiveness is the time the sensor requires to respond on an instant difference of the concentration of the studied gas. Sensitivity is strongly affecting the responsiveness of the sensor, usually the responsiveness of a sensor is around a second and high-end sensors have responsiveness of just a couple of milliseconds.
- ***Monitoring scale.*** The monitoring scale is about the accuracy of the sensor and what's the minimum scale of concentration the sensor can respond to.
- ***Linearity.*** Linearity is referred to the ideal scenario where the increasing rate of the concentration of the studied gas meets the same responsiveness and accuracy of the sensor in which on a graph will de depicted as a straight line, thus the straightest the linearity of the sensor is, the better the sensor is responding and the more accurate is.
- ***Operating time.*** Operating time is either the time in which the sensor can monitor emissions, or in some cases it is referred to the time the sensor is operating properly without calibration. In the case of Low-Cost sensors usually operating time will refer to the amount of time the sensor will reliably operate without requiring calibration.
- ***(Longevity.*** Longevity is an additional characterization used on Low-Cost sensors, which it defines the lifespan that the sensor has before it completely fails. It is only used in Low-Cost sensors because due to their constructive nature they tend to have a limited lifespan.***)***

### 2.2.1 Optical Laser Technology

There are two different types of optical laser technologies.

The first one is the regular NDIR which consists of an Infrared LED a reflective tube and an optical detector and it is used for measuring CO, $CH_4$ and $CO_2$ concentrations. It is based on Beer Lambert Law and it is measuring the absorption of the infrared light by the molecules of the studied gas.

An infrared bulb is lighting within a reflective tube with the studied gas. The infrared light hits the end of the tube where a group of filters are set (reference filter and active filter), the light is absorbed by the particles of the gas throughout the tube and the group of sensors calculate the difference between the total light of the Infrared source and the amount of light that hits the sensors. Finally an optical detector receives the data from the two filters and conducts calculation and translates them into data [25].

This type of monitoring sensor is highly accurate, has a long term accuracy and requires minimal maintenance. The only drawback of this technology is that its high accuracy is only in certain gases and Air Pollutants as mentioned above.

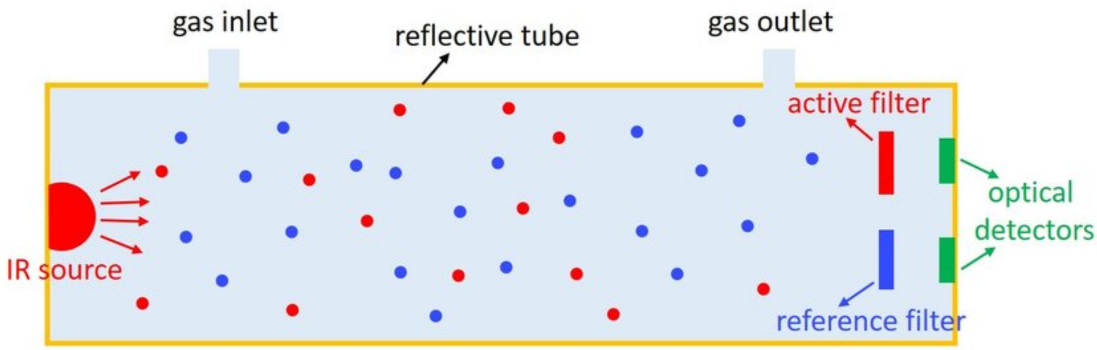



**Illustration 4: Visual representation of an NDIR gas sensor.**

The second technology is Light Scattering Technique, in which a light (usually infrared light) is pointing at a direction within a filter container (usually a 37mm filter) where the gas particles pass through, on an opposite direction of the light a photodetector is located and it detects the particles that are hit by the light and it translates them into data. The infrared light has no direct connection with the photodetector, as (illustration 5) showcases. In some cases these optical sensors also utilise a heat resistor to enhance the accuracy of the data and minimise possible faults of the photodetector [26]. The heat resistor is individually calculating particles that have developed high temperatures by being exposed at the light.

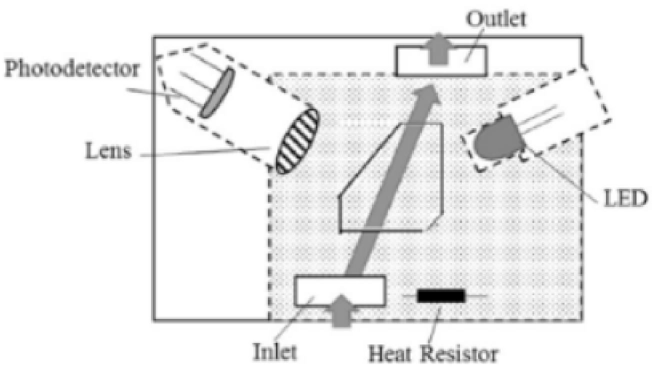



**Illustration 5: Visual representation of a Light Scattering IR sensor.**

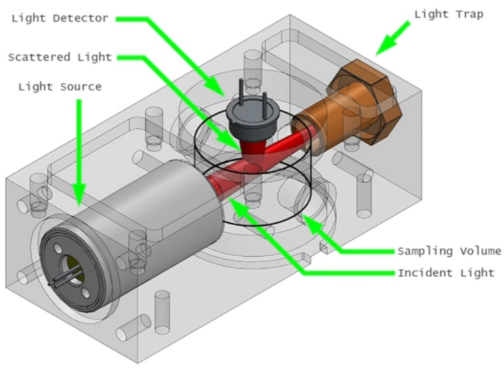



**Illustration 6: The main parts of an Infrared PM sensor.**

This type of sensors are usually used for the monitoring of $PM_x$ due to the high accuracy they provide on $PM_x$ monitoring. They are also used for other gases but with a lesser reliability of the data provided.

The pros of this technology are:

- The large price range in which you can find this sensors, depending on the operational needs and quality of data.

- They tend to maintain high performance without calibration for long periods of time.
- They are uneffected by sensor corrosion.
- They maintain the same performance under different sampling rates.
- They have no risk at metering flammable or explosive gases.
- The overall high accuracy with $PM_x$.
- When monitoring $PM_X$ they have no gas cross-interference effect.

The cons of this technology are:

- Expensive to repair.
- They retain high accuracy mostly on $PM_X$.
- Are strongly affected by the humidity levels and slightly by the drastic temperature changes.
- For metering other gases than $PM_X$ they have a strong gas cross-interference effect.
- They are limited at monitoring only infrared absorbing gases.
- Even though it is relatively small construction it can't get smaller.

### 2.2.2 Electro-Chemical reactors

Electrochemical reactors are the most common sensor types for traditional monitoring sensors and are used since 1970. Electrochemical sensors are mostly used to monitor toxic gases, some of them are $CO_2$, CO, $H_2S$, $SO_2$, $NH_3$, CL, HCN etc.

Electrochemical reactors usually consist of three electrodes, the sensing electrode on which the studied gas will interfere with, the reference electrode that has a stable voltage with the sensing electrode and finally there is the counter electrode (Illustration 7). The gas reacts to the sensing electrode causing it to increase or decrease the resistance between the sensing electrode and the stable electrode thus getting an electro motive difference which is depended by the amount of the studied gas that has reacted to the sensing electrode. This difference transmitted through the pins and it is then translated into data.

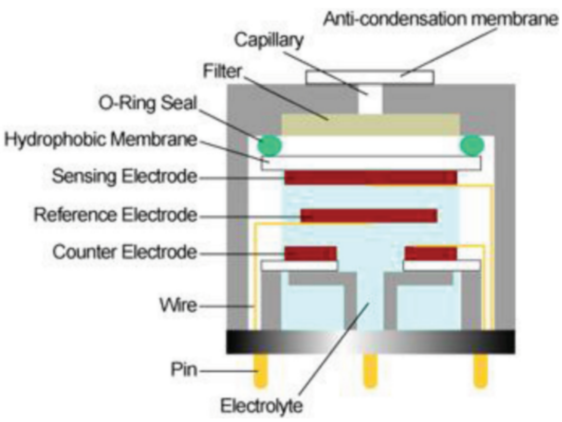



**Illustration 7: Visual representation of an Electro-Chemical sensor.**

This type of sensors are called potentiostatic cell sensors and they are some of the most common electrochemical sensors in the market. The sensor also consists of an Anti-condensation membrane where the air passes through and water and large particles are filtered, a capillary tube that leads to a filter that filters out the other gases (to prevent gas cross-interference effect), an O-Ring Seal that traps the sampled air for not connecting with the electrode's wires nor the electrolyte. A hydrophobic membrane repels all the remaining humidity of the sampled air and allows the gas to move to the sensing electrode. Electrolyte is filling the container where the three electrodes are set and wires are connecting the electrodes to the pins of the sensor.

The above example of an electrochemical sensor is one of the many structures used, fundamentally every design follow the same functionality the main difference comes to price and size of the sensor.

The pros of this technology are:

- With the appropriate filters these sensors can deliver reliable data aimed at high-end and highly specialised systems.
- They are capable of metering within ppm scale.
- They have high resistance of sensor corrosion.
- They have silent operation.
- They operate on low energy consumption.
- They have a linear performance.
- High reliability.

The cons of this technology are:

- They are sensitive to high humidity levels (and even damage the device).
- Extreme temperatures can highly affect their accuracy.
- They are significantly vulnerable to gas cross-interference effect (which can be decreased by the usage of expensive filters and membranes).
- Their lifespan can get critically affected if their filters and membranes get damaged.
- Their measuring can be affected by electromagnetic activity.

## 2.3 Models of Monitoring Air Pollutions (Maps and Models)

When it comes to studying a specific area of Air Pollution there are many parameters that needs to be considered and that greatly affect the study and thus it is highly likely that the equipment needed for the monitoring of such area is specialised or more targeted to the parameters that the area has. The primary purpose of those models are to calculate the approximate amount of the *primary* pollutants that are produced in the area on the air and to some extend calculate the amount of *secondary* pollutants that may are formed within the area (exclusively from the activity of the area). On top of that such models also are greatly effective on calculating the possible increase of pollutants concentrations in the area that originate from outside sources (transferred by the air or water).

For the development of a monitoring station a proper modelling study is required in order to ensure the smooth operation of the monitoring station. Such models take into consideration aspects such as [29]:

- The geological characteristics the area has,
- The climatological characteristics the area has,
- The meteorological characteristics the are has
- The meteorological characteristics the areas bordering with the studied area have,
- The activity the area has (busy roads, industrial etc.),
- The type of the station (ref chapter 2.1).

The most widespread and used models are:

1. **Dispersion Model,** this model is limited to just ground-level emission and are mostly used to estimate the concentration of pollutants around emissions sources (usually factories and industries, rarely for high traffic streets). They are taking into account meteorological data and is mostly use for policy assessment especially on Prevention of Significant Deterioration (PSD).
2. **Photocemical Model,** this model uses mathematical and numerical equations for estimating the inert and chemically reacting pollutants over large spatial scales. It is mostly used for regulatory or policy assessments.
3. **Receptor Modelling,** this model studies the chemical and physical characteristics of an area through simple observatory methods, it identifies the type of gases as well as estimating their individual concentration.
4. **Multi-Pollutant Modelling,** multi pollutant modelling is a vague approach of studying a group of pollutants all in once and it consists of many different sub-models. The most commonly used is the approach of Hart and coworkers [30] in which they are studying a group of Pollutant in once based on their health effects and they estimate a combination of the possible concentration as well as the health effects of Air Quality has on the area's residents.

These models are using a multitude of tools to provide an accurate estimation and further provide useful data for an area that is either not monitored or poorly monitored. Some of these tools either consists of sensors that are aimed at being used for a couple of days so the model can report an estimation within a relatively short period of time, or even a digital mapping system like Geographical Information Systems (GIS) technology to absorb data important for the conclusion of the final estimation.

### 2.3.1 Brief Introduction to GIS and Air Pollution

Geographical Information System technology has greatly contributed on Air Pollution modelling for both the monitoring station installation studies as well as prediction of possible high risk waves of Air Pollution and general Air Pollution spreading.

GIS is a map generating tool that takes into consideration a set of parameters to deliver a detailed map that provides a set of information based on the needs of the user. In the case of Air Pollution models GIS is providing information of Air Pollutants sources, detailed information for the direction of wind, temperature and humidity levels (that will affect the further concentration of the Air Pollutants) etc. Finally GIS technology is used to visualise the data provided from monitoring stations and to further process the data and provide a greater map, showcasing all the possible cross-interference of areas, transportation, wind and meteorological effects and outsider factors specific to the area (Illustration 8) [31].

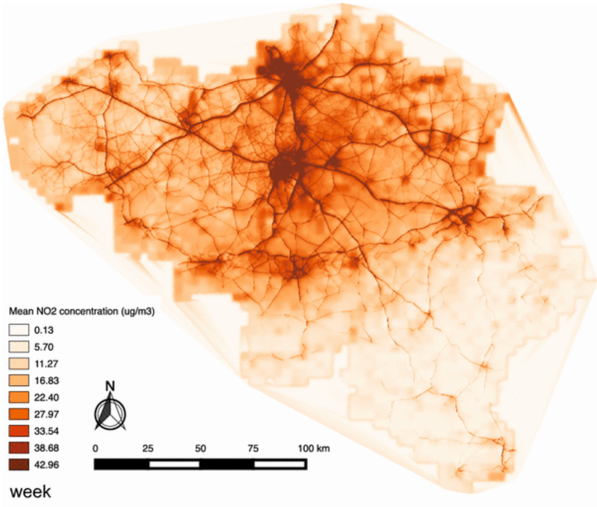



**Illustration 8: GIS generated Air Pollution Map.**

### 2.3.2 Introduction on the potential of Online Maps

Due to the high demand for applications and software like GIS many individual sensor manufacturers have started introducing Online Maps with data provided by their users or in some cases data found on the web. Companies like Google with great amounts of databases are also providing relatively detailed maps of similar applications. These maps even though are not as complex and inclusive as GIS generated maps they provide a decent amount of data, but most importantly they provide an accessible and comprehensive image of AQ for a regular user with no background in Air Pollution.

Some of these maps are:

- World's Air Pollution: Real Time Air Quality Index (WAQI). World's Air Pollution is an organisation based on Beijing China that provides two online sites offering data for AQ worldwide. The first site is WAQI.INFO (Illustrator 9), which is a visualised worldwide map offering data for AQ provided by individual users, from a variety of sensors. The organisation has set standards for the data accepted and used for the site, leading to every data source being relatively accurate, each source has a different level of reliability based on the equipment they use [32].

  The second site provided by World's Air Pollution is AQIN.INFO (Illustrator 10), which allow the user to have a more detailed look at each data provider individual. The interface they offer for AQIN.INFO allows the user with data about the humidity, temperature, pressure and wind as well as a reading in AQI scale for all the Air Pollutants the sensor monitors.

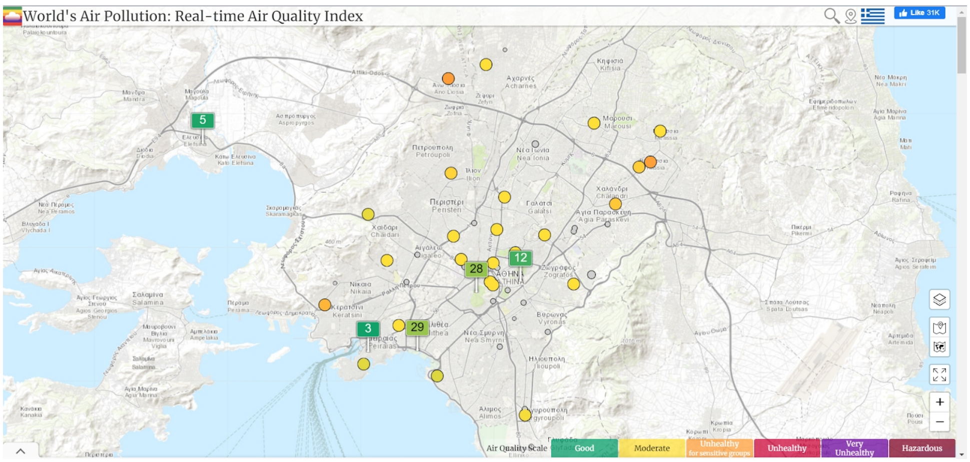



**Illustration 9: The Interface of World's Air Pollution online map.**

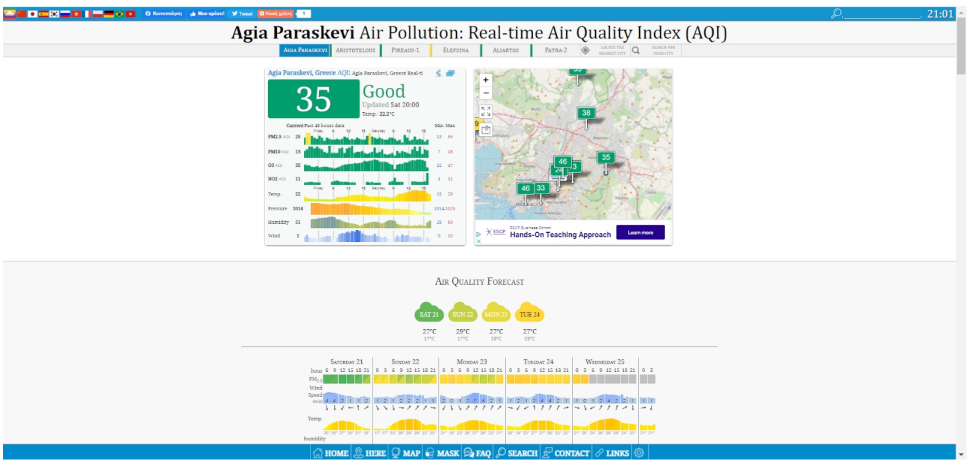



**Illustration 10: The Interface of World's Air Pollution online map**

- Purple Air Map. Purple Air is a low-cost sensor provider company that has developed a map showcasing the reported AQ levels provided by their devices that are used by regular consumers. Purple Air is specialised at Low-Cost sensors that monitor PM. The sensors provided by Purple Air provide internet connectivity, which will upload the data in the web and showcase its reports on the map of Purple Air (illustration 9). People can navigate through their area and see the amount of sensors being online and have access to their data as well as information about the sensor (if the sensor is located outdoors or indoors, the model of sensor, a visual graph of its data etc.). Purple Air map is using the colour patterns provided by AQI in order to visualise the AQ levels and also provides a short text of information for the current AQI levels each sensor is reporting (illustration 11) [33].

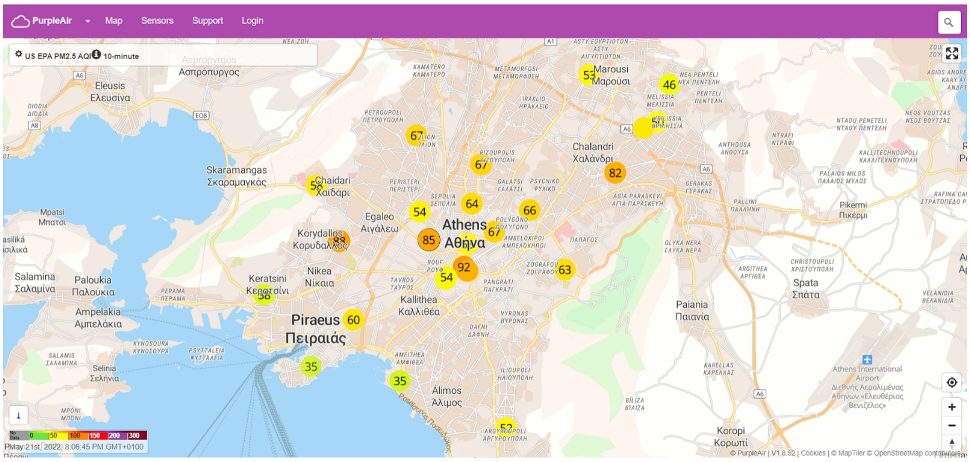



**Illustration 11: The Interface of Purple Air online map**

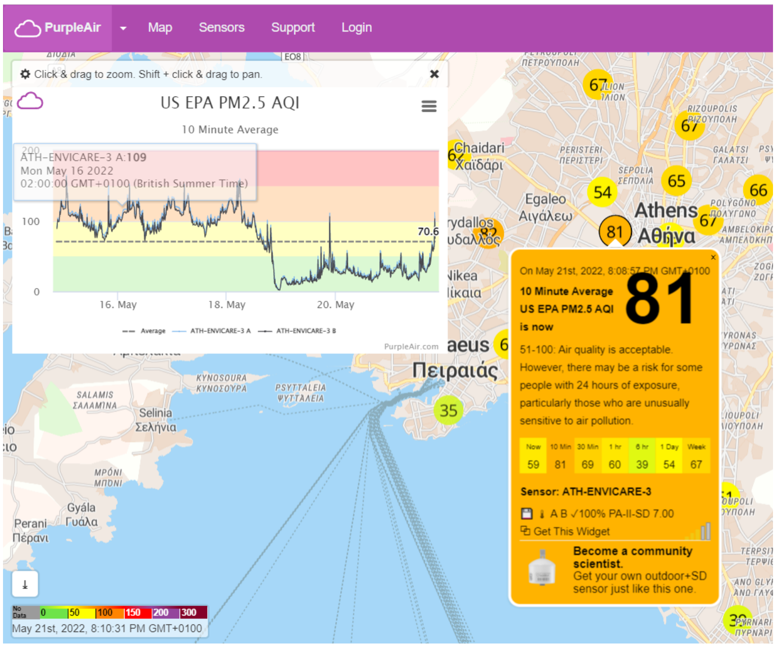



**Illustration 12: The Interface of Purple Air online map**

- Breezometer Map. Breezometer map is a highly sophisticated map application that collects data worldwide and through an algorithm it translates the data into spatial indication of AQ. The results the Breezometer offer are hard estimate with possible inaccurate data, but the aim of this map is to provide a well visualised map showcasing the levels of Air Pollution in every possible position. Breezometer provides the data in EAQI (European AQI) scale and it has option for other indexes as well (AQI, IQA, AQHI etc.), they have also developed their own index (BAQI) that is supposed to be an easier to read scale for the average user. Breezometer also offers Tools to calculate an approximate exposure of each individual by using their algorithm's data. Breezometer covers CO, $NO_2$, $SO_2$, $O_3$, $PM_{10}$ and $PM_{2.5}$ data and it recognise what's the dominant pollutant of an area, providing information about what target group is affected the most from that pollutant and what to be aware of.

  Breezometer is sophisticated map that offers a variety of information and strives at educating people for the importance and the dangers of AQ, through easy to use tools.

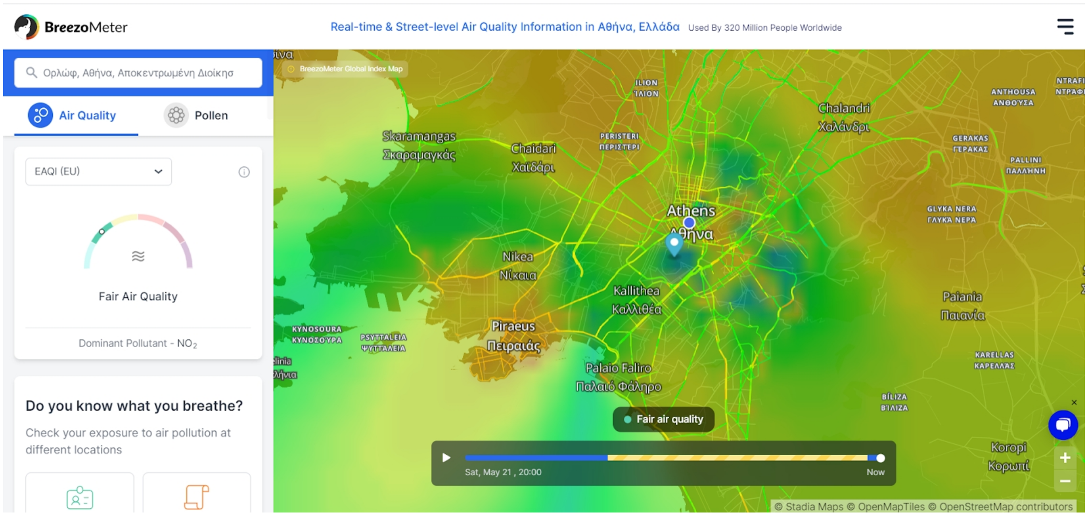



**Illustration 13: The Interface of Breezometer online map.**

## 2.4 Legal Framework and the law behind the methods and models

Since the Vienna Convention took place in 1969, a set of voluntary measures were agreed in order to decrease the CFC production in order to fight the Ozone Layer Depletion. This was the first time that a worldwide initiation took place into the creation a planning that would reduce the emissions of Air Pollutants. In 1987 the Montreal Protocol was signed and for the first time the initiation moved from voluntary measurements to a Legal Framework that had a target of reducing the Air Pollution and guaranteeing a better Air Quality. Ever since the Montreal Protocol was signed the increase of strictness on the initial Legal Framework is observed and every state is focusing more and more at regulating the most crucial pollutants. In the year of 2021 World Health Organisation (WHO) updated their Air Quality Guidelines (AQG) with a set of much stricter regulations on $PM_{2.5}$, $O_3$, $NO_2$, $SO_2$ and CO levels [34].

### 2.4.1 European Legislation

European's Union Legislation is aimed at setting levels of Air Quality that will indirectly improve the quality of fuels used for transportation, energy production and industrial activity. That been said the European's Union plan is also strict in ensuring a low amount of harmful substances emissions in the atmosphere as well as a high-quality atmosphere for a better quality life [13].

In order for EU to accomplish that they have set these policies into effect:

- Setting Ambient Air Quality standards decided by human health standards and environmental standards (table 7 and 8). Such standards are required to be complied by Member States throughout their territory and creating plans based on EU's standards.
- Establishing the National Emission Ceiling Directive, which requires each Member State to set an Air Pollution control programme.
- Annual Plans of Emissions, from European Union, in energy production, industrial activity, vehicle activity and transportation of fuels and good.
- The Seventh Environmental Action Programme, which recognise a long-term goal that does not burden negatively any significant health issue caused by Air Pollution.
- Setting a number of validated air sampling methods and Air Pollution models of which Member States must adopt when reporting their National data.

**Table 1.1 Air quality standards for the protection of health, as given in the EU Ambient Air Quality Directives**

| Pollutant | Averaging period | Legal nature and concentration | Comments |
|---|---|---|---|
| $PM_{10}$ | 1 day | Limit value: 50 μg/m³ | Not to be exceeded on more than 35 days per year |
| | Calendar year | Limit value: 40 μg/m³ | |
| $PM_{2.5}$ | Calendar year | Limit value: 25 μg/m³ | |
| | | Exposure concentration obligation: 20 μg/m³ | Average exposure indicator (AEI) (a) in 2015 (2013-2015 average) |
| | | National exposure reduction target: 0-20 % reduction in exposure | AEI (a) in 2020, the percentage reduction depends on the initial AEI |
| $O_3$ | Maximum daily 8-hour mean | Target value: 120 μg/m³ | Not to be exceeded on more than 25 days/year, averaged over 3 years (b) |
| | | Long-term objective: 120 μg/m³ | |
| | 1 hour | Information threshold: 180 μg/m³ | |
| | | Alert threshold: 240 μg/m³ | |
| $NO_2$ | 1 hour | Limit value: 200 μg/m³ | Not to be exceeded on more than 18 hours per year |
| | | Alert threshold: 400 μg/m³ | To be measured over 3 consecutive hours over 100 km² or an entire zone |
| | Calendar year | Limit value: 40 μg/m³ | |
| BaP | Calendar year | Target value: 1 ng/m³ | Measured as content in $PM_{10}$ |
| $SO_2$ | 1 hour | Limit value: 350 μg/m³ | Not to be exceeded on more than 24 hours per year |
| | | Alert threshold: 500 μg/m³ | To be measured over 3 consecutive hours over 100 km² or an entire zone |
| | 1 day | Limit value: 125 μg/m³ | Not to be exceeded on more than 3 days per year |
| CO | Maximum daily 8-hour mean | Limit value: 10 mg/m³ | |
| $C_6H_6$ | Calendar year | Limit value: 5 μg/m³ | |
| Pb | Calendar year | Limit value: 0.5 μg/m³ | Measured as content in $PM_{10}$ |
| As | Calendar year | Target value: 6 ng/m³ | Measured as content in $PM_{10}$ |
| Cd | Calendar year | Target value: 5 ng/m³ | Measured as content in $PM_{10}$ |
| Ni | Calendar year | Target value: 20 ng/m³ | Measured as content in $PM_{10}$ |

**Table 7: Table of European legislation.**

**Table 1.2 Air quality standards, for the protection of vegetation, as given in the EU Ambient Air Quality Directive and the Convention on Long-range Transboundary Air Pollution (CLRTAP)**

| Pollutant | Averaging period | Legal nature and concentration | Comments |
|---|---|---|---|
| $O_3$ | AOT40 (a) accumulated over May to July | Target value, 18 000 μg/m³·hours | Averaged over 5 years (b) |
| | | Long-term objective, 6 000 μg/m³·hours | |
| | AOT40 (a) accumulated over April to September | Critical level for the protection of forests: 10 000 μg/m³·hours | Defined by the CLRTAP |
| $NO_x$ | Calendar year | Vegetation critical level: 30 μg/m³ | |
| $SO_2$ | Winter | Vegetation critical level: 20 μg/m³ | 1 October to 31 March |
| | Calendar year | Vegetation critical level: 20 μg/m³ | |

**Table 8: Table of European legislation.**

### 2.4.2 Greek Legislation

Greek Legislation for the atmosphere quality is strongly associated with the guidelines set by the European Union, but they have also implemented some dedicated legislations around critical Air Pollutants such as PM and $O_3$, on toxic pollutants like Cadmium, Mercury and Nickel. Finally Greece has implemented an emergency regulation for the protection of the capital city, Athens, from Air Pollution [34].

Some of the publishes of these legislations are:

- European instruction 2008/50/EK, and KYA HΠ 14122/549/E103, ΦΕΚ 488B/30.3.11 for the regulations of atmosphere quality and cleaner air initiate.
- Instruction 2004/107/EK, and KYA HΠ 22306/1075/E103, ΦΕΚ 920B/8.6.07, for the guidelines of toxic emissions of Arsenic, Cadmium, Mercury, Nickel and Hydrocarbons.
- European instruction 2015/1480/EK, which updates the existing Greek legislation of monitoring methods and data collecting, as well as the models in which monitoring stations are installed upon.
- KYA 70601 National legislation planning of short-term treatment of PM emissions.
- K.Y.A 11824 National legislation on emergency guidelines on treatment of Air Pollution within the capital country Athens.

### 2.4.3 Worldwide (WHO) Legislation

Due to the nature of Air Pollution and the spreading effects Air Pollution tends to have, a worldwide effort on decrease of Air Pollution and a plan on securing the AQ at a respectable level is required. This responsibility has been taken by the World Health Organisation (WHO) alongside with the United Nations Environmental Programme and the United Nations Economic Commission

for Europe (UNECE), decide on global actions and global plannings on maintaining the Air Pollution at a stable level and reducing it in the long-term [13].
The main aim and focus of these organisation is to deliver a plan that takes into consideration mostly health and economic factors with strong emphasis at *transportation*, *energy production* and *agricultural activity.*

At last the latest update on worldwide legislation on Air Pollution was developed at WHO's Geneva Convention, with these guidelines [13]:

- Implementing solutions to reduce burning in any form,
- strengthening action to protect the most vulnerable populations, especially children,
- supporting cities to improve urban air quality,
- enhance joint action between the financial, health and environmental sectors to generate specific actions to improve air quality and mitigate climate change,
- continuing the joint effort for harmonised air pollution monitoring.

# 3 Chapter 3º : State of Art

Low-Cost sensors even though is a concept that is developed for years, due to many limitations and challenges the technology faces it only recently became an established industry's option, as a result the companies that produces validated Low-Cost sensors are just 10 with 6 of them being dedicated at PM monitoring sensors and 4 for various gases sensors [40].

## 3.1 State of Technology on Low-Cost sensors

Summary of applied outcomes of selected large low-cost sensor/monitor projects.

| Project name | Project period | Type of project | Applied outcomes | Operating network | Data access | Location |
|---|---|---|---|---|---|---|
| Government-funded projects | | | | | | |
| ARC- LP16 | 2016–2020 | Network development | Low cost sensor/monitor networks in several cities | In progress | | Australia |
| EuNetAir | 2012–2016 | Network on New Sensing Technologies | Development and evaluation of new sensors/monitors | n.a. | n.a. | Europe |
| EveryAware | 2011–2014 | Enhance Environmental Awareness | Games, and temporary personal monitoring campaign | n.a. | n.a. | Europe |
| CamMobSense | -2010 | Small scale deployment of sensor/monitor | | n.a. | n.a. | UK |
| Citi-Sense | 2012–2016 | Developing technological platforms for distributed monitoring | Multi-country sensor/monitor testing/monitoring network | Commercial products still in development including AQMesh | Data accessible through the Citizens Observatory Toolbox (COT) | Europe |
| Citi-Sense-MOB | 2013–2015 | establish mobile air quality measurements | exhaustive evaluation of low-cost platforms | n.a. | n.a. | Norway |
| OpenSense | 2010–2013<br>2014–2017 | investigating community-based sensing using wireless sensor/monitor network | Air pollution map based on mobile sensing platform. Phone-app for route planning | Currently available | Data accessible online over the project's Global Sensor Network (GNS) at http://data.opensense.ethz.ch/ | Switzerland |
| Community Observation Networks for Air (CONA) | 2015 ~ | Establishing low-cost sensor/monitor network | Monitors developed, network building | In progress | n.a. (provided report for participants) | New Zealand |
| PiMi Airbox | 2013–2016 | Indoor Air-quality Monitoring and Large Sensory Data Mining | Monitors developed, network testing | n.a. | n.a. | China |
| Smart Santander | 2010–2013 | applications and services for a smart city | Network of internet-based device including air quality | Still available but not very active | Data stored in a repository and can be accessed once authenticated and authorised by using a web service Interface | Europe |
| U.S. EPA CAIRSENSE | 2013–2016 | Evaluate long-term performance of sensors/monitors and network | Sensors/Monitors tested | n.a. | n.a. | US |
| U.S. EPA Village Green | 2013–2014<br>2015–2016<br>2017 ~ | Building autonomous monitoring systems | Units built and installed in limited number of sites | Online data for limited sites | Data accessible online | US |
| U.S. EPA grants Air Pollution Monitoring for Communities | 2016–2019 | Development and application of low-cost sensor/monitor network | Sensor/Monitor testing facility established | In progress | Data not accessible to the public yet project still ongoing | US |
| Commercial/crowd funded projects | | | | | | |
| AirVisual | 2015 ~ | Global network of air quality monitors | Map of fixed sites and app developed for all users | Network and monitors available | Data accessible by a free AirVisual app and website | Global (US-based) |
| Air Quality Egg | 2012 ~ | community-led air quality sensing network | Map and data function developed for all users | Network and monitors available | Data accessible through an air quality egg, phone app and a website | Global (US-based) |
| AirCasting (AirBeam monitor) | 2012~ | a platform for recording, mapping, and sharing health and environmental data using your smartphone | Map of data from AirBeam monitors and app developed for all users | Network and monitors available | Data accessible through an air beam, phone app and a website | US |
| SMARTCITIZEN | n.a. | a platform to generate participatory processes of people in the cities | Map of data from Smart Citizen monitors and app developed for all users | Network and monitors available | Data accessible through an Smart Citizen kit, phone app and a website | Europe |
| Purple Air | 2015 ~ | An air quality monitoring network built on a new generation of "Internet of Things" sensors/monitors | PurpleAir Map displays the points using the U.S. EPA Air Quality Index (AQI) scale | Network and monitors available | Must be a registered user to access data | Global (US-based) |

**Table 9: List of all the available PM sensors in the market.**

All of the listed sensors designed for PM monitoring are based on light-scattering technology (**2.2.1** & **2.2.2**). Depending on the sensor equipped to the device the sensor will either measure in volume or in individual particle counter [40].

Following is a list of the most widely used PM sensors with their most important technical aspect that showcase the state of the technology of the low-cost sensors [44].

| Manufacturer/ Model/Ref | Dimension (mm) and Weight(g) | Power Supply (V) | Working Current (mA) | Sleep Current (mA)/Low Power Operating Modalities | Laser Power Regulation | Response/Warm up Time (s) | Output Interface s/Level | Flux Type/Inlet-Outlet Position | Lifetime/Ageing Phenomena | Approximate Cost Range |
|---|---|---|---|---|---|---|---|---|---|---|
| Alphasense/OPC/N2/ [81,82,93,94,97,98,114,126, 127,129] | 64 × 75 × 60 /105 | 4.8–5.2 | 175 | 95 mA/laser at minimum power; fan off | Yes | 1.4/10 | SPI/- | FAN/opposite sides | NA | High |
| Honeywell/ HPMA115S0- XXX/ [67,122,129,130] | 43 × 3600 × 23.7/- | 5 | 80 | 20 mA | No | 6/- | UART/- | FAN | 10y | Mid |
| Inovafitness/SDS011/ [57,67,82,113] | 71 × 70 × 23/100 | 4.7–5.3 | 70 | 4 mA/laser and fan sleep/low power operating mode | Laser sleep | 1/10 | UART, PWM/3.3V | FAN/opposite side | Service life is up to 8000 h | Mid |
| Plantower/PMS 1003/ [80,131] | 65 × 42 × 23/- | 5–5.5 | 100 | <1 mA/adaptative acquisition frequency | No | 1–10/- | UART/3.3V | FAN/opposite side | MTTF ≥ 3 Year | Mid |
| Plantower/PMS 7003/ [55,81,82,124,129] | 48 × 37 × 12/- | 5–5.5 | 100 | <1 mA/adaptative acquisition frequency | On/off | 1–10/- | UART/3.3V | FAN/same side | MTTF ≥ 3 Year | Mid |
| Plantower/PMS A003/ [76,125] | 35 × 38 × 12/- | 5–5.5 | 100 | <1 mA/adaptative acquisition frequency | No | 1–10/- | UART/3.3V | FAN/same side | MTTF ≥ 3 Year | Mid |
| Sensirion/SPS30/ [118,132] | 40.6 × 40.6 × 12.2/26 | 4.5–5.5 | 80 | <50 µA/Sleep-Mode–Idle-Mode | NA | 1/30 | UART, I2C/- | FAN | >10 y/maximum long-term number concentration precision limit drift 20 to 1000 #/cm$^3$ ± 12.5 #/cm$^3$/year 1000 to 3000 #/cm$^3$ ± 1.25% m.v./year | High |
| Sharp/GP2Y1010AU0F/ [63,65,67,83,134–136] | 46 × 30 × 17.6/16 | 5 | 40 | No | EXT | 0.001/- | Analog/- | No/opposite side | Laser diode: 50% degradation/5 years | Low |
| Shinyei/PMS1/ [98,137] | 71.4 × 76.4 × 36.7/130 | 12 | 380 | NA | NA | NA | Ethernet/- | Heater | NA | NA |
| Shinyei/PPD20V/ [138,139] | 88 × 60 × 20/38 | 5 | 160 | NA | No | -/60 | PWM/- | Heater | 7y | NA |
| Shinyei/PPD42NJ/ [63,138,140] | 59 × 45 × 22/24 | 5 | 90 | NA | No | -/60 | PWM/- | Auto suction by a built-in heater resistor | 7y | NA |
| Shinyei/PPD60PV-T2/ [138,141] | 88 × 60 × 22/- | 5 | 140 | NA | No | -/60 | PWM/- | Heater | 3y | NA |
| Winsen/ZH03/ ZH03A/ZH03B/ [67,82,142] | 50 × 32.4 × 21/- | 5 | 120 | <10 mA | NA | -/45 | PWM/- | FAN/opposite site | 3y in the air | Mid |

**Table 10: List of the technical properties of the available PM sensors.**

Plantower /PMS 7003 and Plantower /PMS 1003 are the two sensors PurpleAir is using and we will use for this thesis.

The price range categories listed in the table above, are approximate and they also consider the overall budget the sensor requires to be able to function and record data. These sensors are just the monitoring chamber and the sensor but they have no processing power nor a direct control panel, meaning that almost all of the listed ones require an additional processing chip and most importantly power supply. The output interface of each sensor is offering different options of connectivity to different processing chips, meaning that some output interfaces have a limited connectivity option and some of them having a vast amount of connectivity options. The price range considers these options to the price range categorization. Two of the most used processing chip boards are Raspberry Pi and Arduino chip boards, with Arduino boards being at the intermediate cost range (30€ to 70€ ) and Raspberry Pi being at the high intermediate price range with some options entering the high cost range (60€ up to 120€ and can proceed further depending on the modifications added). Arduino is overall the most used and best performing option available and is cost efficient [45].

The overall lifetime of these sensors is around 3 years of use, which after that the sensor may experience some decrease in performance, either in terms of the sensitivity of the sensor or the accuracy. In the case of Innovafitness/SDS/011 the sensor has a lifespan of a year but it requires service to maintain its performance in instances that decreased performance is observed, after a year of use (8000 hours of use) service can increase its performance but the sensor will not perform as intended. Finally Sensirion claims that the sensor SPS 30 can have consistent performance for up to 10 years, if used under specific conditions throughout. No paper is available that can verify this claim nor any paper that reports drifting prior to the 10 years suggested by Sensirion. Similar is the situation of Honeywell/ HPMA 115S0-XXX. Finally Shinyei 2 options that can last up to 7 years.

Next technical aspect that is important to take into consideration is the power consumption and the power saving options the sensor may offer, this aspect is important because for studies that use the low-cost sensors at outdoor scenarios, that are used with power banks, thus the sensors would be ideal to be able to support independency with the use of a portable power bank solution if the overall energy consumption allows it. All the sensors with the exception of Shinyei /PMS1/ allow the usage of commercial power banks that have 5V output, PMS1 requires a heavy duty power bank that has 12V output. Most of the sensor do have a power consumption of 100 or lower mA, those that their consumption is equal to 100 or less mA, also do offer a sleep or low consumption mode that makes the sensor able to be used for long studies with just a single power bank. Alphasense OPC N2 has a realitvely low overall consumption of 175 mA but the sleep mode it offers is as high as 95 mA with the fan off use, meaning that it will has limited amount of activity, considering the fact that fan is required for the proper use of these sensors and it's rare for any scenario for the fan to be unused. Finally Shinyei PMS 1 has a high energy consumption that only allows it to be used for short periods of time with a power bank or it would require multiple power banks.

Finally the warm up time listed on each sensor is high enough for no particular issues occure during data collection, all of them offer a fast and responsive warm up time with the slowest being Honeywell HPMA 115S0 with 6/10 second and the Plantower PMS 7003/1003/A003 with warm up time of 1/10 second up to 1 second, but considering the power consumption of Plantower, the sensors could be used without unplugging them, if there is the option.

## 3.2 The value of Calibration

Considering the fact that low cost sensors by nature of the technical limitations have a lower accuracy and reliability on the data they can collect, calibration has played a major role on surpassing these limitations and delivering data close to reference instruments [46]. Calibration is low cost sensors can be achieved through numerous ways, but the most effective way since we are usually given access to its processing board is to make tests of gas controlled chambers to find the slope of the sensors and to further "correct" the calculation the processor of the sensor does to deliver a closer result to the reality [47]. In some cases some low-cost sensors do offer the option to calibrate the monitoring process on the sensor, which allows you to calibrate and further increase the accuracy of the sensor instead of correcting the incorrect measurements through an equation that considers the slope of the sensor.

Bellow for demonstration purposes a comparison between the performance of a low-cost PM sensor before and after calibration will be presented, the results were conducted from the paper "A new calibration system for low cost Sensor Network in Air Pollution monitoring" by Houxin Cui (a is prior and b after the calibration):

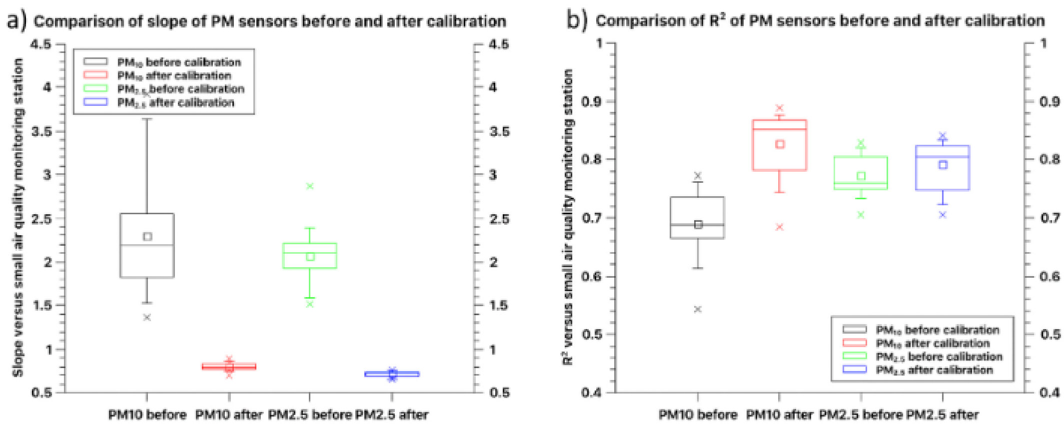



**Table 11: Example of a low-cost sensor, post and prior to calibration.**

## 3.3 People's Science and the possible contribution

People science is an initiate that allows organisations and researchers to withdraw data from the devices of individuals that want to actively contribute in the conduction of researches. This initiate was first introduced through IoT (Internet of Things) networks and was later on used by companies to base their products in such networks. PurpleAir for example has based their online map throughout an IoT data server that all the PurpleAir devices are uploading the data they have collected throughout Wi-Fi connection (if that is possible) and such data is used to furthermore have a visual depiction of Air Pollution and Air Quality throughout the world.

People's science has two major versions, one being the direct contribution of an individual, by buying dedicated devices that will contribute to the data collection [48] or indirect contribution, where individuals contribute data that their mobile phones have collected by agreeing on the data to be used for research use [49].

This data is usually collected to create mappings and charts of Air Pollution on areas that are covered by the collected data and to further collect data about the surrounding factors that may contribute to the levels of Pollution on the area or the possible impact it may have in the near future allowing not just a current depiction of the state of Air but also predictions for the near and sometime distant future.

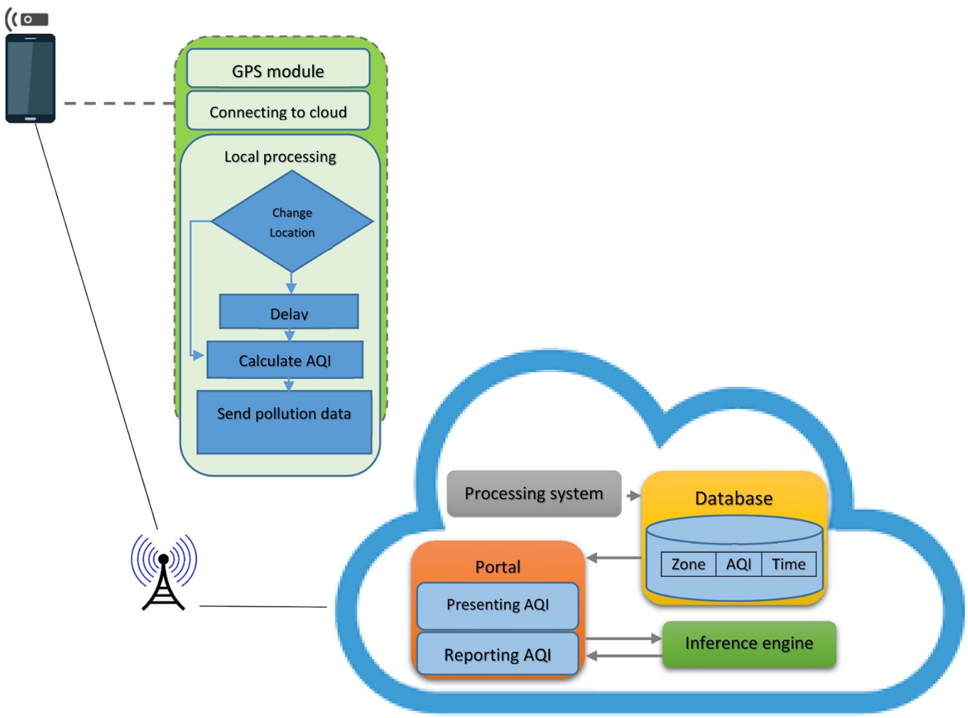



**Illustration 14: Visual showcase of the People's Science initiate.**

Low-Cost sensors are directly connected to this technology and all low-cost sensors are build with the use of an IoT server in mind. People's science has helped at rapidly increasing the information coverage of areas that were never monitored before.

For the Low-cost sensors the data obtained from people's science is used to develop new calibration methods, more accurate calibration processes and testify possible malfunctioning sensors.

# 4 Chapter 4º : Case Study on Calibration

The thesis was parted in two separate phases. The first phase is the Calibration and Evaluation of important characteristics of the sensor that is used in the second phase, Purple Air PA-SD-II. The second phase was the use of the Purple Air sensor for monitoring a route from a suburb area south of Athens, Varkiza, to the University of West Attica (UNIWA), located at Egaleo, through the use of public transportation.

In this chapter we will be introduced to the sensors used for the first phase and have a look at the installation where the sensors were set for the data collection.

## 4.1 Introduction on Purple Air PA-SD-II

Purple Air is a company based in Utah USA and they provide a set of Low-Cost IOT (internet of things) based sensors that are intended of indoor, outdoor and industrial use. Purple Air also provides an Online data map in which each sensor of Purple Air, when connected to a Wi-Fi, are uploading the data and are accessible by everyone around the world.

The specific device we used is the PA-SD-II, which offers the feature of additionally storing the data of the sensor to an SD card in csv (coma separated values) files that are recognisable by any spreadsheet software (Microsoft Excel, Libre Office Spreadsheet, Google Sheets etc.).

The sensors that this device is using are the PMS5003 and PMS1003, both using optical tracking technology and they are connected to ESP8266 chip which is responsible for the communication between the sensors and the Arduino microcontroller board that processes the data collected by the sensors. The PMS5003 and PMS1003 sensors are monitoring Particulate Matter of 0.3, 0.5, 1.0, 2.5, 5.0 and 10.0 μm and through a complex algorithm the data collected from measuring PM of that sizes calculate a final value of $PM_1$, $PM_{2.5}$ and $PM_{10}$ mass concentration in μg/m$^3$, they report data in two separate channels, **Channel A** and **Channel B,** each one corresponding to on of the two sensors. Finally the device offers an additional BME280 sensor that provides data for pressure, temperature and humidity levels [35].

The two sensors in Purple Air device provide two separate scales of the data they provide, the one is on μm/m$^3$ and the second one is an equivalent value on AQI scale. The device offers two separate reads on the AQI scale, the first one is CF and the second one is the atm, which we get one of each for each channel. The CF values are the initial calculation of the AQI values driven by the μm/m$^3$ readings of the sensor and the atm is the CF values but corrected in a way that considers open space factors. CF values are designed for indoor values and atm for outdoors.

Purple Air provide factory calibration on every single device with smoke chamber method [26] and reporting consistent results on further tests. Because of the construction of the sensor no further calibration is possible, the Arduino processing chip is not accessible and the device is reported to consistently maintain its performance for 3 years after the initial purchase.

The technical specs of the device are:

| Laser Particle Counters<br>Class 1 Laser. A Class 1 laser is safe under all conditions of normal use. | |
|---|---|
| Type | (2) PMS5003 |
| Range of measurement | 0.3, 0.5, 1.0, 2.5, 5.0, & 10 µm |
| Counting efficiency | 50% at 0.3µm & 98% at ≥0.5µm |
| Effective range (PM2.5 standard)* | 0 to 500 µg/m³ |
| Maximum range (PM2.5 standard)* | ≥1000 µg/m³ |
| Maximum consistency error (PM2.5 standard) | ±10% at 100 to 500µg/m³ & ±10µg/m³ at 0 to 100µg/m³ |
| Standard Volume | 0.1 Litre |
| Single response time | ≤1 second |
| Total response time | ≤10 seconds |

**Table 12: Technical specs of Purple Air PA-II-SD.**

| Power Supply | |
|---|---|
| Weight | 12.6 oz (357 g) |
| Input | 100-240V AC, 50/60Hz, 1.5A |
| Output | 5V USB Micro, 3A |
| Power supply length | AC side: 12 feet, DC side, 5 feet. |
| Weather resistance | IP68 |
| Plug type | 2 Pins, Type A (USA) |

| Pressure, Temperature, & Humidity Sensor | |
|---|---|
| Type | BME280 |
| Temperature range | -40°F to 185°F (-40°C to 85°C) |
| Pressure range | 300 to 1100 hPa |
| Humidity | Response time (τ63%): 1 s<br>Accuracy tolerance: ±3% RH<br>Hysteresis: ≤2% RH |

**Table 13: Technical specs of Purple Air PA-II-SD.**


**Illustration 15: Purple Air PA-II-SD from the side.**

**Illustration 16: Purple Air PA-II-SD from bellow.**

### 4.1.1 Past usage of Purple Air Devices for scientific purposes

Purple Air has been a popular choice amongst science community, thus a multitude of scientific papers have released an evaluation of the Purple Air device to reference instruments.

A research conducted by the Air Quality Performance Evaluation Center (AQ-SPEC) from South Coast, reported a high performance and a relatively high accuracy at monitoring $PM_{1.0}$ and $PM_{2.5}$ in three separate tests, a 5 minute test, a 1 hour test and finally a 24 hours test. The performance of $PM_{1.0}$ was reported at $R^2<0.93$ for the 5 minute test, $R^2<0.94$ for the 1 hour test and $R^2<0.98$ for the 24 hour test. The performance of $PM_{2.5}$ was reported at $R^2<90$ for the 5 minute test, $R^2<0.91$ for the 1 hour test and $R^2<0.96$ for the 24 hour test. Finally for performance of $PM_{10}$ was reported $R^2<0.42$

for the 5 minute test, $R^2$<0.45 for the 1 hour test and $R^2$<0.50 for the 24 hour test [36].

The conclusion AQ-SPEC concluded was that Purple Air PA has an overall high performance on monitoring PM1.0 and PM2.5 (with PM2.5 performing at average of R2=78-90%) but it has a lackluster performance in the monitoring of PM10.

The sensor that was used as a reference instrument for that evaluation test was the FEM (Federal Equivalent Method) BAM sensor from MetOne and the FEM GRIMM from Grimm - Environmental Dust Monitors.

Another research was conducted at Southhampton, England from Lance Wallace testing the data agreement between two optical sensors identical to the sensors used in the Purple Air device (PMS5003 and PMS1003) and the results were almost identical (Spearman Coefficient of 0.98). In the same paper a comparison of the data is made with the data of the background station that was located to a nearby school with results of data bias ranging from 1.15 to 1.22 [37].

## 4.2 Introduction on TSI DustTrak DRX

TSI DustTrak DRX Aerosol Monitor 8533 is a sensor measuring Particulate Matter with optical laser and light scattering technology. TSI DustTrak DRX is the main reference sensor for a calibration test which consists of a set of Low-Cost sensors (Purple Air).

TSI DustTrak DRX has the feature to both monitor the mass and size of Particulate Matter simultaneous and it can give an accurate reading for Particulate Matter of sizes $PM_{1.0}$, $PM_{2.5}$, $PM_{4.0}$, $PM_{10}$ and $PM_{TOTAL}$. The light scattering sensor used, has a 90º range and a range of 0.001 to 150 mg/m$^3$. The flow rate of the device is 3.0L/min [38].

The sensor has a tabletop control monitor (Illustration 17) and a power brick connected to the monitor.

The instrument consists of:

- The main monitor/control panel:


**Illustration 17: TSI main monitor.**

- The power brick supply (100 mW (20 dBm) @ 922 MHz 50 mW (17 dBm) @ 2.4 GHz):

**Illustration 18: TSI's power cable.**

- The sampling conductive Tube (1m):

**Illustration 19: TSI's sampling conductive tube.**

- Internal flow filter kit:

**Illustration 20: TSI's filters.**

- The 37mm air sample filter:

**Illustration 21: TSI's 37mm filter.**

- Operating software:

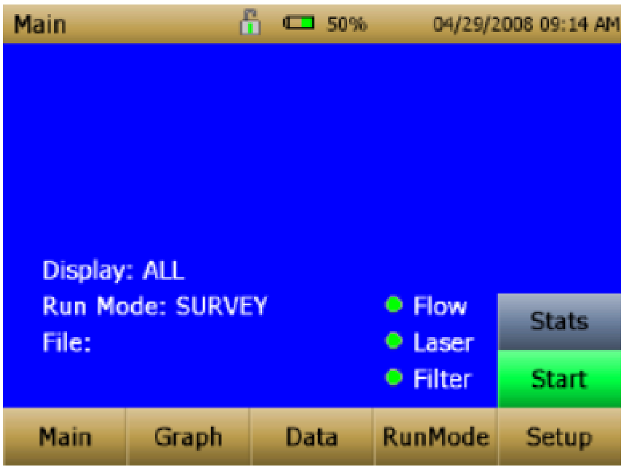



**Illustration 22: TSI's software interface.**

- Zeroing (Calibration) Filter:


**Illustration 23: TSI's Zeroing tube.**

Technical Specs of the device:

**Technical Specifications**

| | |
|---|---|
| Internal Battery Pack | 12 VDC 36 Ah |
| Battery Run-time | 24 to 40 hours (typical) |
| External Battery Pack | 12 VDC 100 Ah |
| Nominal Voltage | 12 volts |
| Indoor/Urban Range - w/ 2.1 dB dipole antenna | Up to 1500 feet (450 m) @ 922 MHz Up to 600 feet (180 m) @ 2.4 GHz |
| Outdoor RF line-of-sight range w/ 2.1dB antenna | Up to 7 mi (11 km) @ 922 MHz Up to 3 mi (5 km) @ 2.4 GHz |
| Outdoor RF line-of-sight range w/ high gain ant. | Up to 20 mi (32 km) @ 922 MHz Up to 10 mi (16 km) @ 2.4 GHz |
| Transmit Power Output | 100 mW (20 dBm) @ 922 MHz 50 mW (17 dBm) @ 2.4 GHz |
| Data Rate | 9600 bps |
| Dimensions (H x W x D) | US: 5.3 x 8.5 x 8.8 in. Metric: 13.5 x 21.6 x 22.4 cm |
| Weight | US: 3.9 lb. Metric: 1.6 kg / 4.5 lb. (2.0 kg) - 1 battery / 5.5 lb. (2.5 kg) - 2 batteries |

**Table 14: TSI's technical specs.**

## 4.3 Introduction on AQ Mesh

AQ Mesh will be used to compare the results of Purple Air devices to the AQ Mesh. AQ Mesh is a Low-Cost sensor that monitors a variety of Air Pollutants including Particulate Matter of sizes $PM_{1.0}$, $PM_{2.5}$, $PM_{4.0}$, $PM_{10}$ and $PM_{TOTAL}$. AQ Mesh uses a light-scattering optical particle counter semsor. In this study we will only use the data of PM. AQ Mesh is also equipped with a meteorological sensor measuring pressure, humidity levels, wind direction and temperature [39].

AQ Mesh provides factory calibration based on the industry standard FIDAS 200 for $PM_{2.5}$, $PM_{4.0}$ and $PM_{10}$.


**Illustration 24: AQ Mesh.**

The technical specifications of AQ Mesh are:

| | | | |
|---|---|---|---|
| **Parameters measured** | NO, $NO_2$, $O_3$, CO, SO2, pod temperature, atmospheric pressure, relative humidity, average noise, peak noise, particle count, PM1[#0] PM 2.5[#0], PM 10[#0] | | |
| **Measurement range** | **Parameter** | **Units of measurement** | **Range** |
| | NO | ppb or μg/m³ | 0 to 4,000 ppb |
| | $NO_2$ | ppb or μg/m³ | 0 to 4,000 ppb |
| | $NO_x$ | ppb or μg/m³ | 0 to 8,000 ppb |
| | $O_3$ | ppb or μg/m³ | 0 to 1,800 ppb |
| | CO | ppb or μg/m³ | 0 to 6,000 ppb |
| | SO2 | ppb or μg/m³ | 0 to 10,000 ppb |
| | Pod temperature | °C or °F | -20 to 100 °C or -4 to 212 °F |
| | Pressure | mb | 500 to 1500 mb |
| | Humidity | % | 0 to 100 %RH |
| | Noise[#5] | dB | 35 to 100 dB SPL |
| | Particle count | Particles/cm³ | 0.3 – 30 μm |
| | PM 1 | μg/m³ | 0 – 200 μg/ m³ |
| | PM 2.5 | μg/m³ | 0 – 500 μg/ m³ |
| | PM 10 | μg/m³ | 0 – 1,000 μg/ m³ |
| **Performance** | **Parameter** | **[#1]Limit of detection** | **[#2]Accuracy (in standard test conditions)** |
| | NO | < 5 ppb | ± 5 ppb |
| | $NO_2$ | < 10 ppb | ± 5 ppb |
| | CO | < 50 ppb | ± 5 ppb |
| | $O_3$ | < 5 ppb | ± 5 ppb |
| | SO2 | < 10 ppb | ± 5 ppb |
| | Pod temperature | 0.1 °C | ± 2 °C |
| | Pressure | 1mb | ± 5mb |
| | Humidity | 1%RH | ± 5 %RH |
| | Noise | 20 Hz to 20 kHz | +/- 1dB |
| **Sensor life** | 2 years | | |
| **Power options** | External 12V DC power option; Solar power pack; Mains power option; Rechargeable NiMH battery and charger option; Lithium metal batteries[#3]. Up to 2 years operation (depending on measurement strategy) | | |
| **Communications** | Raw data sent to remote server via wireless communications – data access contract required | | |
| **Physical** | Enclosure: Polyurethane moulded or ABS, protection IP65; Approx. size: L170xW220xH250mm (not inc. antenna 180mm); Weight: 2 – 2.7 Kg | | |
| **Environmental** | Temperature range: -20 to +40 °C [#4]Humidity range: 15 to 95% RH | | |
| **Mounting** | Various mounting accessories available – supplied with basic bracket and standoffs, other options available. | | |
| **Measurement period** | Variable, from 1 minute to 1 hour | | |
| **Server software** | Web browser based, processing of raw data to give reading, database storage on secure server, data access – tables, graphs, data download, multi-user access, password controlled, optional API data access | | |

**Table 15: AQ Mesh technical specs.**


**Illustration 25: The sensors of AQ Mesh.**

## 4.4 The Installation

The installation was located on the rooftop of the University of West Attica (UNIWA) with all the sensors being located within a range of 2m away. For the installation 12 PurpleAir devices were used, the AQMesh and the TSI DustTrak DRX as the reference instrument.

The PurpleAir devices were all installed on a wooden plank next to each other and they were connected with their power suppliers. All the PurpleAir devices were connected to the local Wi-Fi network with access only to stuff members of the UNIWA Sealab team and they were daily checked if they are on-line and transmitting properly.

**Illustration 26: Purple Air devices for the Calibration phase.**

**Illustration 27: Purple Air devices installed.**

**Illustration 28: Purple Air devices installed.**

AQMesh was also directly power by its power supply. AQMesh was located at height of about 2.5m for it to have enough space for sampling.

**Illustration 29: Purple Air and AQ Mesh devices installed.**

Finally TSI DustTrak DRX was protected within a plastic box to be protected from the weather, the box had an exit for the sampling tube to be open to the air for sampling.

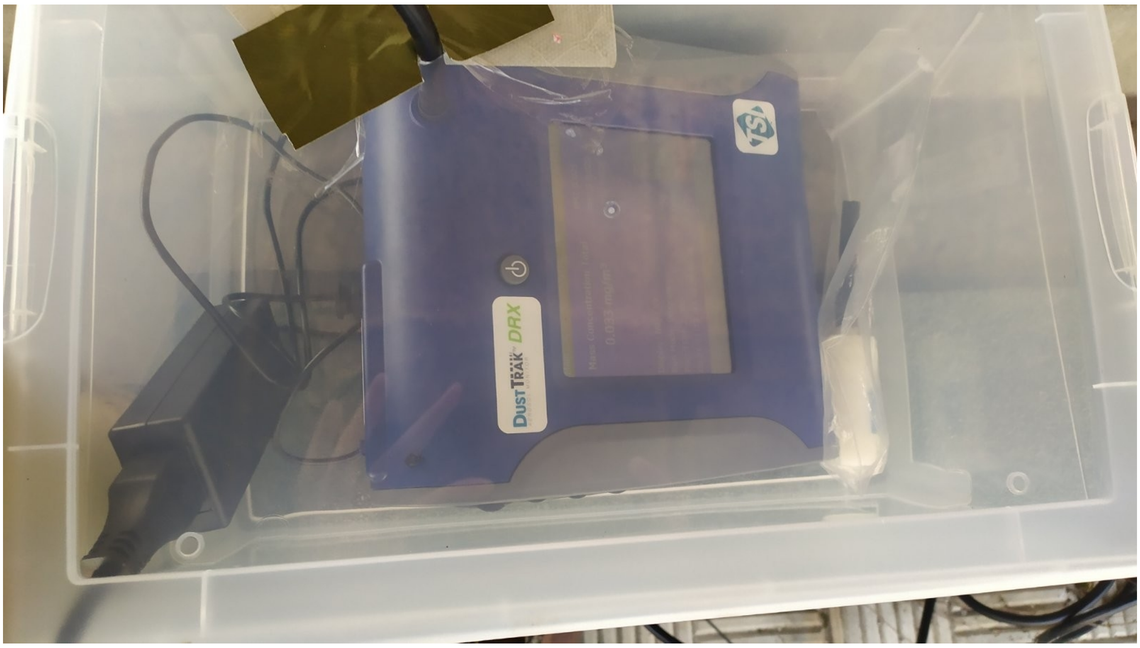



**Illustration 30: TSI DusTrax devices installed.**

The location of the installation is nearby at the end of Thivon avenue street near its connection with Petrou Ralli avenue. Both avenues that are nearby have a high traffic rate during the morning hours until late hours of afternoon with many activity from industrial and commercial vehicles. Near the area are also industrial units of Athenian Brewery and two shopping malls. The building is relatively isolated from the main street roads with distance of 250 m but open fields surrounding the building.


**Illustration 31: The position of the installation from google earth.**

# 5 Chapter 5$^{o}$ : Case Study on Monitoring

The second phase of this thesis study consisted of the Monitoring of the route from a suburb area to the University of West Attica, located at Egaleo near to Petrou Ralli road which is one of the busiest and high traffic road during working times and considered to be a near central area. More specifically the route consisted of two bus rides, two minor walking paths and a major metro ride, which consisted of two different metro lines. The device used for the monitoring was a PurpleAir device, PA-SD-II that was set at monitoring.

## 5.1 Equipment used

The main equipment used for the Monitoring was the PurpleAir sensor which was connected to a power bank through a MICRO USB to USB C cable. Purple Air was connected to a wireless Wi-Fi router. A smartphone was connected to the Wi-Fi channel of PurpleAir device to monitor the live monitoring report of Purple Air network. Finally a note app was used to write down the time in which the route progressed next to the instant live measuring of PA for further connecting the measuring data to the according time.

<u>Power Bank:</u>

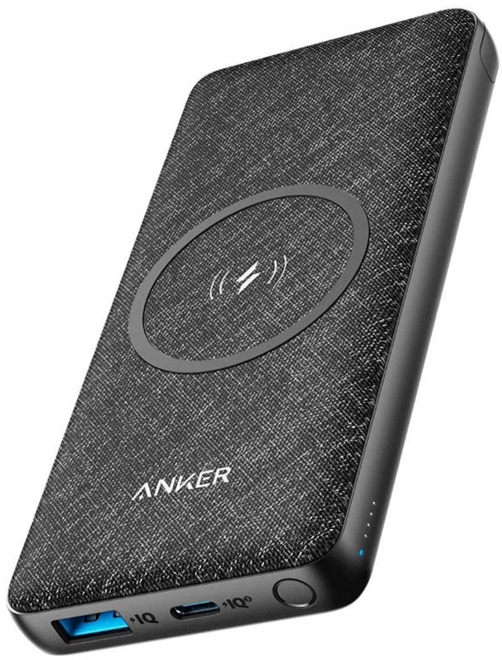



**Illustration 32: The Power Bank used in this study.**

The power bank used for the monitoring is the Anker PowerCore ii Sense and it had the same output specifications the provided power brick PurpleAir offers for the PA-SD-II.The total capacity of the 10000mAH. The specifications are [41]:

**Specification:**

- Capacity: 3.7Vdc,10000mAH/37wh
- Input: USB-C: PIQ3.0 5V=3A 9V=2A
- Input：USB-C：PIQ3.0 5V=3A 9V=2A
- support PD QC charging， work with all C-C/USB A-C
- USB-C：PIQ3.0 5V=3A 9V=2A
- USB-A：PIQ 2.05-6V=3A / 6-9V=2A / 9-12V=1.5A
- Wireless WPC Qi 1.2 5W/7.5W/10Wz
- wireless output: 10w max
- total output 20w
- weight: 243g
- size: 147 x 65 x 19 mm

**Total Output**

- USB-C + USB-A 5V=3.6A
- USB-C+ Wireless wireless charging up to 5W，USB-C output 5V/2.4A
- USB-A+ Wireless wireless charging up to 5W，USB-A output up to V/2.4A
- USB-C +USB-A +Wireless wireless charging up to 5W，USB-A+USB-C total output up to 5V/2.4A

**Table 16: Technical specs of the Power Bank.**

<u>USB Type C to MICRO USB cable:</u>

The cable was used to connect the power bank with the PA sensor. The cable had maximum power support of 15W (5V/3A) [42].

**Illustration 33: The Power cable used in this study.**

SmartPhone and Notes

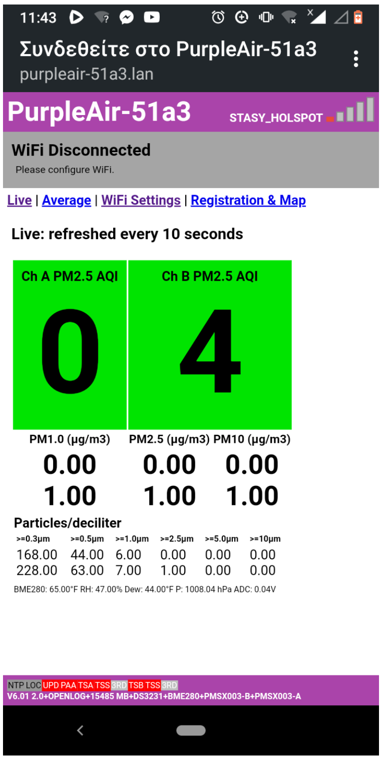



**Illustration 34: The Purple Air LiveView interface.**

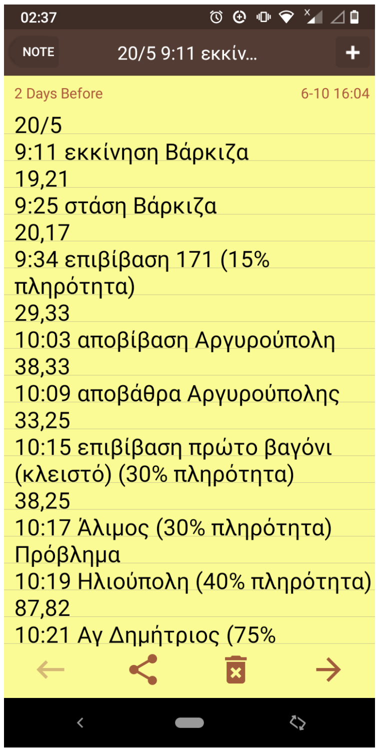



**Illustration 35: Notes used for tracking the monitoring routine.**

For tracking down the route, measurements and the time an android 11 was used to connect to the Wi-Fi of PA device to write down the spot-on measurement the time and the position within the route. The notes were taken on a note android app.

## 5.2 Route of Study and the different means of Public Transportation

The main means of Transportation used was Buses and Metro. There are two different routes, the first route from Varkiza to University of West Attica (UNIWA), the main change between the two routes are the route to UNIWA has a different bus line (171) that uses the traffic road of Vouliagmenis avenue while during the returning route to varkiza a different route is taken (122) which uses the seafront avenue of Poseidonos. The reason for this change is because during the early morning hours of the day the most consistent road to the centre of Athens is the Vouliagmenis avenue, meanwhile seafront Poseidonos avenue has a high amount of traffic and downtime, instead during afternoon and night time seafront Poseidonos avenue is the fastest way to Varkiza with the least amount of downtime.

The second difference between the two routes is the metro station in red line. On the route towards UNIWA, Argyroupoli is the metro station to be used which is the second station of the red line (Elliniko to Syntagma to Anthoupoli). In the route towards Varkiza Elliniko is the metro station to debark. The reason for this difference is mostly convenience of Public Transportation as well as the fact that during debarking from Elliniko to Syntagma it is common for technical issues to occure and possibly cause issues on the monitoring, Argyroupoli station is a solution to such problem and allowed for consistent data collection.

The part of the route from the red line metro to UNIWA and the part of the route from UNIWA to red line metro is the exact same.


**Illustration 36: The overall monitoring route.**

### 5.2.1 Part of route on Foot

The two walking routes that are part of the route case study are from the Varkiza starting point to the 171 bus station and the second walking route is from Egaleo metro station to the bust station (845). In the case of the route from UNIWA to Varkiza, only the walking route from bus station (845) to the metro station occures.

The walking path at Varkiza is at the seafront traffic street which has little to no street lights and stops as a result most cars either drive at average speed or high speed, with minor to no stops. The route consists of multiple coffee shops that offer take away options (situationally causing concentration of groups of people outside of coffee stores) and a minor amount of restaurants and super/mini markets.

The walking path at Egaleo is next to a high density, high traffic road of Iera avenue. The street has little to no car passing due to its narrow nature, it has a high amount of motorcycle activity. The street is heavily populated from take away coffee shops that also offer on the sidewalk seats and many stores overall. At the end of the street right before the bus station that follows a minute walk is taken place at Thivon avenue with high traffic car and motorcycle activity.

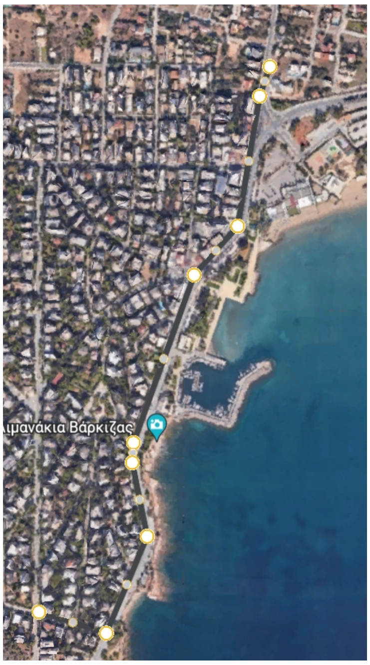


**Illustration 37: The walking route on Varkiza.**


**Illustration 38: The walking route on Egaleo.**

### 5.2.2 Part of route on Public Buses

Three buses are used throughout the studied route. Two of them are starting or going towards Varkiza (122 and 171) and the third one is located at Egaleo (845).

The bus used for going from Varkiza to Argyroupoli Metro station through Vouliagmenis avenue has a frequent routes early in the morning and around 14:00 o'clock the routes are getting shorten at 2-3 rides every hour (30-45 minutes downtime). Overall throughout the morning hours and early hours of noon the bus has a relatively low density and throughout the route the concentration rarely surpasses 75% of the total bus seat capacity. Due to inconsistencies in the Public Transportation at the area of Varkiza it is a frequent occurrence for a bus to skip it's route leading to some buses having double the passengers which can lead to a capacity of up to 140% passengers compared to the passenger's seats.

The bus used for returning from UNIWA to Varkiza, 122 is taken from Elliniko Metro's Bus station, Varkiza is halfway of the route of the bus and the bus continues up to Saronida. During the early hours of afternoon (around 18:00) the bus even though has frequent routes is usually pact due to the instant increase of passenger that are returning home from work, since Saronida has only one bus that connects it to Metro Station and furthermore the centre of Athens. The passengers capacity usually start at 80%-140% and after passing Glyfada station the passengers ratio goes down to 60%-80%. After the busy hours between 18:00-19:00 o'clock the bus has a low passengers density throughout its schedule with aprox. 40%-60% passengers at Elliniko station and after Glifada station aprox. 20%-30% of passengers remain. The route is longer that the one of 171 but Poseidonos avenue has less busy roads, less street lights and overall vehicle tend to maintain a high speed throughout the avenue. Both 122 and 171 are two car buses meaning that they have around 64 seats available. In this study we will consider 100% passenger capacity to be the exact amount of the seats available.

Finally the 845 bus is used to go from Thivon avenue, which is close to the Egaleo Metro Station, to UNIWA and from UNIWA to Thivon avenue. The Thivon bus station hosts a big amount of buses that cross Thivon street, but for the sake of consistency of the monitoring 845 was picked. 845 is a single car bus meaning that has around 34 seats available. 845 bus has no consistency or pattern over its capacity, at any time of the day the bus can carry around 10% passengers or 100%. From the measurments done the average capacity of the bus is around 35% to 125%.


**Illustration 39: Photo of a double car bus (171,122)**


**Illustration 40: The route of 171.**


**Illustration 41: The route of 122.**


**Illustration 42: The route of 845.**

### 5.2.3 Part of route on Metro

Metro routes is the main emphasis of this thesis, the route I studied consisted of blue and red line with Syntagma station being the station I changed lines. The most important distinction in this Thesis will later be proven to be the difference between passenger increase on each wagon and the activity of passengers. Even though in some stations the increase or decrease of passenger be high (20% +) that may be the overall activity of the passengers as well, in the contrary there are some Stations like Dafni and Sygrou Station that even though the end result was even (~5%) the amount of people debarked and barked on the wagon might surpass 40% of the wagon capacity. Activity as will later be also shown is the prior factor that influences the most the PM2.5 measurements and effects the result the most.

Data backing the passenger rates are showcased at supplement A, collected by personal research.

On the way to UNIWA the sequence of metro stations was as shown bellow:

- Argyroupoli Station: Argyroupoli station is the second metro station after Elliniko and the average increase of passengers on the wagon is around +10%, the overall activity is not over 15% with mostly people entering the wagon and little to not more than aprox. 3 individuals debarking at Argyroupoli Station.

- Alimos Station: Alimos has little passengers in general, with only having passengers barking into the wagon during morning hours and the amount of passengers embarking never surpassed 10%.

- Ilioupoli Station: Ilioupoli has a consistent passengers embarking of around 5% to 15% wagon capacity with a minor 5% of passenger debarking leading the overall passenger activity from 10% up to 20%.

- St. Dimitrios Station: St. Dimitrios is the first station of red line that showcases a significant amount of passengers debarking at a rate of around 10% to 15% and people embarking at around 10% to 30%. Peaking at 30% embarking passengers is a rare occasion that consistently happens almost daily but mostly at peak hours for a couple of metro routes. St. Dimitrios has 30% to 45% passenger activity and it's also noted that consistent wagon debarking delays were taking place due to technical reason usually affected by passenger's activity.

- Dafni Station: Dafni station has the highest passenger activity with many people debarking up to the rate of 25% and an even higher amount of embarking passengers of around 35% consistently. Dafni Station rarely has less that 15% of passengers barking or debarking.

- St Ioannis Station: St Ioannis is the first station that debarking passengers usually will surpass or be equal to the passengers embarking with average of 10% embarking and 15% debarking, the final amount of passengers prior and post to St. Ioannis station usually is even out or slightly decreased.

- Neos Kosmos Station: Neos Kosmos is another station were passengers activity is high but less compared to both Dafni Station and St. Dimitrios Station, the barking and debarking rate is aroung 15% and usually the overall amount of passengers after Neos Kosmos Station will either have increased or decreased by 5%.

- Syggrou Station: has the second highest activity and will almost always have more people debarking on Syggrou. The debarking rates are up to 25% and the embarking rates around 20% with overall passenger activity consistently being around 45% to 50%.

- Akropoli Station: Akropoli has the least passenger's activity throughout the route with usually less than 5% of passengers embarking or debarking. The main passengers embarking and debarking on Akropoli are tourists or individuals working on the touristic section of Akropoli area.

- Syntagma Station: On Syntagma Station the route demands debarking for changing to blue Metro line.
  Syntagma Station on blue line has a higher amount of debarking passengers (aprox. 40%) and an amount of embarking passengers of around 20% to 30%. Usually the capacity of the

wagon from Syntagma is around 30% to 50% on non-busy hours or 90% to 110% on busy hours.

- Monastiraki Station: Monastiraki Station being one of the most centric stations has a high rate of passenger activity with mostly debarking passengers overpopulate the embarking passengers for around 5% to 10%. The overall passenger activity rate can reach up to 70% and on average will be 40%.

- Kerameikos Station: Kerameikos station has an inconsistent rate of passenger activity with many occasions the activity not passing 5% and occasions where the activity reaches up to 25%. The final passenger capacity difference of the wagon will either be 0% or ±5%.

- Eleonas Station: Eleonas has a consistent amount of 5% passenger debarking. Here to note that on OASA Metro Subway Eleonas is also used for drivers shift exchange which leads to a minor a minute or two minute delay of debarking.

- Egaleo Station: Final destination of the metro route towards UNIWA, on Egaleo a rate of 20% up to 45% of the passengers are debarking.

On the way to Varkiza the sequence of metro stations was as shown bellow:

- Egaleo Station: Egaleo Station is the first station on the returning route on the Metro. During noon times of around 15:00-16:00 o'clock and afternoon hour of 18:00-19:00 the wagon at Egaleo is usually high in passengers capacity and the passengers embarking surpass the 20%, usually in such ours the final capacity of the wagon is around 70% to 90% capacity. Outside of these peak hours the wagon is usually around 30% to 50%.

- Eleonas Station: Eleonas station has the least reported passenger activity and it is common for no passenger to embark or disembark the overall increase or decrease will never surpass 5%.

- Keramikos Station: Keramikos station had a minor passenger embarking of around 5% and around 10% to 15% of passengers disembarking, the overall passenger activity of the wagon would rarely surpass 20%.

- Monastiraki station: On Monastiraki station as explained prior the highest amount of passenger activity has been reported (in either route of going to UNIWA or going to Varkiza) with passengers activity reaching up to 85% and average passenger disembarking being 50% and around 40% of passengers embarking, usually on Monastiraki station a decrease of total passengers was reported usually around 10% but it could reach up to 35% to some occasions.

- Syntagma Station: at Syntagma Station disembarking is required to change to red line of metro. Syntagma station on red line has probably the highest reported passenger activity with peak times having a 100%+ activity ratio. At peak hours (15:00-16:00 and 18:00-19:00) the usual capacity of the wagon is around 180% to 210%. At regular hours the capacity is around 75% to 100%.

- Akropoli Station: Minor to no activity whatsoever, activity rarely surpasses 10% and usually the rate of embarking or disembarking passengers is at 5%.

- Syggrou Station: Syggrou is the first major station for people disembarking, with peak disembarking rate 30% and peak embarking passengers 10%. Activity is relatively high too with peak at 50% but the usual is around 30%.

- St. Ioannis Station: St. Ioannis usually reported only disembarking rates, usually around 10% to 15%, embarking rates never surpassed 5%. Overall passenger activity peaks at 20% but usually is at 5% to 15%.

- Dafni Station: Dafni is the highest passenger activity station alongside with Syntagma Station. Peak passenger activity can reach up to 80%. Disembarking passengers rate is around 30% and can peak at 50% and embarking rate is around 20% but can peak at 35%. Usually the total passenger difference after Dafni Station was -15% to -20% passengers.

- St. Dimitrios Station: St. Dimitrios has high passenger disembarking rates and relatively low embarking rates. Average the disembarking rate was around 25% and it can peak at 40%, usual passenger embarking amount is at 10% up to peak case of 20%. Usual decrease of passenger total capacity of the wagon was around 20%.

- Ilioupoli Station: Ilioupoli had a consistent disembarking rate of 10% to 15%. Embarking rates were rarely reported above 5% with many occasion of embarking rate being at 0%.

- Alimos Station: Alimos has similar characteristics to Ilioupoli Station with peak disembarking rate at 10%. Disembarking rate was also around 0% to 5%.

- Argyroupoli Station: Argyroupoli station had a consistent 10% disembarking rate that could peak at 20%, rarely did Argyroupoli reported less than 10%. Embarking rate is also consistently at 5% to 10% with overall passenger activity consistently being at 15%.

- Elliniko Station: Elliniko Station is the final station of red line Metro’s route, disembarking is required from all passengers. The wagon would reach at Elliniko station at 10% to 20% passengers capacity.

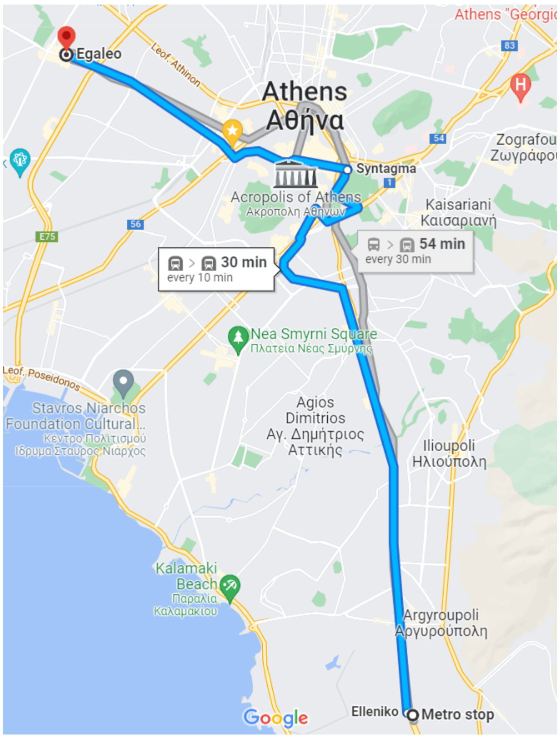



Illustration 43: The metro route used (both blue and red line).


Illustration 44: Map of routes of Metro of Attica.

### 5.2.4 Deeper look on the Stand Points

There are four stand points on which I was waiting on a bus station for a bus part of the monitoring route and most of the bus stations are located on different places of Athens with different AQ characteristics and different influential contributions. The first station is at Varkiza for the bus line of 171. The bus stop is located on a road with limited amount of street lights next to a main avenue (Poseidonos avenue), cars overall had a consistent travelling speed of 50km/h to 70km/h, during morning hours many product transportation vehicles are using these roads.

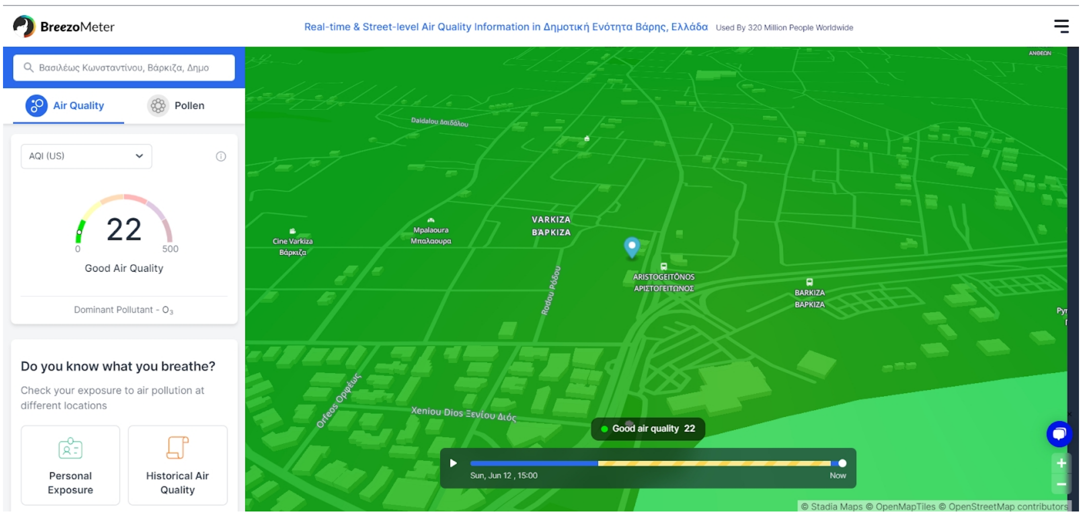



Illustration 45: Visualisation of Air Pollution on Varkiza (Breezometer).

The second and third bus stations are located at Thivon street, one facing towards Petrou Ralli avenue and the second one facing the Iera avenue. The street can be a high traffic road at peak working hours, causing a car blockage with average travelling speeds being around 10km/h to 20km/h with constant stops. Outside of working peak hours due to dense street lights the travelling speed of cars doesn't exceed 50km/h but without constant stops.

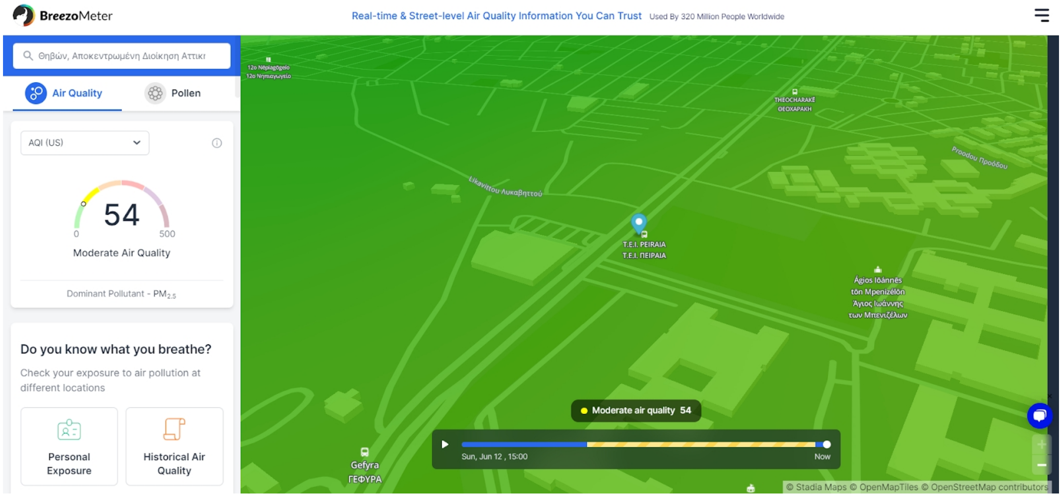



**Illustration 46: Visualisation of Air Pollution on UNIWA/Egaleo (Breezometer).**

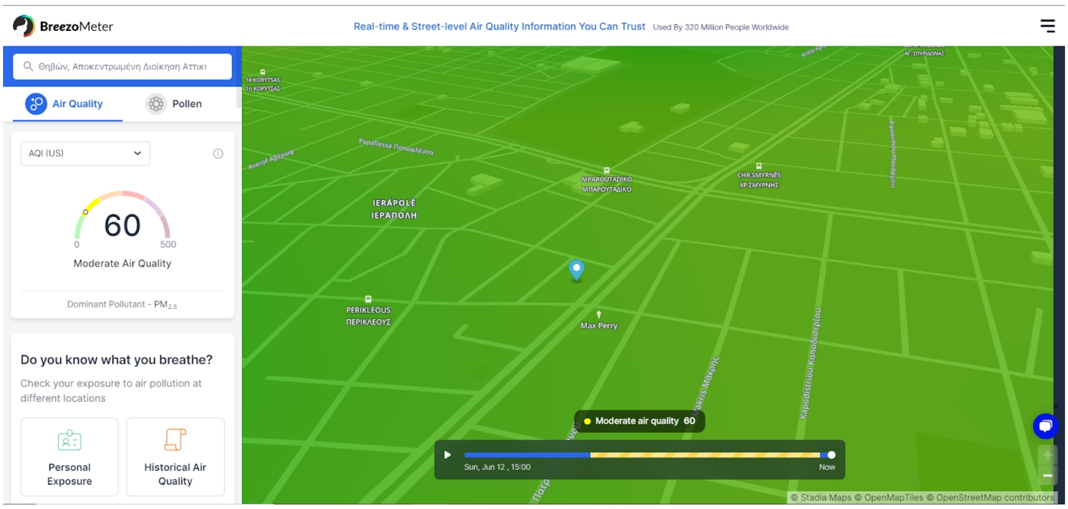



**Illustration 47: Visualisation of Air Pollution on Thivon Bus station (Breezometer).**

Finally the last bus station of the route is the Elliniko bus station. The station is located right outside of the metro entrance causing the station to have many passengers waiting for a bus. The station is located on Vouliagmeni avenue before a street light. Traveling speed of cars is consistently at 60km/h to 80km/h and situationally even higher. Buses are stopping frequently aprox. every 15 minutes and stops from cars happen only because of the street lights and rarely the line of cars reach the level of the bus station.

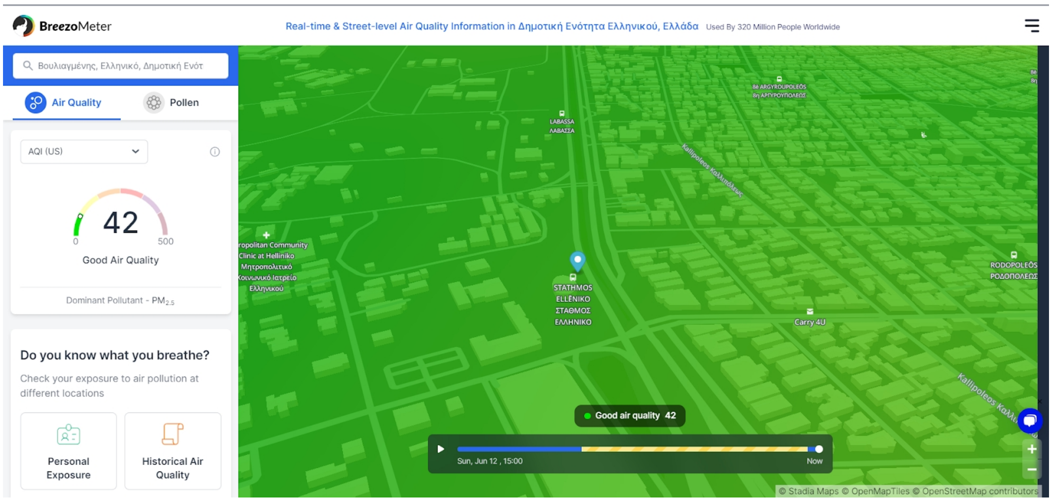



**Illustration 48: Visualisation of Air Pollution on Elliniko Bus station (Breezometer).**

## 5.3 Geographical Characteristics of the Studied Areas

The route could be argued that is separated at two parts, Varkiza to Argyroupoli and Argyroupoli to UNIWA, by the geographical characteristics they have.

### 5.3.1 Suburb study (Varkiza to Elliniko/Argirupoli Metro Station)

Varkiza throughout the level of Argyroupoli is connected through two main street avenues, the Poseidonos avenues and Vouliagmeni avenue. Up to the point of Upper Glyfada the suburbian area of Varkiza to Argyroupoli is strongly effected by the nearby shore, with only a tiny portion of Upper Glyfada to Argyroupoli being minorly (but still) affected by the shore.

The main results caused by the sea is lower temperatures early in the morning and overall higher humidity levels throughout the day with intense increases early in the morning and late at night. Throughout the monitoring period Varkiza was consistently reporting much lower PM2.5 concentration and higher rates of winds especially early in the morning. Overall up to the point of Argyroupoli level the geographical situation of this part of the route is ideal for better scattering of Air Pollution due to the reinforced winds from the sea side.

Another major factor that contributes to the geographical benefits of this area is the lower density of residents and lower amount of high traffic roads the areas consists of.

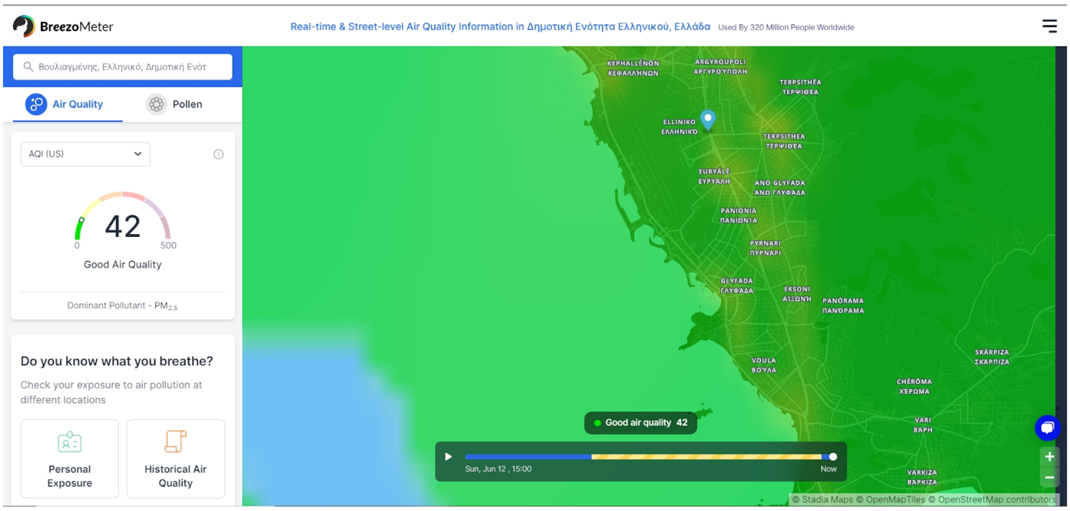



**Illustration 49: Visualisation of Air Pollution from Varkiza to Argiroupoli (Breezometer).**

### 5.3.2 Sub-Center study (Aigaleo to Petrou Ralli/UniWA)

Egaleo in reality is a sub-central area separated by a set of major central avenue streets (Petrou Ralli avenue, Kifisos avenue, Iera avenue and Thivon avenue). That greatly affect the PM2.5 concentration around that area, the main reason is because the main source of PM emissions are roads that shape a square shape within the area of Egaleo making the scattering of such emissions harder and more time-demanding.

Throughout the monitoring routines Egaleo showcased consistently higher temperature rates, lower humidity levels and less wind (the data compared had an hour of difference from each area which might played a role at the resutls).

The area overall consists of many major avenues streets and smaller roads that tend to get traffic during working peak hours. Many stores and coffee shops are located throughout Thivon and Iera avenues and nearby Petrou Ralli and Kifisos avenues many small and major industrial activity takes place. The street are consistently throughout the day populated by many commercial vehicles.

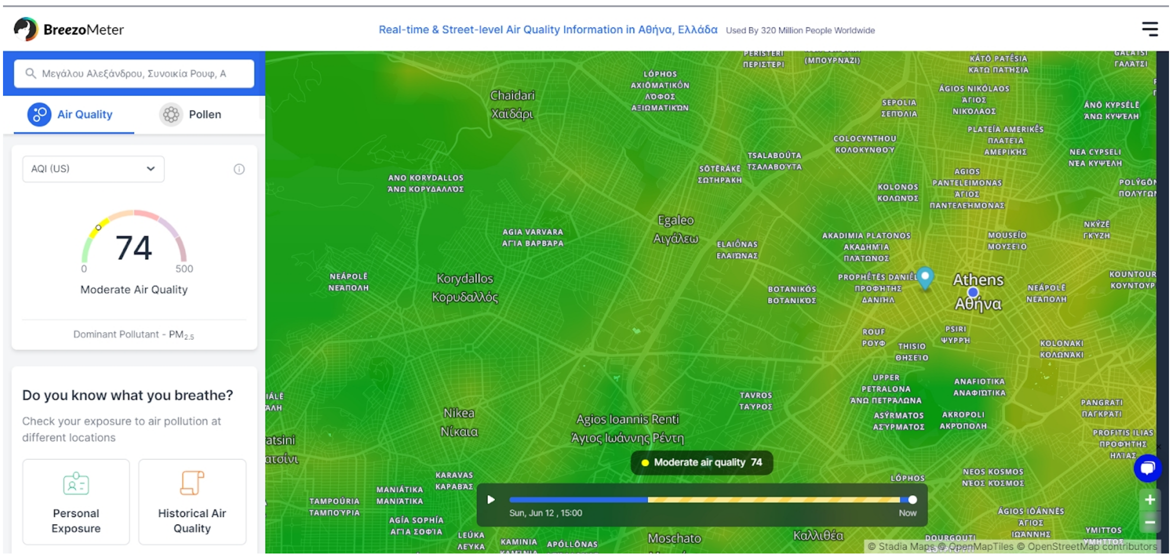



**Illustration 50: Visualisation of Air Pollution of the centre of Athens (Breezometer).**

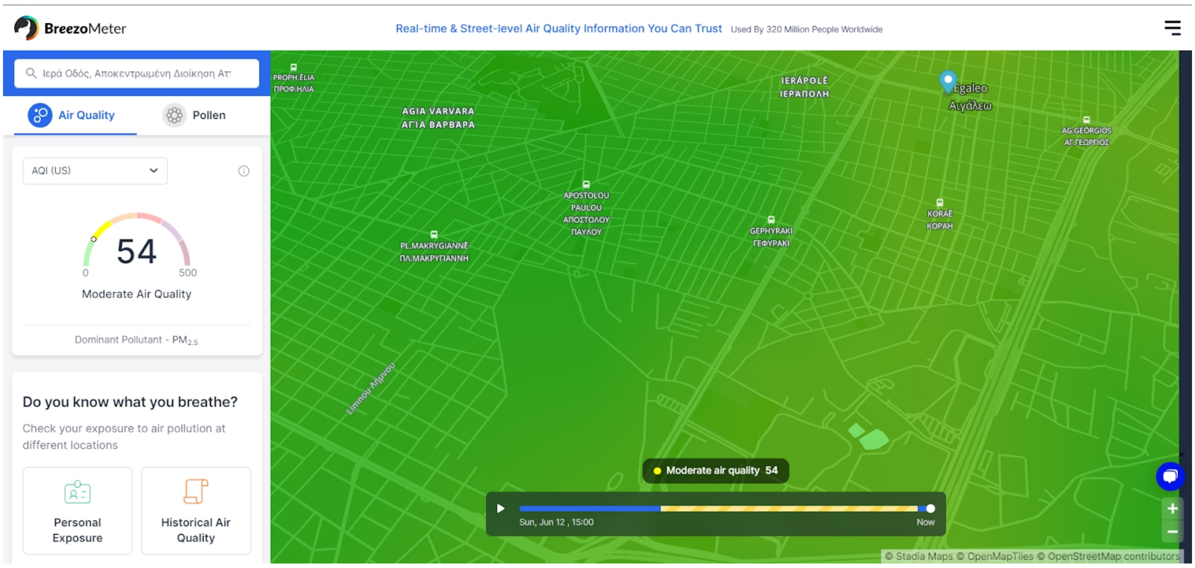



**Illustration 51: Visualisation of Air Pollution of Egaleo (Breezometer).**

# 6 Chapter 6º : Methodology

In this Thesis two phases are conducted as mentioned prior. For each phase a different methodology was used to be concluded. Calibration required minor actions while the sensors were gathering data with only the reference instrument requiring zeroing for achieving the highest accuracy possible. Calibration mostly required post editing of the data on excel and Python for the right management of the data and for the depictions of the results through graphs.

Monitoring required a methodology process prior to the beginning of the monitoring process. First and foremost a monitoring plan had to be made that would determine what the monitoring route would be, what the hours of monitoring would be and how the data will be processed and presented.

## 6.1 Zeroing of Sensors

As mentioned above during the calibration phase the reference instrument required daily zeroing. Both AQMesh and PurpleAir are sensors that allow no further calibration outside of the factory calibration the companies provide.

TSI DustTrak DRX offer an option for daily calibration feature, referred by the manual as zeroing, the process consists of a reference gas filter and a set of option selection on the interface of the TSI DustTrak's monitor, once the filter is positioned and the setting selected the DustTrak need 60 seconds and the process is complete, once the zeroing is complete the filter must be removed and the sampling tube be set back.

The zeroing process is as follow [43]:

Step 1: Press the stop option so the sensor stops sampling air.

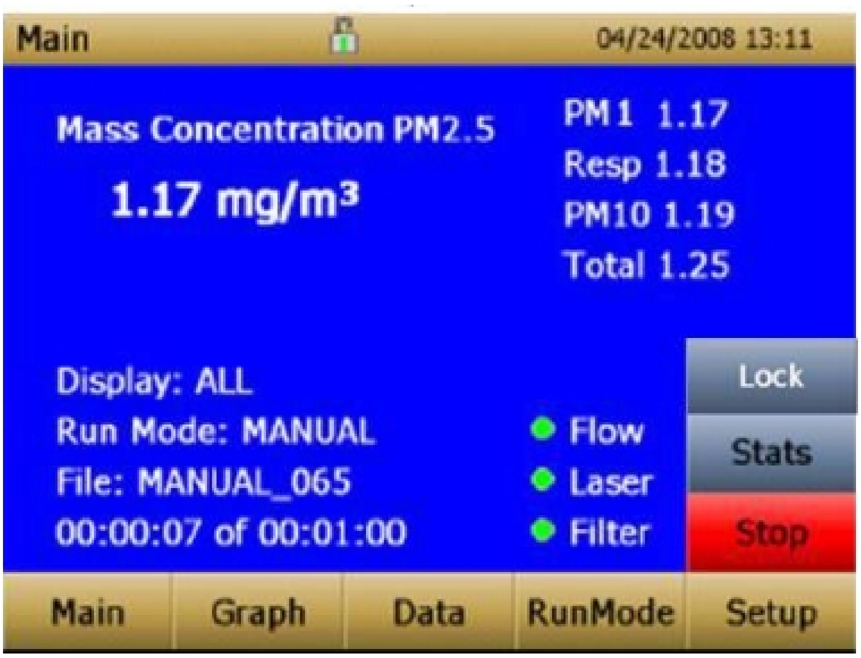



**Illustration 52: Step one for zeroing of TSI.**

Step 2: Remove the monitoring tube from the sensor and replace it with the calibration tube, with the calibration container facing down.


**Illustration 53: Step two for zeroing of TSI.**

Step 3: Select the option setup and press the Zero Cal option, then proceed to press Start and wait for 60 seconds until the Zero Calibration is complete (illustration 53).

Step 4: Remove the calibration tube and set up back to the sensor the sampling tube.

Step 5: Press the option “Main” and then “Start” for the sampling and thus monitoring to start.

## 6.2 Processing of Calibration Data

For the of the first phase an installation that consisted of 12 Purple air devices, AQ Mesh and a reference instrument were set, gathering data from 14/3/2022 until the 5/5/2022. The data that was used for the calibration test was from 16/3/2022 up until 4/5/2022.

The data of Purple Air was collected through the website of Purple Air that the sensors were connected and reporting to. Though the site the option for the data is given in reports of 10 minutes 60 minutes and 24 hours. The data used were in hourly report (60 minutes). Because in the case of Purple Air devices a group of devices were compared individually to TSI data and one of the devices showcased a lot of data equal to 0 causing a correlation of less than 60% meanwhile every other device showcased a correlation of around 90% - 95%. For that reason that device was not considered for the overall evaluation of Purple Air.

After the first individual correlation test, all the data from all the Purple Air devices were combined in one average, which was later on used for the comparison of Purple Air and the AQ Mesh and TSI.

TSI reported data in $mg/m^3$ which was converted in $\mu g/m^3$ by multiplying by 1000. TSI's data was also reported in 10 minutes and the average was calculated through the use of python into hourly data. The data was withdrawn by the device through a computer device.

Finally AQ Mesh had by default the option for a 15 minute, 30 minute and 60 minute report, the 60 minute report was used for the correlation test.

## 6.3 Processing of Monitoring Data

For the data of the second phase, in which was the monitoring of the route of Varkiza to UNIWA and from UNIWA to Varkiza, PurpleAir was the only sensor used. The device used in this case was the SD version in specific and only the data provided from the SD card and the format PurpleAir uses in CVS files was used for the results and the depiction of graphs.

In the CVS files from the SD card the device offers the following data:

UTCDateTime: It consists of the year, month and day that will automatically fill up, up to the current one. In this time is also recorded, during the data process the time had to be calculated in Greek time zone meaning that the time reported had to be x+3 to be converted.

Mac_adress: Is the ID of the individual sensor.

firmware_ver: Is the firmware version in which the device is operating at.

Hardware: Is the code of the processing board that the device has identified and operating on.

Current_temp_f: Is the temperature that is monitored from the BME280 sensor, the temperature reported is in Fahrenheit. Temperature was was only used for qualifying data from different days as comparable in terms of outside conditions., in that cases the temperature was converted to Celsius with this equation $(x°F - 32) \times 5/9 = y°C$.

Current_humidity: Current humidity is reported in percentages. Current humidity was only used for qualifying data from different days as comparable in terms of outside conditions.

Current_dewpoint_f: It's the current dewpoint in Fharenheit. Due to the fact that dewpoint had rarely any major difference during monitoring (within the range of 1-3°F) it wasn't used at all.

Pressure: it's the current pressure of air in millibars. Pressure was only used for qualifying data from different days as comparable in terms of outside conditions. For that purpose pressure was converted in atmosphere with this equation x/1013= y atm.

Adc: The voltage reading on the analog input of the control board.

Mem: Free HEAP memory on the control board. Due to an issue that occurred during the monitoring routine, data was drawn from the memory card of the device at the end of each routine, thus this information had little value.

Rssi: Wi-Fi signal strength in dBm. Due to the limited signal on the subway Wi-Fi was not used in the routine.

Uptime: Firmware uptime in seconds.

Next is the data collected from the PM sensors in the PurpleAir device, channel A and channel B, for the following cells of data we have one for each channel and each headline is devided on the title with nothing following next which is for the channel A and "_b" for the channel b. Additionally Purple Air offers values of CF and atm. CF are values that are "correcting" the values to fit the characteristics of a indoor space or for data collected under control environment. CF tend to be higher than the values of atm. Atm are the original values of the sensor, for the calculation of AQI atm is considered to be closer related to values for outdoor conditions.

Pm1_0_cf_1: PM1.0 particulate mass in ug/m$^3$.

Pm2_5_cf_1: PM2.5 particulate mass in ug/m$^3$.

Pm10_0_cf_1: PM10.0 particulate mass in ug/m$^3$.

Pm1_0_atm: ATM PM1.0 particulate mass in ug/m$^3$.

Pm2_5_atm: ATM PM2.5 particulate mass in ug/m$^3$.

Pm10_0_atm: ATM PM10.0 particulate mass in ug/m$^3$.

pm2_5_aqi_cf_1: AQI values calculated using JavaScript and further corrected to fit indoor conditions.

pm2_5_aqi_atm: AQI values calculated using JavaScript and further corrected to fit outdoor conditions.

P_0_3_um: 0.3 micrometer particle counts per deciliter of air.

P_0_5_um: 0.5 micrometer particle counts per deciliter of air.

P_1_0_um: 1.0 micrometer particle counts per deciliter of air.

P_2_5_um: 2.5 micrometer particle counts per deciliter of air.

P_5_0_um: 5.0 micrometer particle counts per deciliter of air.

P_10_0_um: 10.0 micrometer particle counts per deciliter of air.

As mentioned before similarly the same data are offered for channel B with the difference that they are followed by "_b", for example for the values of AQI the title for channel A will be "pm2_5_aqi_atm" and for channel B "pm2_5_aqi_atm_b".

Because PurpleAir is using the same sensor for both channel A and B the results should have approximately 95% overall agreement on the data, situational drifting is expected. For that reason a graph comparing the two channels was made.

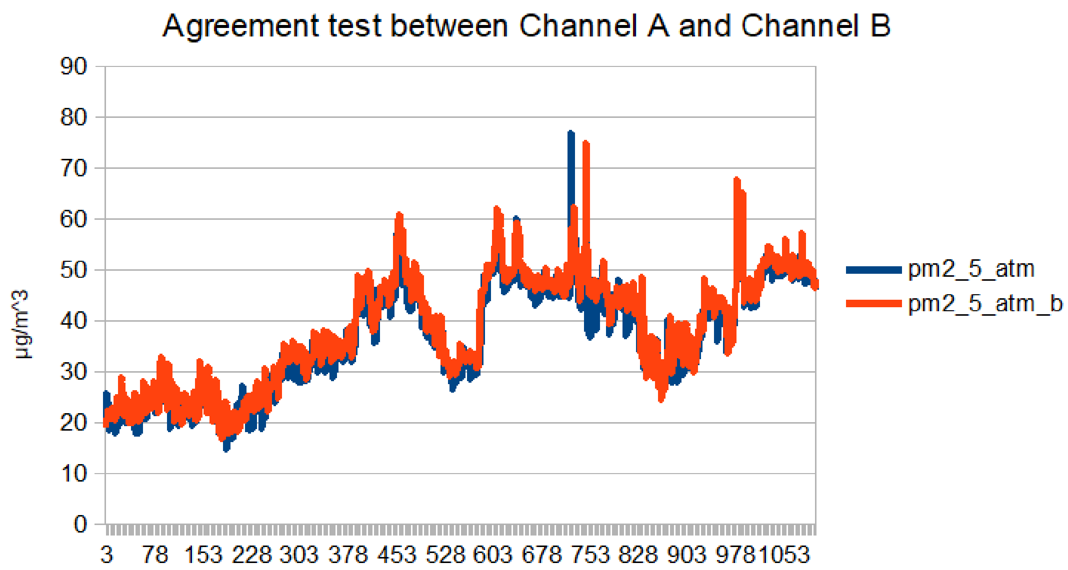



**Figure 1: Correlation coefficient of Channel A and Channel B of the Purple Air sensor used.**

For formation of any data both for AQI and μg/m$^3$ the average value of the two channels was used, the equation would be $\frac{(AQIChannelA + AQIChannelB)}{2}$ or in the case of Excel this command was used, "=average(AQI Channel A, AQI Channel B).

For the case of calculation of metro stations AQI and μg/m$^3$ average values, all the individual average values were used added up and divided by the number of values added. For example if for the station of Dafni 15 values were collected, those 15 average values would be added and then divided by 15.

## 6.4 Multi-Criteria study on time zones of monitoring (/sampling)

For the selection of the sampling hours for the data collection a multi-criteria study was conducted which examined three different options.

The three options were:

1. Monitoring during the early morning working hours of 6:00 – 9:00 where most people are going to job.
2. Monitoring during late morning hours of 9:00 – 12:00 were the passengers rate has been stabilised after the rush hours and there's still an amount of people using public transportation to go to work and at their universities.
3. Monitoring in different time groups to gather data of different scenarios and simulate the realistic week schedule of a full-time employee with a rolling working schedule or an average student. The time groups consisted of 6:00 - 9:00, 9:00 – 12:00 and 12:00 – 15:00 and the first two groups would be monitored twice each every weak and the third group that is predicted to have the least valuable data just once every week.

The criteria studied for the multi-criteria study was, *the usability* of the data which refers to how much the data could be used to draw conclusion and observations after their processing. The next criteria was *the consistency* which was showcasing how consistent the result of each time group would be and how random the data influencing conditions that each time group possessed, could be. Then it was *the representability* which was showcasing the characteristics that made each time group distinctive from each other and would showcase the presence of characteristics specific to each time group. Finally it was *the accessability* which was the ease on which I could daily conduct data gathering on each option without missing the time group due to outside factors such as delay of public buses, possible route skip of a bus, high traffic etc.

The following tables were made in order to calculate the importance of each criteria.

| ΕΛΕΓΧΟΣ | | Usability | Representability | Consistancy | Accessability |
|---|---|---|---|---|---|
| 1 ΑΡΧΙΚΟΣ ΠΙΝΑΚΑΣ | Usability | 1 | 2 | 3 | 5 |
| | Representability | 1/2 | 1 | 2 | 3 |
| | Consistancy | 1/3 | 1/2 | 1 | 2 |
| | Accessability | 1/5 | 1/3 | 1/2 | 1 |
| | total | 2 1/30 | 3 5/6 | 6 1/2 | 11 |

| ΕΛΕΓΧΟΣ | | Usability | Representability | Consistancy | Accessability | Μ.Ο. ΓΡΑΜΜΗΣ |
|---|---|---|---|---|---|---|
| 2 Κανονικοποίηση | Usability | 30/61 | 12/23 | 6/13 | 5/11 | 0.48 |
| | Representability | 15/61 | 6/23 | 4/13 | 3/11 | 0.27 |
| | Consistancy | 10/61 | 3/23 | 2/13 | 2/11 | 0.16 |
| | Accessability | 6/61 | 2/23 | 1/13 | 1/11 | 0.09 |
| | total | 1 | 1 | 1 | 1 | |

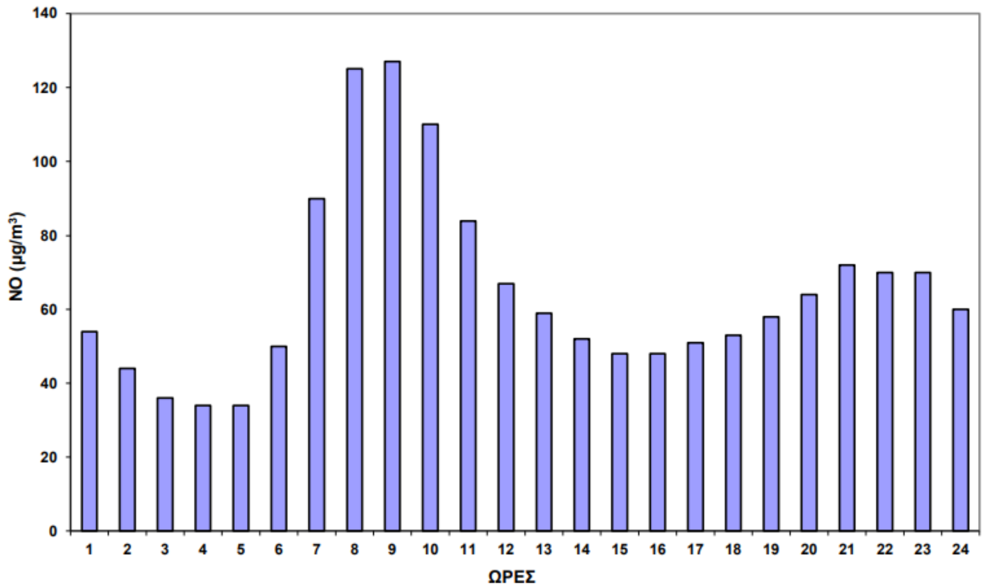
**Table 17: Multicriteria study: criteria evaluation.**

Once the importance of each criteria was calculated the evaluation of each solution took place.

| | 6:00-9:00 | 9:00-12:00 | Συνδυασμός |
|---|---|---|---|
| Usability | 7 | 5 | 8.5 |
| Representability | 9 | 7 | 8 |
| Consistancy | 9 | 7 | 6 |
| Accessability | 7 | 8 | 9 |
| total | 7.86 | 6.12 | 8.01 |

**Table 18: Multicriteria study: options evaluation.**

The grading for the consistency and represent-ability were decided by public data given from YPEKA that showcase what are the emissions and concentration of various gases that can be used to predict the activity and the busyness of early morning hours.




*Σχήμα 2.20 Ωριαία μεταβολή NO στο σταθμό Πατησίων για το έτος 2020*

**Table 19: YPEKA data table for NO.**

From the graph above which showcases the concentration of NO during every 1 hour of the day we can see that the highest movement occures during 8:00 and 9:00 but given the fact that the monitoring of these concentration has a delay of half up to one hour the grading for consistency and represent-ability occurred. Usability was graded based on the possible rate of different graphs we can draw from the data collected and the different possible observations we could have. Due to the fact that the third choice offers a wide range of data of different characteristics the usability was graded accordingly. Finally accessibility was graded based on how possible was for me to consistently gather data in the set time groups, which considering the buses schedule and personal programme was decided.

The third choice was decided for the final study of the route of Varkiza to UNIWA with three different sampling time groups, group 1 being at 6:00 – 9:00, group 2 being at 9:00 – 12:00 and group 3 being at 12:00 – 15:00.

For the returning route of UNIWA to Varkiza only one time group was used which was 18:00 – 21:00.

## 6.5 Monitoring Routine

The monitoring routine started from the starting point of Varkiza following the time schedule decided from the multi-criteria study above. The routine begins by connecting the PurpleAir sensor to the portable power bank and checking through the phone that the sensor is transmitting and that the monitoring values it reports are correct, then the walking route begins, after the starting time has been noted. Once I get to the bus station at Varkiza for the 171 bus the current value listed in the live view monitoring app that PurpleAir offers is noted alongside with the arrival time to the station. After at least 5 minutes on the station after the arrival the next 171 bus that passes by is used. Once a 171 bus passes by the value is noted alongside with the embarking time and the total percentage of the passengers. After the disembarking from 171, I move to the ticket booth level and I am standing next to the ticket booths, on arrival the time as well as the value measured is noted. After at least five minutes waiting next to the ticket booths I move to the platform level writing down the value measured as well as the arrival time to the platform. After at least 5 minutes of waiting the next subway wagon is used, in Argyroupoli station the first wagon was always used for obtaining the maximum consistency of data possible. The first and last wagon is the optimal option because it is usually close to the staircases of each station, yet not directly facing the staircases of each station and in every station a bench is located in front of the position of the first and last wagon leading to a consistent amount of people using those wagons. Once in the wagon both the time and current value is noted as well as the age category of the wagon and the total passenger percentage of the wagon. For each station once at the next stop and the doors open the current measurement is noted alongside with the time, the name of the station, the total passengers percentage and the amount of passengers that embarked and disembarked. After the disembark at Syntagma station is noted with the current measurement and time, I move to the platform level of blue line and after at least 5 minutes the next wagon is used, embarking again at the first wagon, noting down time and current measurement. A similar process is followed as previously at the red line metro. After disembarking at Egaleo and noting the disembarking time and current measurement, 5 minutes next to the ticket booths are taking place. Once the 5 minutes are complete the time and current value are noted down. Then the walking route to Thivon bus station takes place. Once at Thivon bus station the time and the current measurement is noted down. After at least 5 minutes the next 845 bus is taken and both time and current measurement is noted. After the disembark at UNIWA station the time and current measurement is noted down and the sensor is disconnected from the battery.

On the returning route the same process occures. The only difference in this case is that the disembarking station in the red line route is Elliniko and the bus taken from Elliniko station is 122. The times on each place measuring doesn’t change at all with 5 minutes waiting at least at the ticket booth level of Egaleo station and Elliniko station, 5 minutes at least of waiting must be done in both the Egaleo subway platform and finally at least 5 minutes of waiting at bus stations of Elliniko station and UNIWA station as well.

# 7 Chapter 7º : Data Processing and Results

The data provided from every sensor part of the process was later processed on Excel, the data of calibration was initially processed with the use of Python Pandas to Excel.

For the visualisation of the $R^2$ diagrams for the comparison between devices the hourly (60 min) data reports were used. For the case of TSI the values were converted from 10 minute reports to 60 minute reports through Python. Finally for the linearity comparison the data that was used was from the days of 16/3/2022 up to 4/5/2022. Both TSI and AQ Mesh were used as is, meanwhile for the case of the Purple Air an average of the 11 devices was calculated and further used for the linearity tests.

For the visualisation of the monitoring data the data of each individual day was used to calculate the average PM concentration in μm/m³ and later for AQI values respectively. The individual days were later used to calculate the average exposure and AQI values and then the data were visualised with the use of scatter (with additional theoritical lines) graphs showcasing each the individual concentration or AQI value for the respective number of measurment.

The device used for monitoring the route, as mentioned above, is the PurpleAir PA-SD-II set at measuring every 10 seconds. Unfortunately due to hardware limitations the sensor was unable to consistently offer 6 measurements every minute at the rate of 10 seconds, instead the approximate measuring rate was between 8 to 13 seconds leading to scenarios where within a minute the data had been collected were just 3 values and scenarios where within a minute the data that had been collected had 9 values. Thus for the data to be more accessible were combined at 30 seconds average values. PurpleAir had also showcased an error that occurred every 10 minutes were it recalibrates and reports a single row of n/a PM data, which was decided to be deleted during the data processing. During the data processing some values were observed to be more than 300% higher than the previous and following measurements with no logical explanation, these values were studied and if no possible explanation could be given they were deleted.

Finally in the case of the data processing of the metro route data which we will emphasise at, the data for each individual station were combined in one total average value. The data range was selected from the reported data that was collected at the time the doors of a wagon closed at a station, to the point that the doors are opening at the next station. Throughout the noting of time and location for tracking down the raw data in excel, the current passenger capacity was also noted down as well as the amount of passengers that were embarking and disembarking from the wagon on each station, those were considered as a major factor on effecting the results of the data.

The graphs provided to showcase a specific phenomenon or observation are drawn from the raw data sheet the PurpleAir device offers, meanwhile the graphs that showcase the average concentration and AQI values of PM are formed from the processed data Excel spreadsheet. No data that could not be backed by a logical explanation was used for any of the following graphs.

For most of the graphs that visualise the concentration of PM2.5 on the x axis the amount of data is used, the reason for that was that because of the high density of the data and because information can be absorbed and phenomenons be showcased by just a small set of data it was impossible for a different scale like time for the x axis. So the number on the x axis is corresponding to the number of the data.

## 7.1 Results of Calibration and Graphs

The main purpose of this calibration is the evaluation of the accuracy of the Purple Air device to further use it in a real-case study. The calibration tested mostly the $R^2$ linearity the sensors are delivering when compared to a high accuracy reference instrument (TSI) and a more expensive low-cost sensor (AQ Mesh). For the sake of this evaluation the main goal was to verify that the sensor can deliver a reliability and accuracy of t 90% or above, which further means that the device is good enough for the monitoring and observational purposes considering that only Purple Air of all the sensors in the test are capable of been used on the go. With a more complex and in depth calibration an correcting equation could be produced that would further improve the accuracy of the data given during the post processing phase of the data management. In this case no such equation was calculated since 90% accuracy was high enough to have accurate data for observatory purposes and would contribute in no major way.

### 7.1.1 Purple Air Data to TSI DustTrax

The first linearity that was tested was Purple Air's to TSI's. The values of Purple Air that are on the x axis and TSI on y axis.

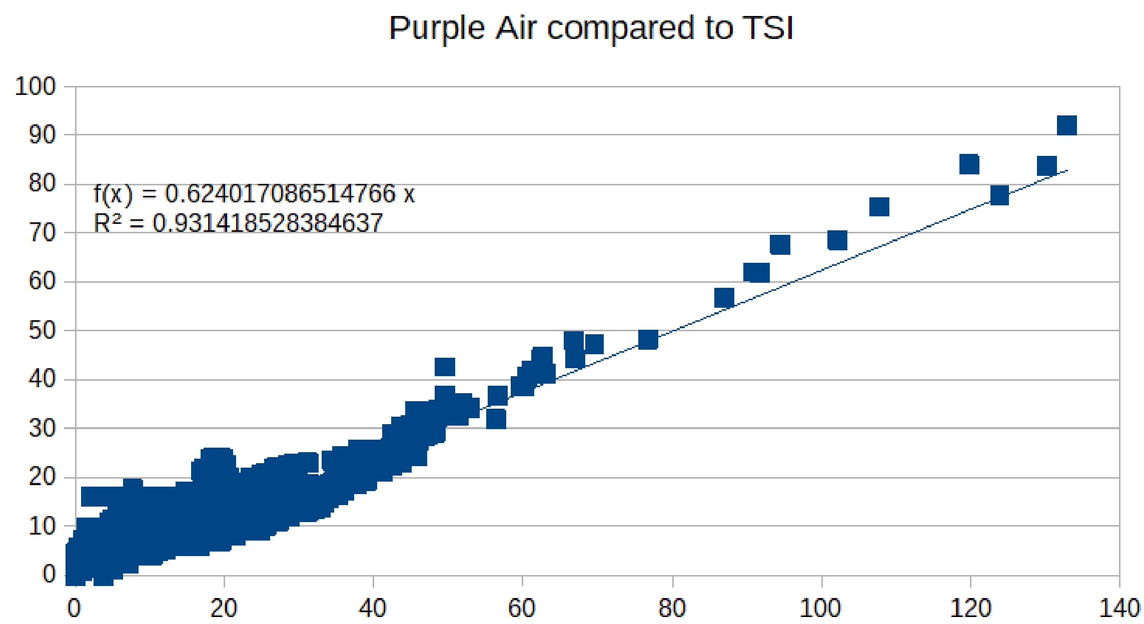



**Figure 2: Correlation Coefficiency Between Purple Air and TSI.**

The overall linearity correlation between the two is at 93.14%, which is considered to be high for a low-cost sensor.

From the data collected overall one thing that can be noted is that Purple Air has a consistent tendency to over report PM2.5 concentration with around 10% higher values once the concentration is above 25 μg/$m^3$.

### 7.1.2 Purple Air Data to AQ Mesh

The next linearity tested was the low-cost sensors Purple Air and AQ Mesh that showcased the lowest correlation percentage throughout this test of 89.65% which is still high enough. The Purple Air data is on y axis and on AQ Mesh on x axis.

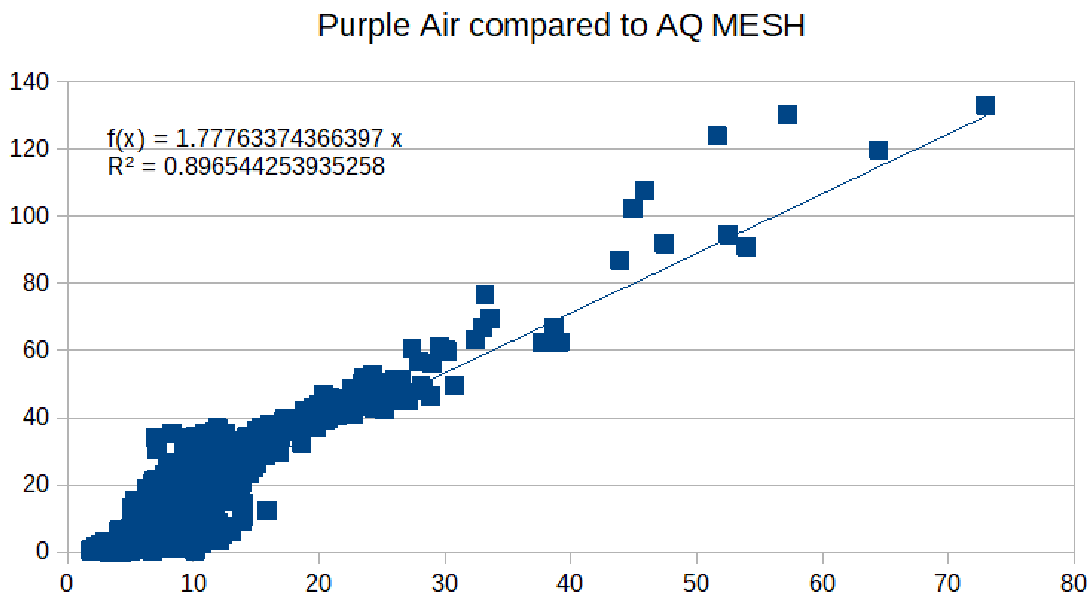



**Figure 3: Correlation Coefficiency Between Purple Air and AQ Mesh.**

Considering that this comparison is between two low cost sensors 89.65% (~90%) is a high correlation percentage.

### 7.1.3 AQ Mesh to TSI DustTrax

Finally is last linearity test was between AQ Mesh and TSI with TSI data being on y axis and AQ Mesh data on x axis.

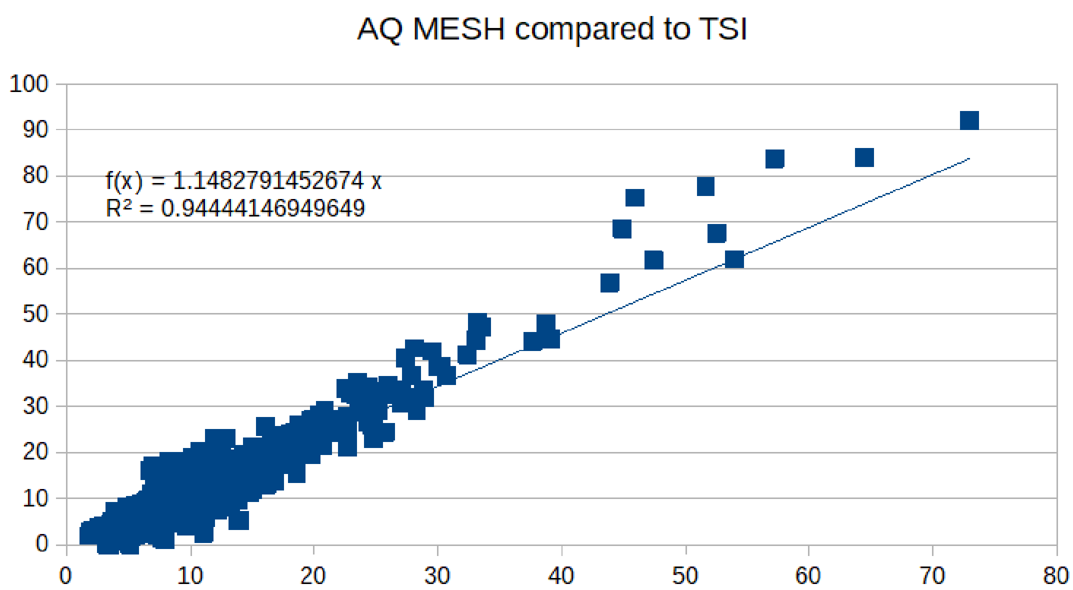



**Figure 4: Correlation Coefficiency Between AQ Mesh and TSI.**

The linearity correlation test between AQ Mesh and TSI was the highest at 94.44% scoring 1.3% higher than the correlation result of Purple Air to TSI. This means that probably AQ Mesh is slightly better performing compared to Purple Air.

## 7.2 Results of overall study route and Graphs

Bellow are presented the graphs that showcase the average exposure by concentration (μm/m$^3$) and AQI values of PM2.5 throughout the week of an average student or worker using Public Transportation.

The graphs are showcasing the exposure from the route of Varkiza to Egaleo, followed by the same graph but for the returning route of Egaleo to Varkiza, finally a combined version of the two routes is showcased as well.

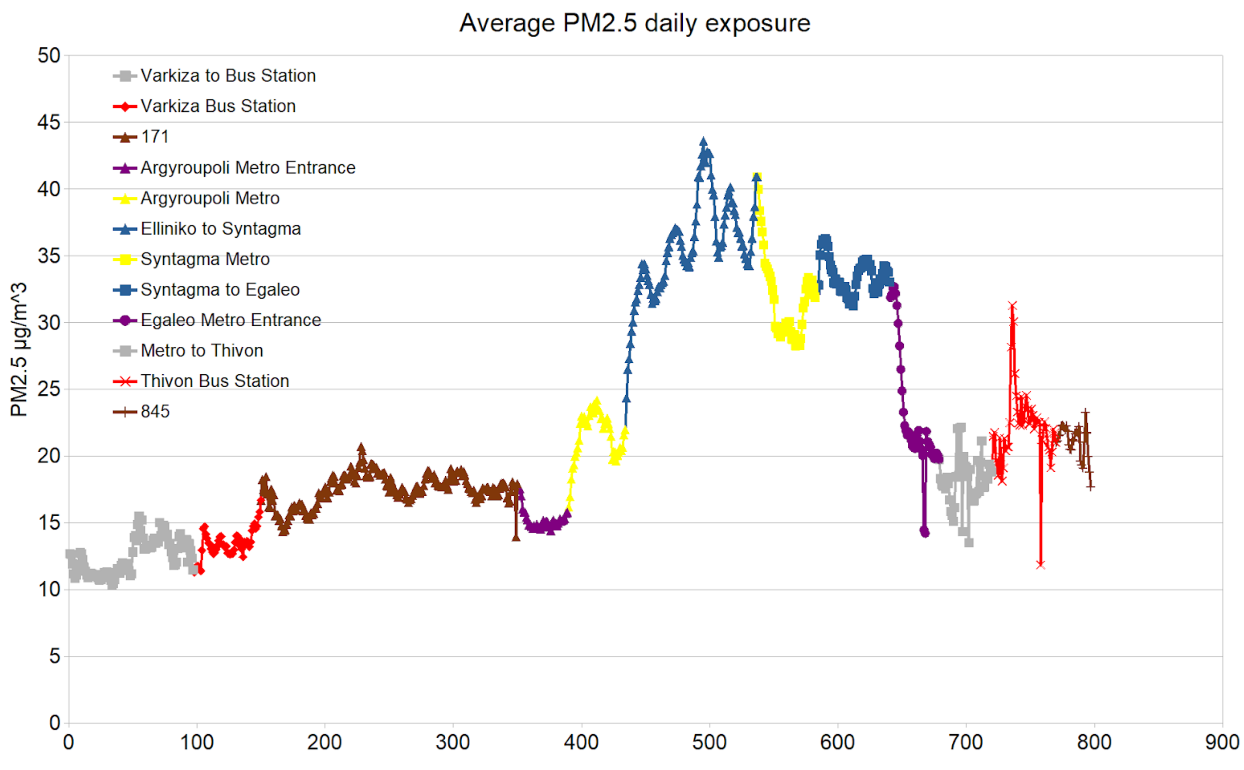



**Figure 5: Overall PM2.5 concentration on the route from Varkiza to UNIWA of the 17 days of data.**

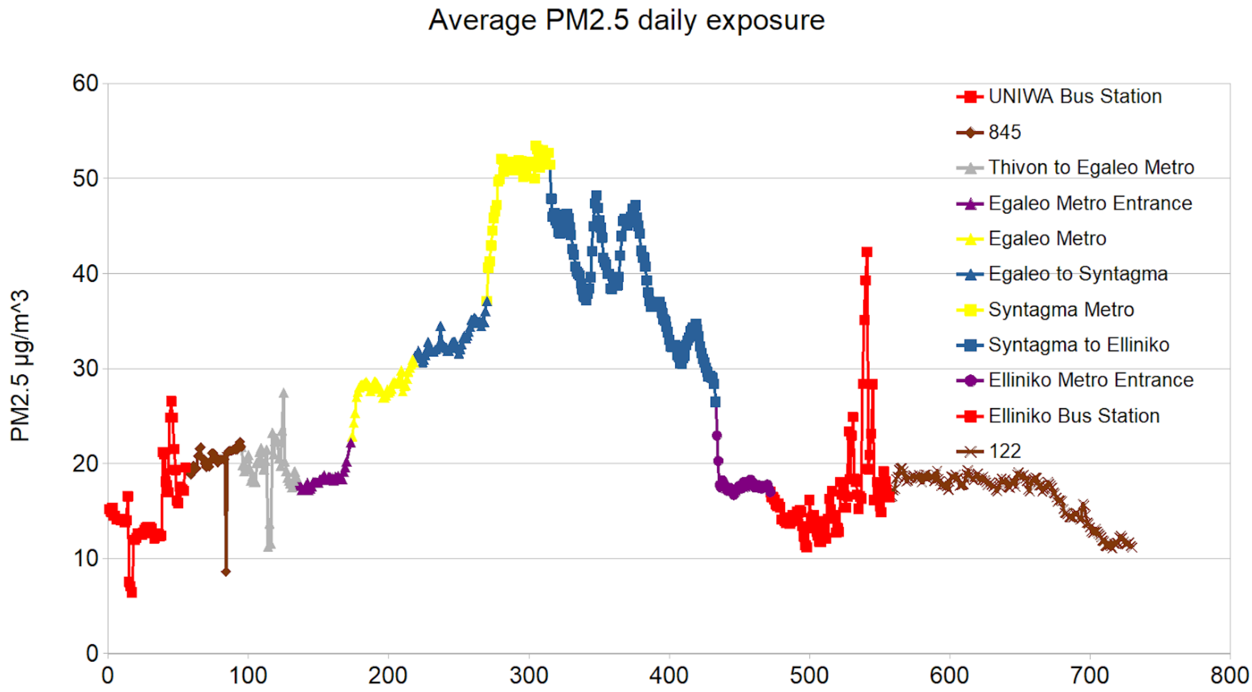



**Figure 6: Overall PM2.5 concentration on the route from UNIWA to Varkiza of the 17 days of data.**

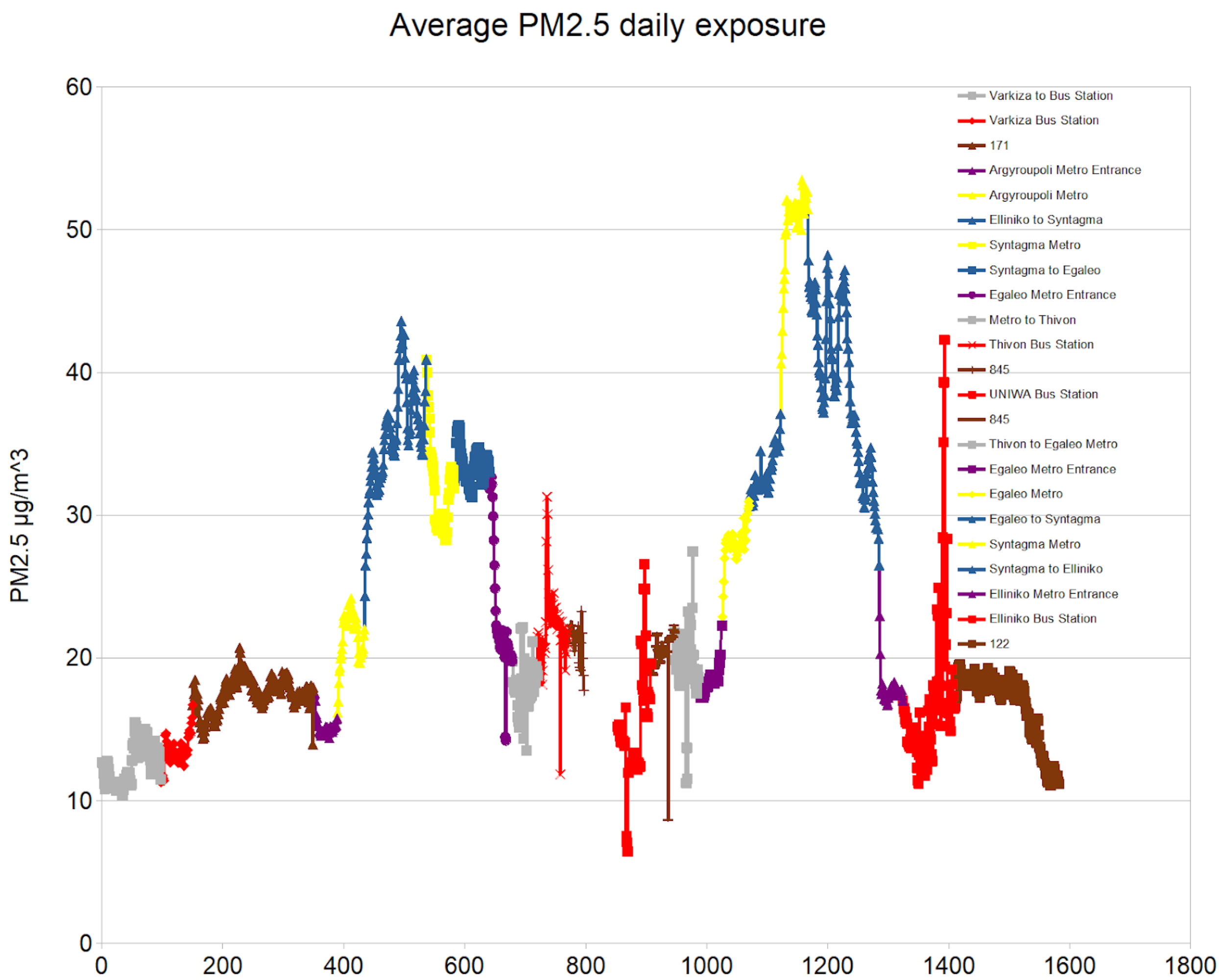



**Figure 7: Overall PM2.5 concentration on the route from Varkiza to UNIWA and from Uniwa to Varkiza of the 17 days of data.**

As showed in the graphs above there is a clear level distinction between the different transportation options. Metro has the highest concentration out of any other option of transportation available with increasing concentrations emerging at central stations near Syntagma and with further metro station being relatively "cleaner" (Egaleo, Argyroupoli, Elliniko etc.). Overall the graph (3) as well as graph (1) and (2) indicate that the subway is rich in PM2.5 emissions at the lower levels of the subway infrastructure, with moments of concerning increase of PM2.5 concentrations, (in graph (3) throughout the values between 1100 to 1300), meanwhile the ticket booth level show the lowest amount of PM2.5 exposure on average indicating that the metro wagons are the main sources of PM2.5 emissions, since the concentration is increased once we move at the platform level. Ticket booth level in some situations also seem to have lower PM2.5 concentration reported than outside spaces (graph (1) values between 100-200, graph (2) values between 425-500), possibly the reason is because of the temperature difference between the outside conditions and the conditions in the platform level, strong waves of air are created causing dispersion of the emissions.

On the graphs above, bus routes are showcased as being relatively low in PM2.5 concentration but during the data processing there were noticed instant increases in concentrations that seemingly had no pattern, possibly the reason for such spikes are outside influences in combination with open windows (ex. the bus passing by a construction site), even though those spikes were impossible to foresee, they cannot be ignored nor be showcased well at the graphs of the average concentration of the seventeen days. Bellow some of those examples will be highlighted.

Finally bus standing points should be mentioned that are also inconsistent in their depiction. Many intense concentration spikes were recorded mostly contributed to a nearby passenger smoking. In many cases due to many station gathering big groups of people waiting, it increases the chances of a multitude of people lighting up a cigarette, thus causing immense spikes at the measurements. Also during wait time situational traffics may occure which can cause emission increases as well.

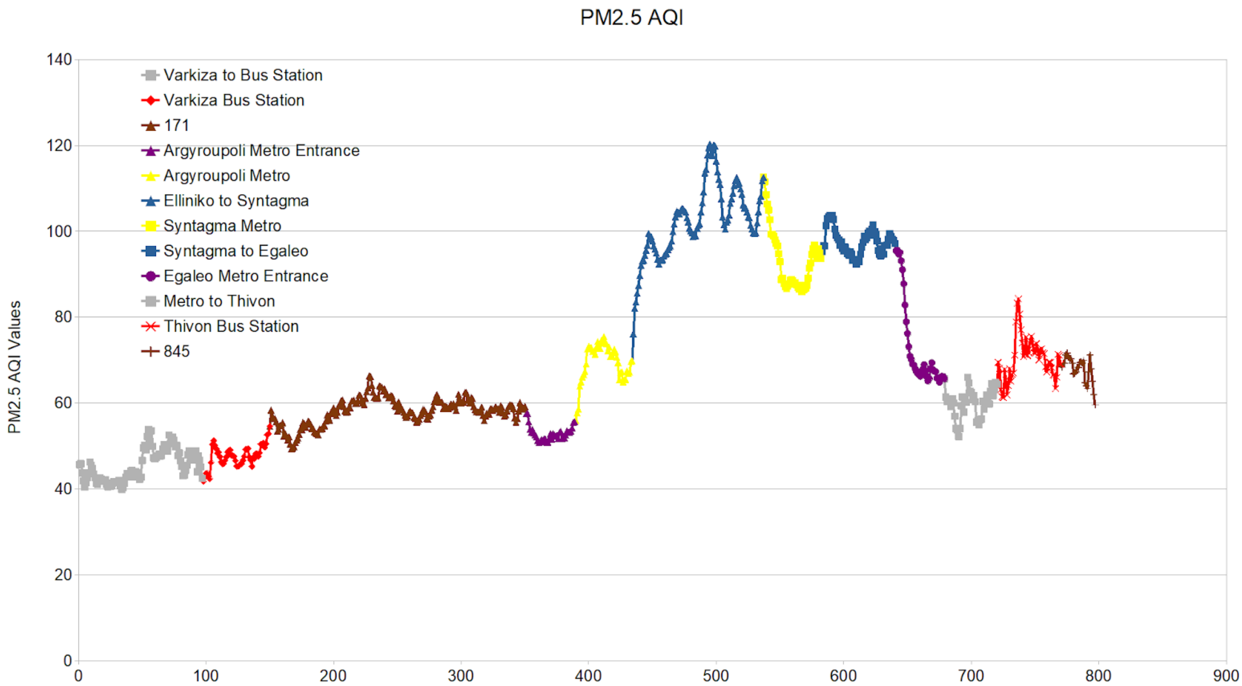



**Figure 8: Overall PM2.5 AQI on the route from Varkiza to UNIWA of the 17 days of data.**

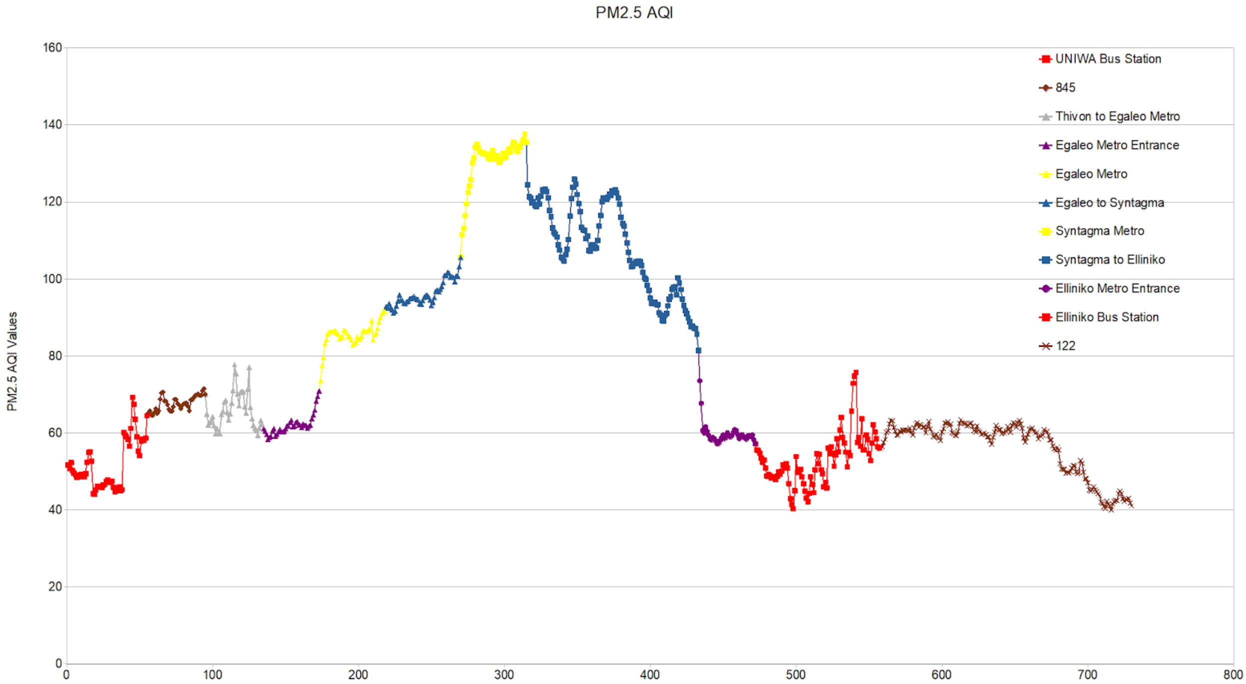



**Figure 9: Overall PM2.5 AQI on the route from UNIWA to Varkiza of the 17 days of data.**

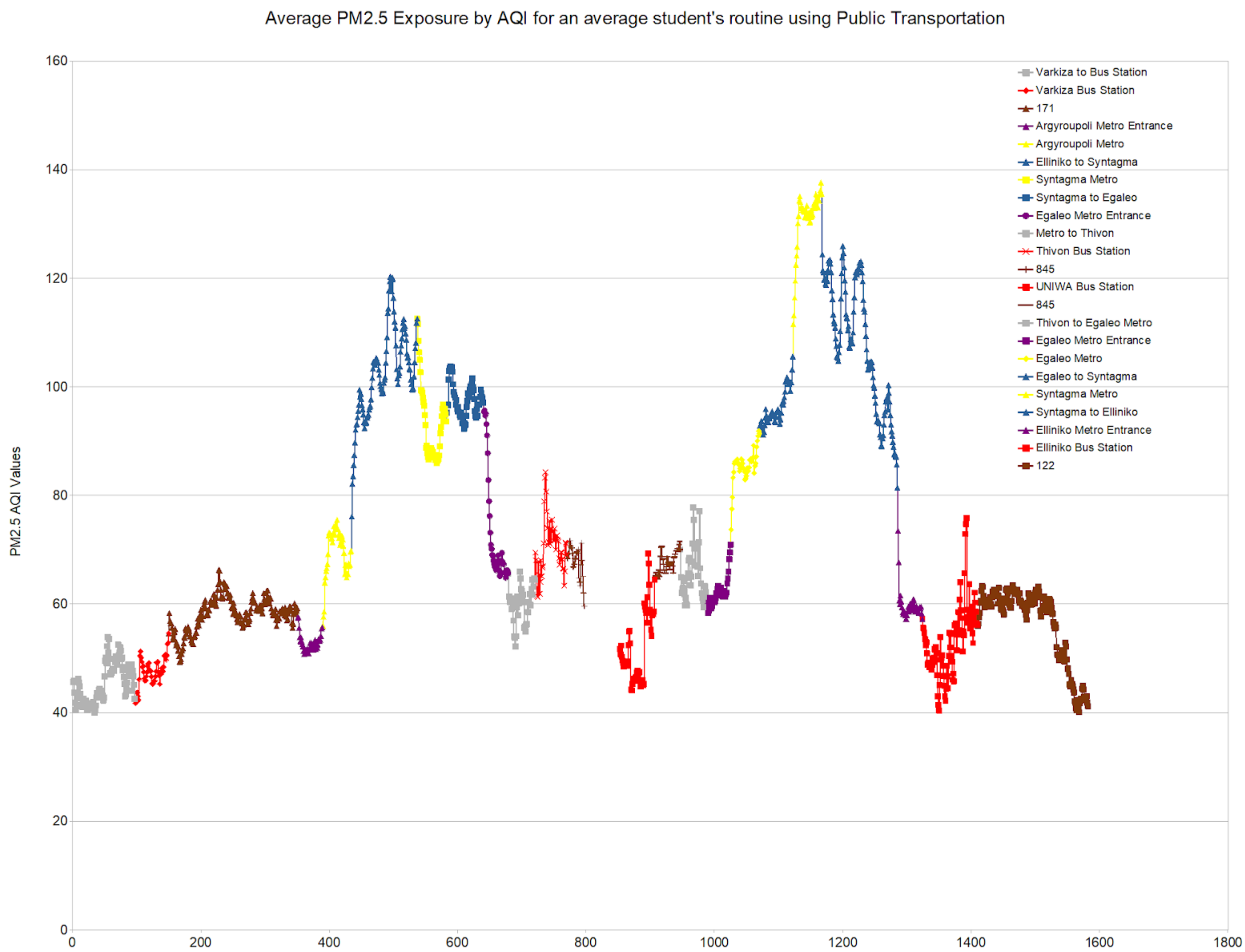



**Figure 10: Overall PM2.5 AQI on the route from Varkiza to UNIWA and from UNIWA to Varkiza of the 17 days of data.**

Similarly the graphs of AQI values showcase the same results. Through the route towards UNIWA there is a distinction of three different groups of AQI levels exposure. The first one is from Varkiza starting point until the subway platform level where the AQI levels throughout the route hardly surpass the value of 60. After the subway platform the AQI levels surpasses 60 and even reach up to 70 consistently. Once in the subway wagon the AQI levels are consistently increasing the more we are approaching Syntagma station. We should mention that while going towards Syntagma Station there are many passenger disembarking at various stations to go to their work and similarly many passengers are embarking to move to the station of their destination, naturally the more we approach the centre of Athens the higher the amount of people using the subway to get to their jobs will be, but overall the desired stations for disembarking are spread throughout the route. It doesn't take long for the metro wagon to reach an AQI level of 80 and above, with many points reaching levels of above 100 reaching up to 120. At the platform of Syntagma station the AQI levels do stabilise at around 85. The next metro route which has a shorter distance to cover maintane a relatively stable AQI levels of around 100. Finally the ticket booth at Egaleo station could be considered the third group of AQI levels that going up and down throughout, but within the range of 60 and 80. Additionally we should comment on the fact that the further we move from the centre the lower AQI values we get, some important to note reasons for that is the geographical and weather we get once we get at Argyroupoli/Elliniko. Throughout the monitoring routine a notable one to two Celsius degrees difference was reported from Egaleo to Elliniko and Argyroupoli and a slight increase on wind. In short one of the reasons such difference is noted is because from Argyroupoli and onwards the heat island effects is wearing off or it is not as strong as it is on around Egaleo.

On the returning routine, the emissions on Thivon street, while at the bus station, the bus and walking from Thivon to Egaleo metro station, has a lower values than those of the route to UNIWA with overall average exposure around 70 AQI. From the subway platform until the ticket booth level of Elliniko metro station the concentration is mostly above 100 AQI which can be concerning for a some group of people. More specifically the route from Egaleo to Syntagma has a steady increase of AQI values starting at 90 and reaching slightly higher than 100. At the platform of Syntagma we observe a concerning spike skyrocketing the AQI value from slightly over 100 to nearly 130. The main reason for this spike is mostly the fact that the platform for the red line at Syntagma has a frequent schedule of wagons passing from both directions (with average subway passing every 3 minutes). The constant stops of the subway wagons greatly increases the PM2.5 emissions, but it also increase the activity of passengers with many passengers embarking and disembarking. As we will observe in detail later, high passenger traffic is a major influence to the PM2.5 concentration. Once at Elliniko metro station, the AQI values are maintained at around 60 AQI value, with minor instant and short-term spikes of AQI values, mostly due to situational road traffic or nearby smokers.

## 7.3 Results of the Metro routes and Graphs

In this chapter we will delve deeper into the different circumstances that may affect the results of the data and after breaking down and understanding the different factors a breakdown of the overall results will be showcased and further commented.

The three time groups that the data were collected are, group 1 6:00-9:00, group 2 9:00-12:00 and group 3 12:00-15:00. Within each week data for the route of Varkiza to UNIWA was collected, two days for group 1 and group 2 and one day for group 3.

Bellow will be presented the average concentration values throughout the route of Varkiza to UNIWA within the 3 different sampling time groups. Then a comparison graph will be presented showcasing all three graphs into one. Finally a detailed graph of the metro concentrations between the three different sampling time groups will be presented, separating the two different rides from Argyroupoli to Syntagma and Syntagma to Egaleo.

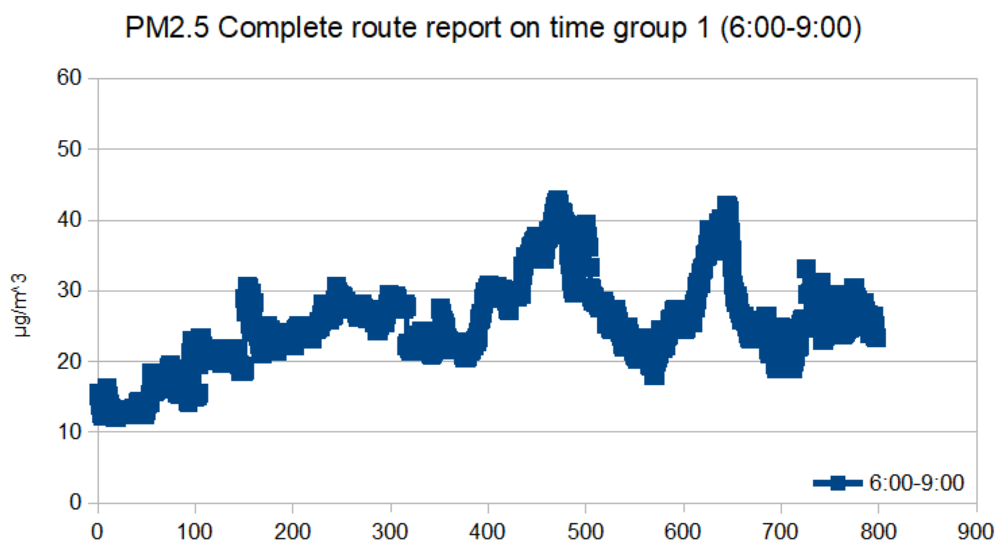



**Figure 11: PM2.5 concentration of the complete route on group 1 sampling hours.**

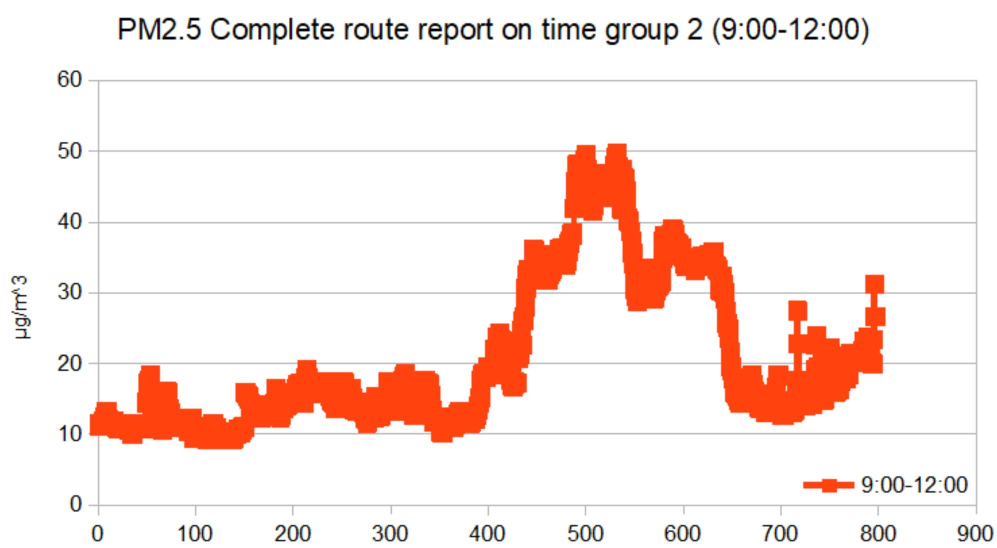



**Figure 12: PM2.5 concentration of the complete route on group 2 sampling hours**

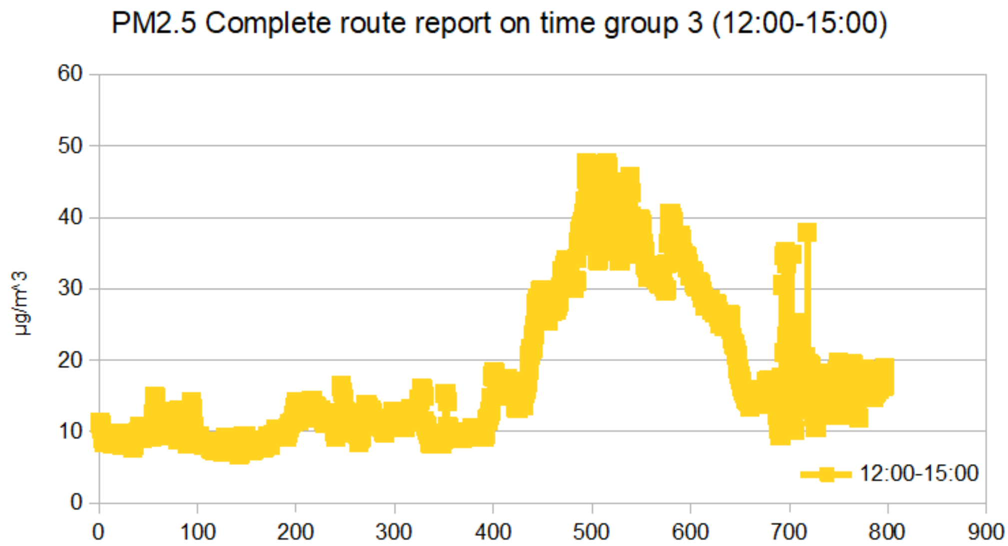



**Figure 13: PM2.5 concentration of the complete route on group 3 sampling hours**

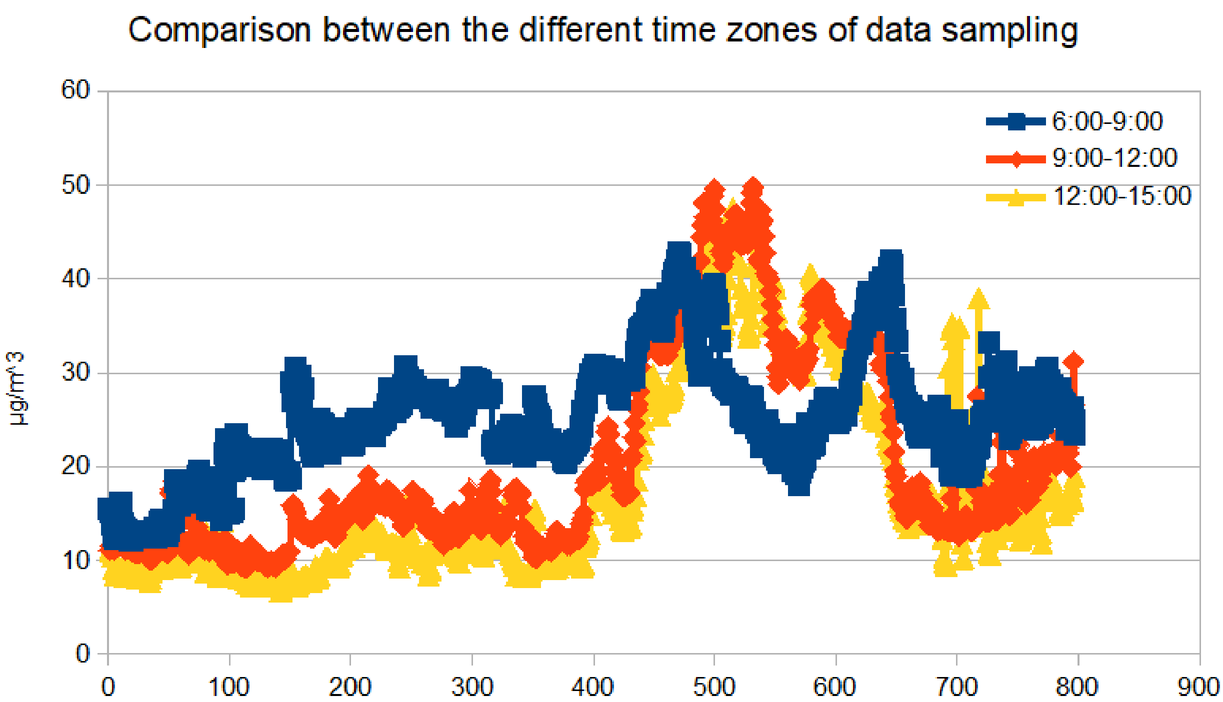



**Figure 14: PM2.5 concentration of the complete route of the three groups of sampling hours.**

First of all we can see a clear similarity to the results of the data for the sampling time group 2 and group 3, with group 3 following the same characteristics as group 2 but slightly decreased, but with some concentration spikes on the values around 700 to 750 which is during the bus station at Thivon avenue for the bus of 845 for UNIWA. The reason for the two time groups being so similar is because the activity throughout the public transportation used in this study after 9:00 o'clock is the same, it's consisted mostly of employees going to their job, students going to their Universities and a small group of people going for shopping. The reason for the decrease of sampling time group 3 from group 2, is because much less jobs have a schedule that start post 10 o'clock, meaning that the main groups of people that use public transportation at that time are primarily people that go to universities and shopping as well as some people that their job starts within 12:00 to 14:00 o'clock.

As can be observed the first sampling time group is significantly higher than the other two up to values of 420. Until the values of 350 the graph is covering the walking distance from the starting point of Varkiza to Varkiza bus station and the bus from Varkiza to Argyroupoli metro station (through Vouliagmenis avenue road). From values of 350 up to 420 the data are covering the sampling of ticket booth level of Argyroupoli metro station and the platform level of Argyroupoli metro station. The reason for the significant increase during this time zone is because for employees that their jobs starts at 8:00 o'clock up to 10 o'clock (which are the most common starting working hours) and are residents of any of the suburb area between Argyroupoli and Varkiza, if they use public transportation to get to their job it is required to start around this time zone. Similarly as we will see later on, this is also presented by the concentration levels of Metro stations where concentration is higher on station furthest from central stations such as Syntagma, Sygrou and Neos Kosmos. Later on the passengers that use public transportation is stabilised throughout the time zone of 9:00 to 12:00.

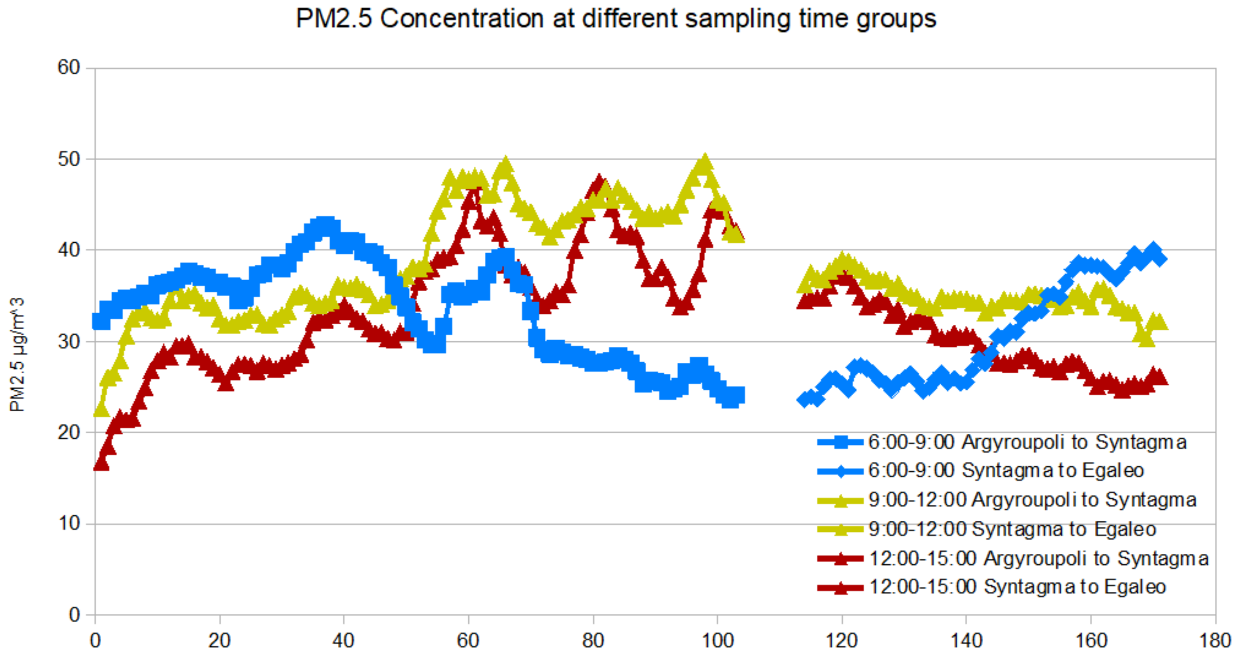



**Figure 15: PM2.5 concentration of the metro routes of the three groups of sampling hours.**

As mentioned previously during the first data sampling time group, PM2.5 concentration is higher at the furthest stations from the center. The reason for this it's because during this time the metro is primarily used from people that leave in the suburbs and have to cover big distances and they do so by starting early on. Throughout the monitoring routine it was noted that in the first time group, wagons had mostly passengers embarking until the station of Neos Kosmos (which is connected with Tram line) with almost no passengers disembarking up to Neos Kosmos. After the station of St. Dimitrios the passenger embarking is decreased throughout the route, mostly because people that have access near the stations after St. Dimitrios have no reason to start that early. At the second route of Syntagma to Egaleo the same scenario is showcased. At the central stations of Syntagma and Monastiraki the concentration is low and the concentration increases from the point of Keramikos to the point Eleonas and Egaleo.

Second and third groups have a rather similar pattern. In both cases the concentration starts low at Argyroupoli station and gradually picking up from each station onwards. In both scenarios the first concentration spikes happen values of 60-65 which is at Dafni station. The main difference between group 2 and 3 is that in group 2 the increase is maintained for the station of St. Ioannis (values of 65) meanwhile in the group 3 the concentration falls off right after Dafni station and starts picking up at Neos Kosmos station. The reason for that is because as explained prior within the group 2 there are more people using the public transportation to go to their jobs and St. Ioannis station is a convenient station for people that work nearby areas (like Vironas, Kaisariani, Imitos etc.) due to many bus lines that are covering the surrounding areas. Then the second concentration spike happens at Neos Kosmos station (which is more significant in the group 3). Group 2 maintains a stable concentration with a minor increase at Akropoli and finally falls of at Syntagma.

In the second route once again group 2 and 3 have similar depictions, with group having a lesser decrease of concentration the further the wagon moves from the centre towards Egaleo station. In both cases Monastiraki is the highest concentration station, mostly due to the higher amount of people for shopping being within these two groups comparatively with group 1.

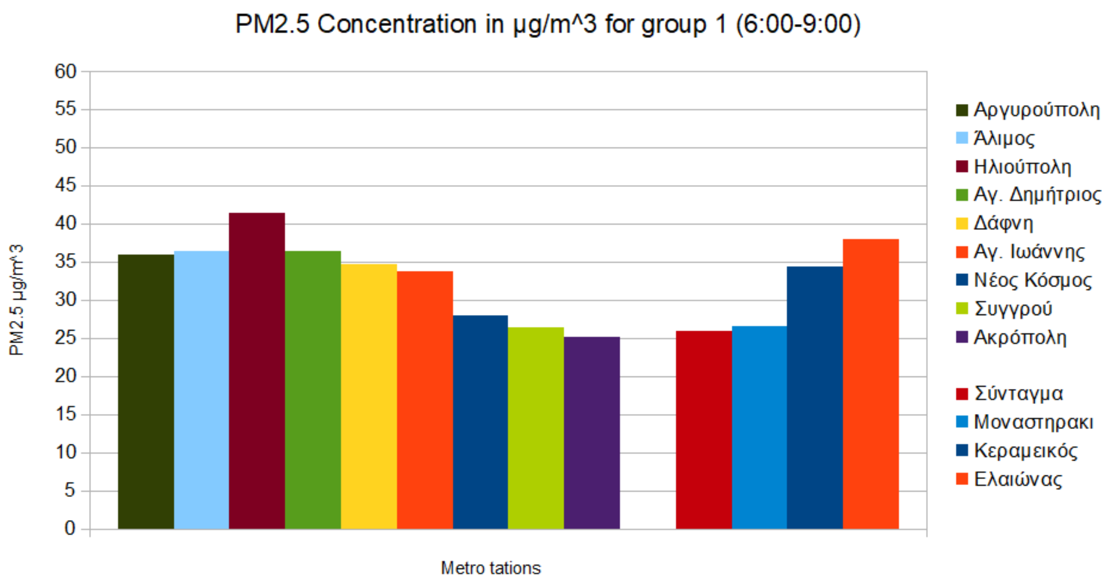



**Figure 16: PM2.5 average concentration on each metro station for the group 1.**

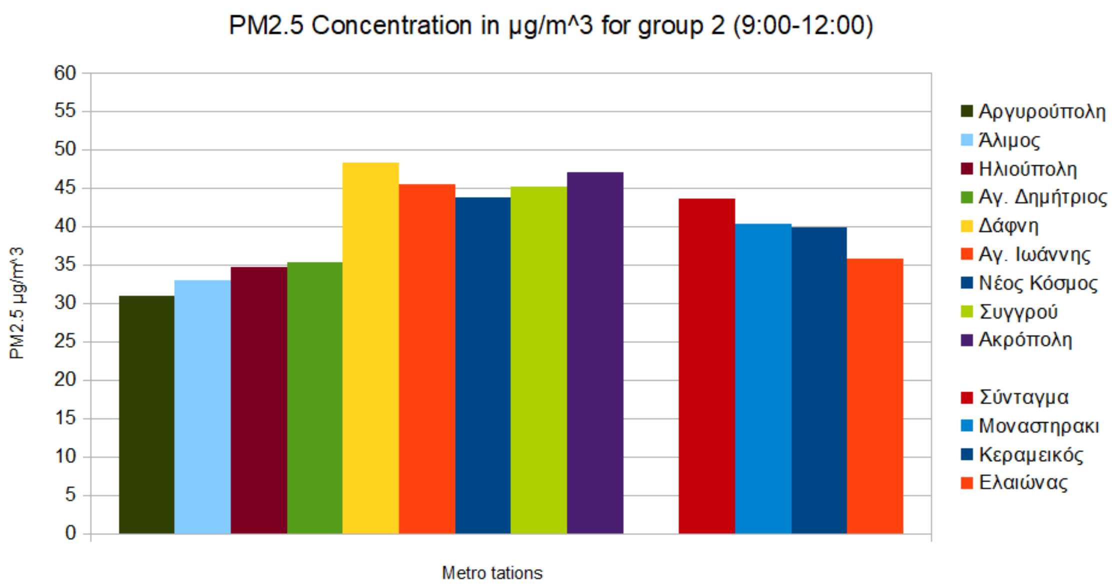



**Figure 17: PM2.5 average concentration on each metro station for the group 2.**

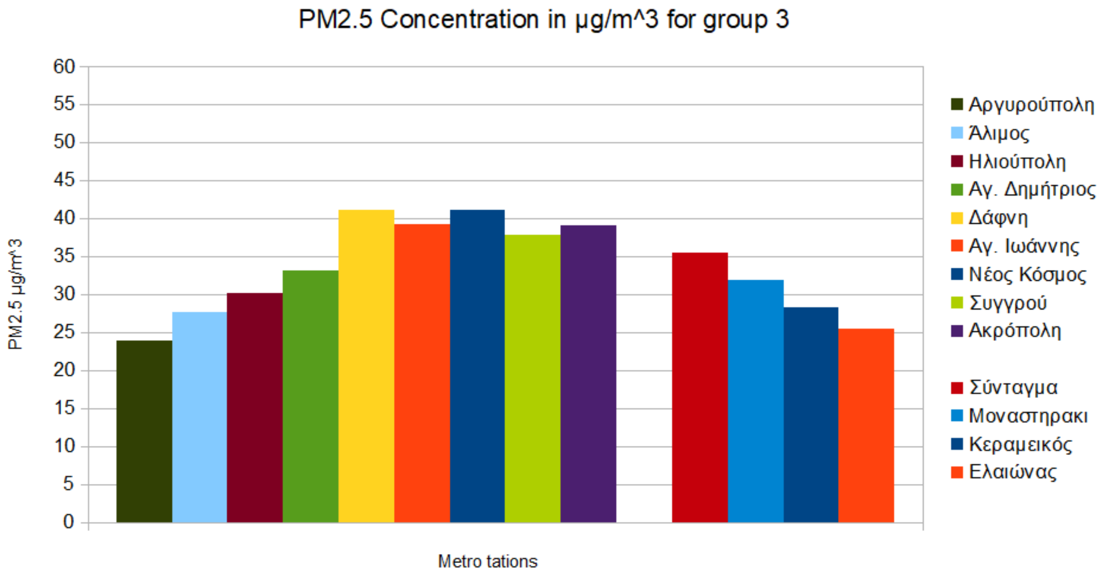



**Figure 18: PM2.5 average concentration on each metro station for the group 3.**

Above we can see the average concentration on each Metro station for each sampling time group. Each bar represents the concentration that was measured from the starting of that station untill the opening of the doors of the next station, for example in the case of Argyroupoli, the data used are the data collected when embarked at Argyroupoli station until the opening of the doors of Alimos Station. As we mentioned previously group 1 showcases the fact that stations the furthest from center tend to have higher PM2.5 concentration with Ilioupoli station being the highest one with concentration equal to 41.4 μg/m$^3$.

In both group 2 and group 3 the concentration is greatly increasing from Dafni station and onwards. Dafni station was the highest activity station on average within the timespan of the 17 days of data collected.

Group 2 has been the one with the highest overall concentrations, with 7 station being above 40μg/m$^3$ and around 5 of them being around 45 μg/m$^3$. Regardless the passengers capacity of the wagon the concentration never dropped below 20 μg/m$^3$.

Finally the average concentration in group 1 was calculated at 35.5 μg/m$^3$, in group 2 was calculated at 40.2 μg/m$^3$ and in group 3 was calculated at 33.4 μg/m$^3$. Even though in group 1 the concentration starts high at average 36.4 μg/m$^3$ this level of concentration is maintained for only 4 stations with the fifth station of Dafni station already falling below 35 μg/m$^3$ and after Neos Kosmos station the concentration falls of below 30 μg/m$^3$ with only exception being Keramikos station that is roughly below 35 μg/m$^3$ and Eleonas station that is roughly above 35 μg/m$^3$. Group 2 has a consistent increase on the first 4 stations (from Argyroupoli to St. Dimitrios) with Argyroupoli being around 32 μg/m$^3$ and St. Dimitrios being slightly above 35 μg/m$^3$. Dafni station showcase an instant spike in concentration reaching to 48 μg/m$^3$ and until Akropoli station the concentration remains above 45 μg/m$^3$ with only exception of Neos Kosmos that is at 43.8 μg/m$^3$. From Syntagma to Egaleo the concentration is around 40 μg/m$^3$ with the highest being Syntagma station reaching at 43.6 μg/m$^3$ and Eleonas the lowest at 35.7 μg/m$^3$. Finally group 3 showcases the least overall concentration with the highest concentration being at 41 μg/m$^3$ at Dafni and Neos Kosmos stations. Argyroupoli station has the lowest concentration below 25 μg/m$^3$ with the concentration for the next station gradually being increased by 3 μg/m$^3$ until Dafni station that has a spike increase at 41 μg/m$^3$ (Ilioupoli, which is the station before Dafni was at 33.1 μg/m$^3$). The next stations are stable at the range of 41 and 39 μg/m³ with only exception of Sygrou station which drops at 37.7 μg/m³. Finally on the route of Syntagma to Egaleo the concentration is steadily droping by 3 μg/m³ with Syntagma being the highest at 35.5 μg/m³ and the lowest being at Eleonas at 25.5 μg/m³.

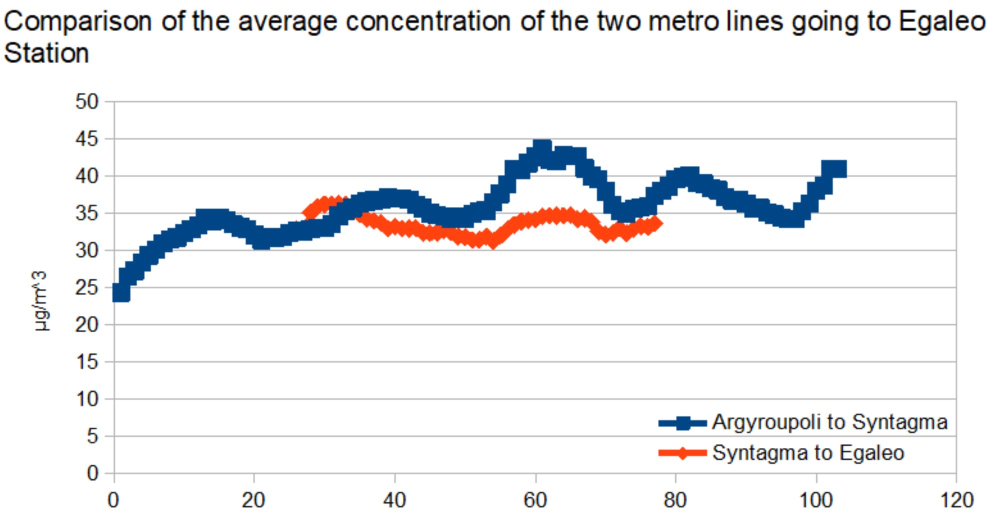



**Figure 19: Comparison of the PM2.5 concentration between red and blue line for the route of Argyroupoli to Egaleo.**

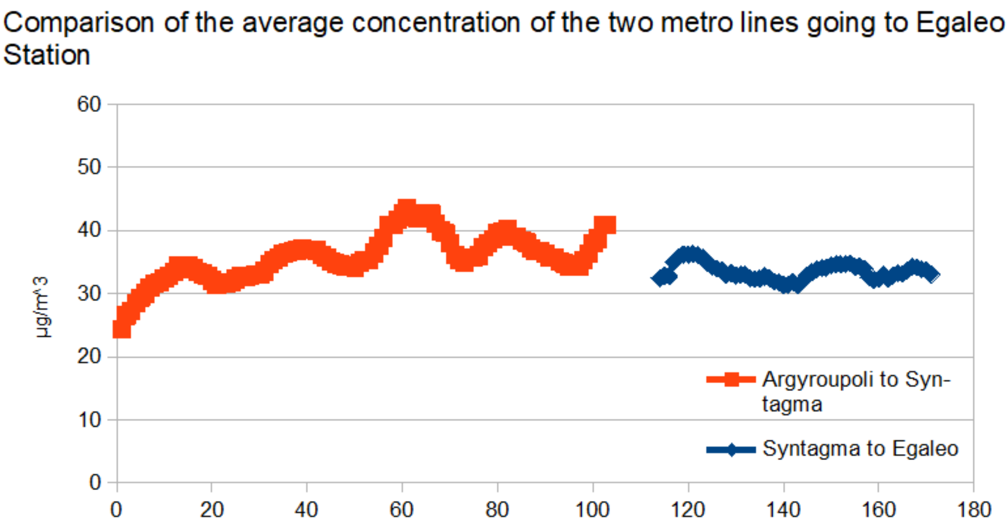



**Figure 20: Comparison of the PM2.5 concentration between red and blue line for the route of Argyroupoli to Egaleo**

The graphs above are showcasing the comparison between the average concentration of the subway routes (Argyroupoli to Egaleo and Egaleo to Elliniko). Egaleo to Elliniko route is consistently between 30 μg/m³ to 35 μg/m³ with the only station being relatively high being Syntagma station where the passenger activity is high. The Argyroupoli to Egaleo route has many fluctuations depending on the characteristics of each station, the concentration is consistent enough above 35 μg/m³ that could be considered that the wagons may have negative effects on vulnerable groups of people.

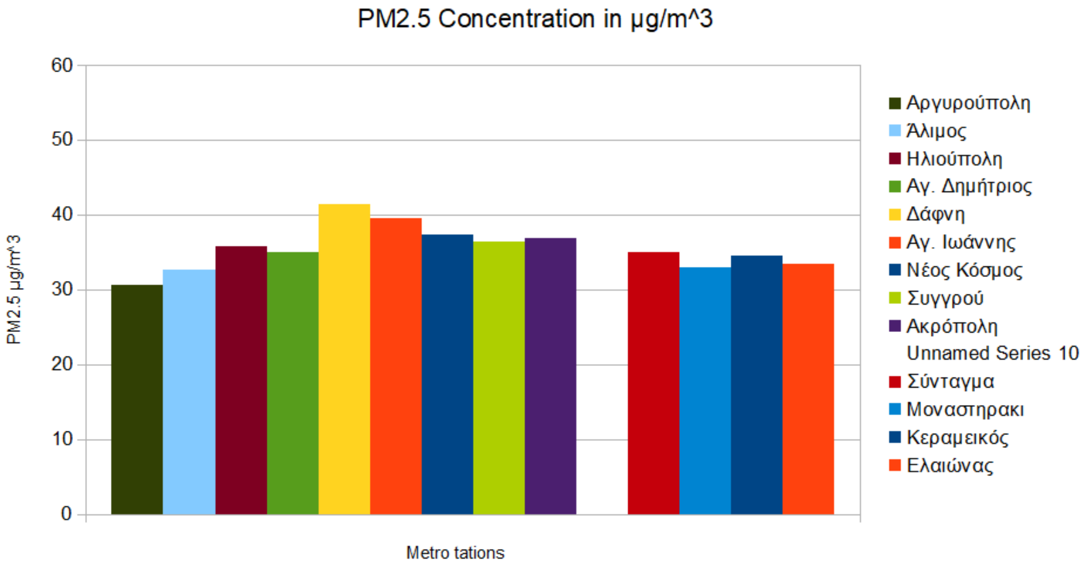



**Figure 21: Overall average PM2.5 concentration on each metro station from the route of Argiroupoli to Egaleo of the 17 days of data.**

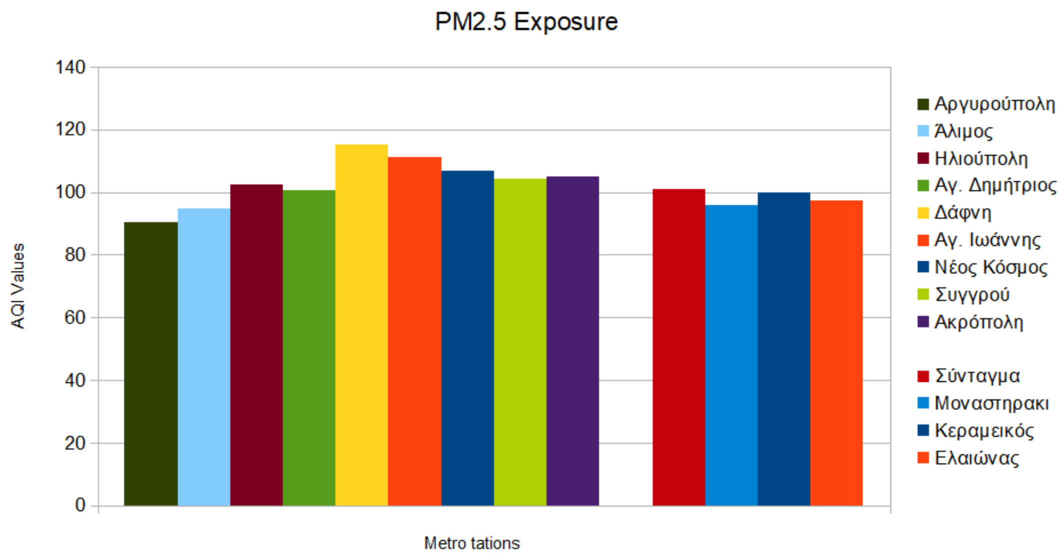



**Figure 22: Overall average PM2.5 AQI on each metro station from the route of Argiroupoli to Egaleo of the 17 days of data.**

Finally above is presented the overall average concentration and AQI values of PM2.5 exposure on each station of metro on the route of Argyroupoli to Egaleo. We can see from the graph that showcases the AQI values that the subway could be considered to be a risk for vulnerable groups of people especially at the central stations of red line (Dafni station through Akropoli station) that are consistently above 100. The blue metro line has mostly values above 90 AQI and below 100 with only exception of Syntagma station with 101. Considering that the whole trip of both lines in total is around 45 to 60 minutes the AQI levels within the subway wagons are considered not ideal, with specific groups of people being at risk.

Below will be presented the graphs of average concentration and AQI values of each station on the route of Egaleo to Elliniko Station.

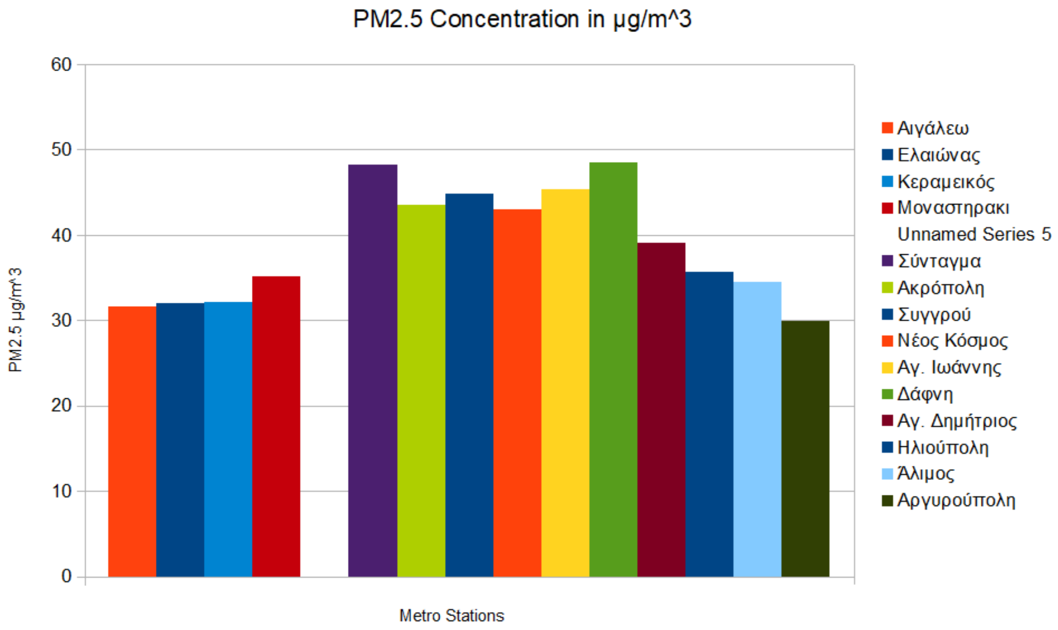



**Figure 23: Overall average PM2.5 concentration on each metro station from the route of Egaleo to Argiroupoli of the 17 days of data.**

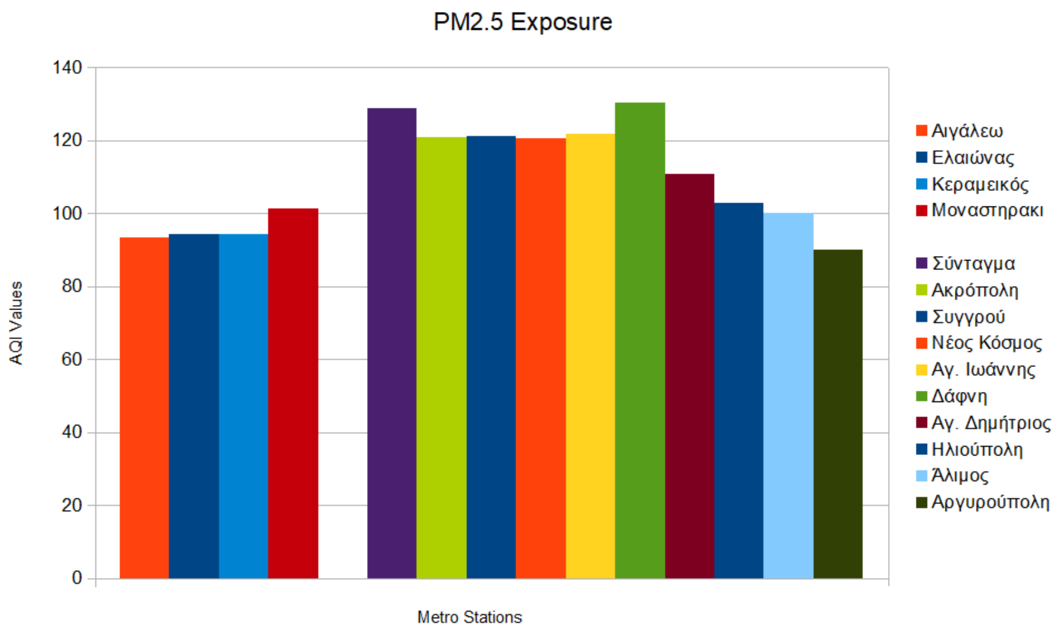



**Figure 24: Overall average PM2.5 AQI on each metro station from the route of Egaleo to Argiroupoli of the 17 days of data.**

The concentration of PM2.5 throughout route of Egaleo to Elliniko are worryingly high, with average concentrations reaching close to 140 AQI values and with individual situation reaching up to 160 AQI (day 12, supplement A). In this route more than half of the station are above 100 AQI with mostly blue line having stations below 100 AQI and just two station of red line being below 100 AQI, which they are the last stations of the line (Argyroupoli and Elliniko station) and Argyroupoli being at 99 AQI. Similarly the highest concentrations are observed at central stations with Syntagma and Dafni being the highest and the in-between stations being higher than the rest of the route.

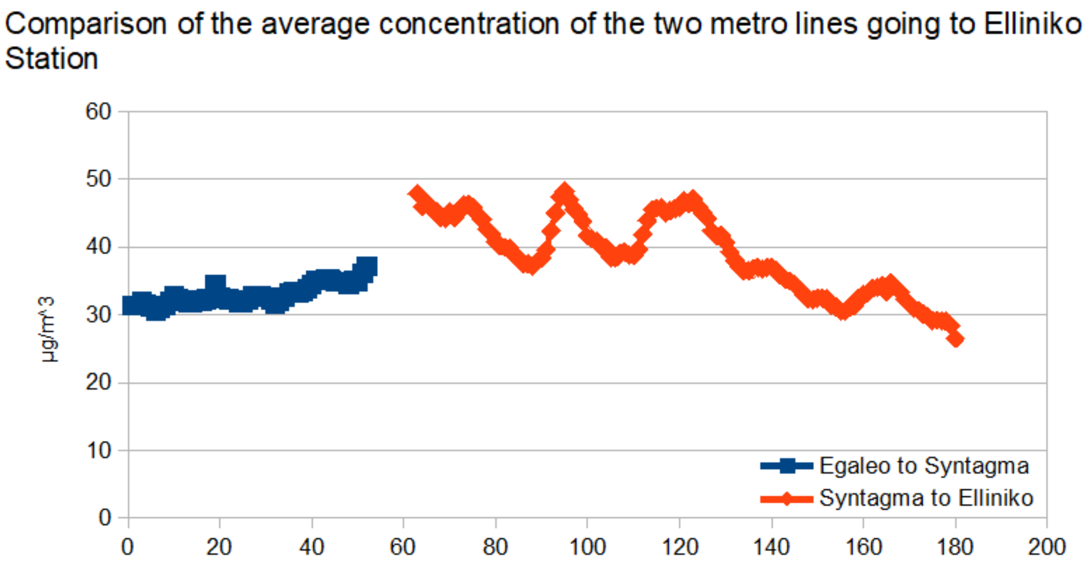



**Figure 25: Comparison of the PM2.5 concentration between red and blue line for the route of Egaleo to Argiroupoli of 17 days of data.**

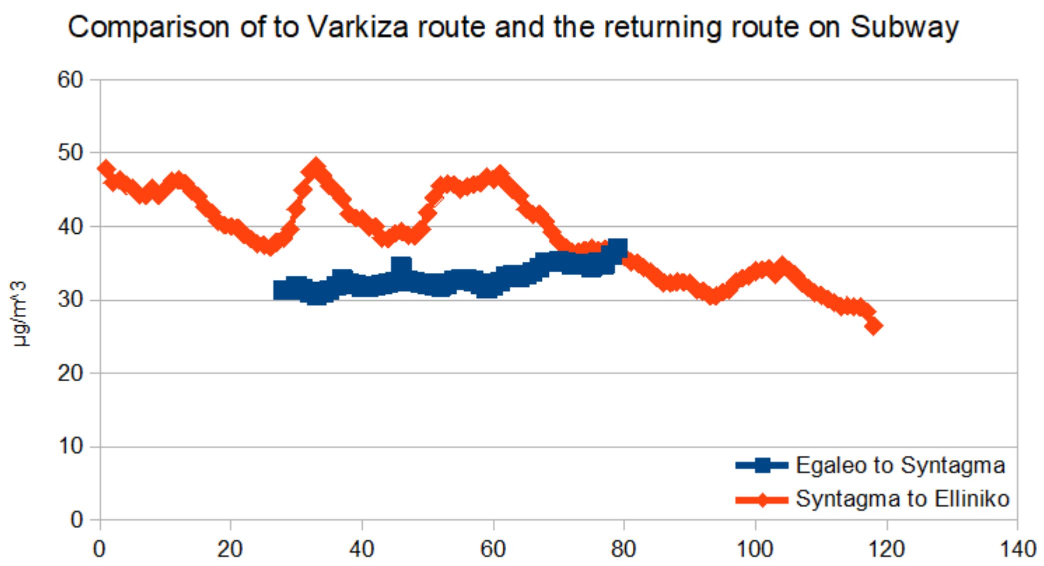



**Figure 26: Comparison of the PM2.5 concentration between red and blue line for the route of Egaleo to Argiroupoli of 17 days of data.**

Blue line has a more consistent and stable PM2.5 concentration sticking at the range of 30 μg/m$^3$ to 35 μg/m$^3$ (and slightly higher 35near Syntagma Station). Within the first half of the route of Syntagma to Elliniko the concentration is mostly on the range of 40 μg/m$^3$ to 30 μg/m$^3$ with some situations being below 30 for a short period of time. The second half of the route the concentration is within the range of 35 μg/m$^3$ to 30 μg/m$^3$ and near Elliniko station even drops bellow 30μg/m$^3$.

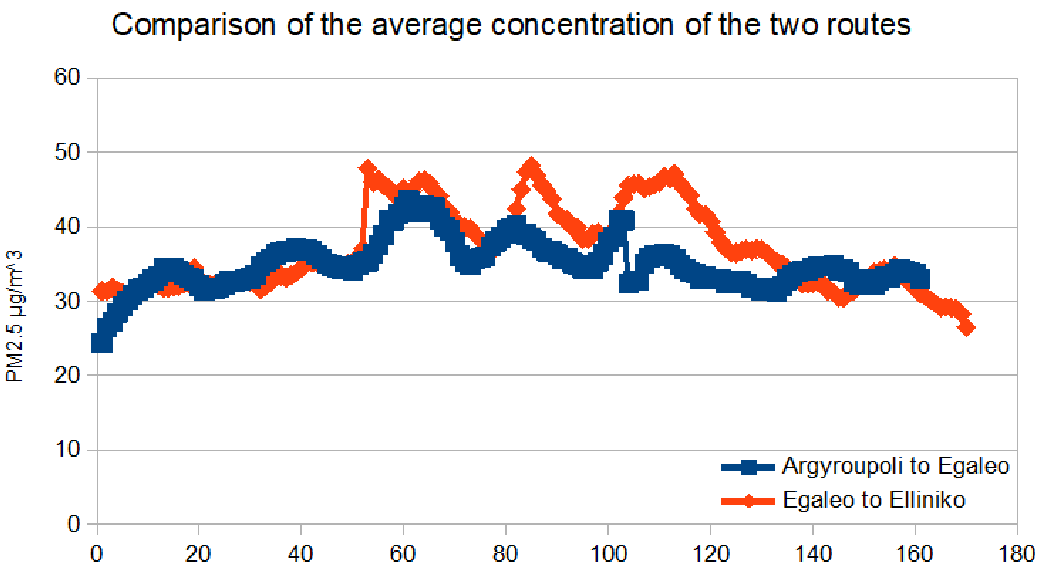



**Figure 27: Comparison of the PM2.5 concentration of the metro routes of Argiroupoli to Egaleo and Egaleo to Elliniko of 17 days of data.**

Finally we can clearly see that from the graph above the concentration during the metro route of Egaleo to Elliniko is overall higher with rare occasions of Argyroupoli to Elliniko route being higher and only for short periods of time and with minor differences. We should not that the returning route is mostly separated in two different concentration levels the first level is the beginning and the end of the route where the concentration of the PM2.5 are within the range of 30 μg/m$^3$ and 35 μg/m$^3$ and the second one being from 35 μg/m$^3$ to 45 μg/m$^3$. Similarly the same could be said for the route of Argyroupoli to Egaleo, with the beginning and ending of the trip being within the range of 30 μg/m$^3$ and 35 μg/m$^3$ and the middle of the trip being around 35 μg/m$^3$ to 40 μg/m$^3$ with only a short period which surpasses 40 μg/m$^3$.

### 7.3.1 A look on the platform level AQ and ticket booth level AQ

Bellow a graph comparing the average of the two levels of Metro (the platform level and the ticket booth level) with the average of the outside PM2.5 concentration. The data on the first graph are from the outside of the Argyroupoli station, the ticket booth level of Argyroupoli station and finally the platform level of Argyroupoli station. The data on the second graph are from the outside of Egaleo station, the ticket booth level of Egaleo station and finally the platfrom level of Egaleo Station.

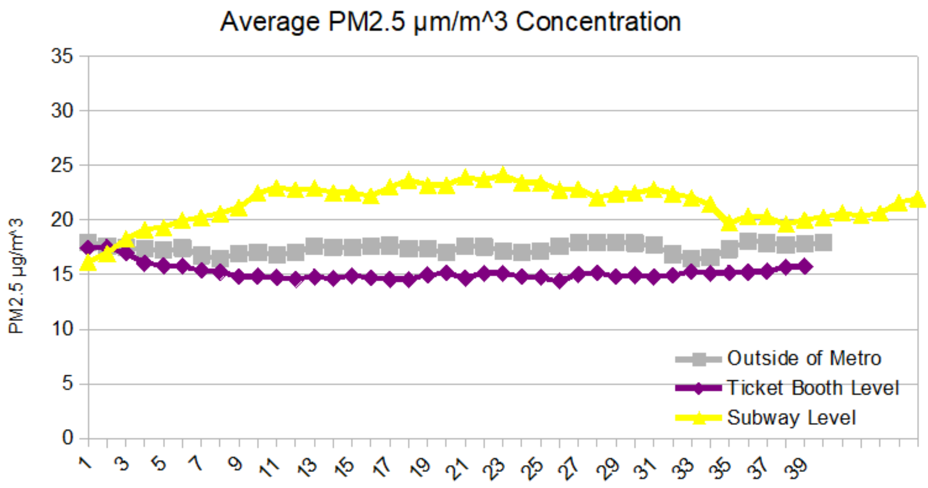



**Figure 28: Comparison of PM2.5 concentration of Argiroupoli Station between the outside of metro level, the ticket booth level and the platform level of the 17 days of data.**

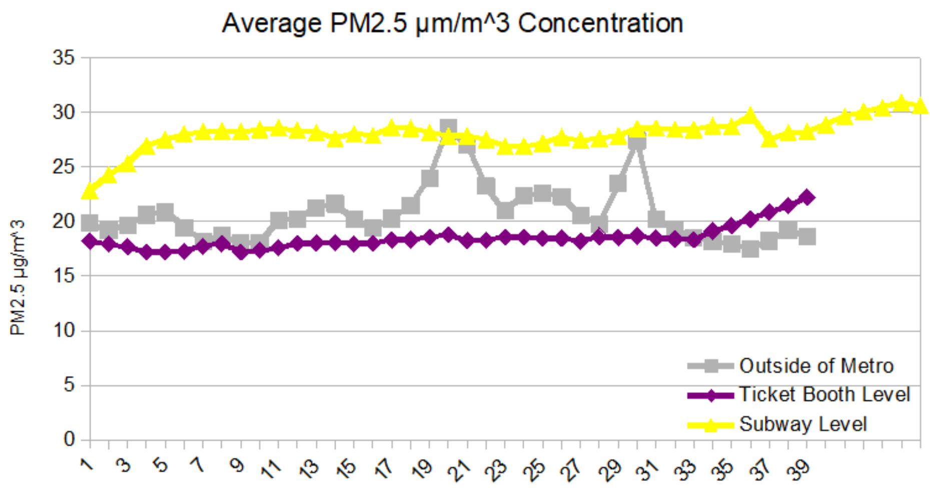



**Figure 29: Comparison of PM2.5 concentration of Egaleo Station between the outside of metro level, the ticket booth level and the platform level of the 17 days of data.**

As showcased on the graphs above we can see that the PM2.5 concentration on the level of ticket booth remains the lowest comparatively to the outside conditions and the platform level.

The data from outside of the station in the case of Argyroupoli is consistently at the range of 16.5 $\mu g/m^3$ and 17.9 $\mu g/m^3$, being at a state that no much health risk are presented, especially considering that the Argyroipoli station is next to Vouliagmenis avenue. The ticket booth level start with a concentration close to the one showcased in the outside level, mostly because the first data collected are strongly influence from the previous conditions that the outside space was. Throughout the waiting in the ticket booth level the concentration is stabilised at the range of 14.5 $\mu g/m^3$ and 15.5 $\mu g/m^3$ (excluding the first few measurements that are strongly influenced from the outside conditions). The platform level of Argyroupoli station showcases a rapid increase on the previous concentration of the ticket booth levels, mostly associated with the PM2.5 emissions of the subway wagons, some of the sources of these emissions are the breaks of the subway wagons that are wearing out during the use especially considering the high speeds the subway wagons are travelling at, the strong winds created from the instant decrease of speed of subway wagons that raises dust particles from the ground and the walls of the subway and most likely from the dust particles that are trapped from the outside air in the subway level as well as the dust brought from passengers. In the case of the Argyroupoli station the concentration is mostly within the range of 20 $\mu g/m^3$ and 25 $\mu g/m^3$, which even though it can be considered harmful for some groups of people, considering the fact that this exposure is for around 5 minutes of wait to 10 minutes until the wagon arrives it shouldn't be risky for most people.

In the case of Egaleo station we see a pattern from the previous graph of Argyroupoli station being repeated, in which the ticket booth level is the lowest one in terms of PM2.5 concentration, with the outside open air level being slightly higher and the subway platform showcasing a significant increase from both the outside conditions and ticket booth conditions. More specifically the data from the outside of Egaleo station showcase a concentration within the range of 18 $\mu g/m^3$ and 23 $\mu g/m^3$, this data is not quite stable nor consistent throughout with many fluctuations within the given range, but with some instant increases and drops above and bellow the range mentioned, with one measurement in specific exceeding 25 $\mu g/m^3$. The main reason for such inconsistency to occure in the case of Egaleo is mostly because there are more people passing by the Egaleo metro station with some restaurants being around as well. We should also mention that it was noted that many people used the area around the metro station for a cigarette break due to the lack of benches in the area. The ticket booth level is slightly higher than the one showcased in the graph of Argyroupoli station but it does share the same characteristics of being stable throughout and with lower values than those of the outside area. The concentration levels of the ticket booth level in Egaleo is within the range of 17.2 $\mu g/m^3$ and 19.5 $\mu g/m^3$ with the last few measurements being affected probably because the sensor was nearby the stairs towards the platform level for the monitoring routine. Finally the concentration on the platform level seems to be rapidly stabilising at the range of 26.9 $\mu g/m^3$ and 29.7 $\mu g/m^3$ with an increase during the last few measurements probably affected by the subway wagon stopping.

Overall we can see that ticket booth level in both scenarios have the lowest concentration. Considering the graphs presented previously in this chapter we can see that ticket booth level of metro stations are the safe when it comes to PM2.5 levels. The main reason for this case is mostly the natural ventilation effect of the ticket booth level, with at least two staircases leading to the outside air and with the temperature difference that the subway maintains, air streams are created causing an effective scattering of the PM2.5 concentration. The platform level has overall high concentration levels with the case of Argyroupoli station being within the range of 20 μg/m$^3$ to 25 μg/m$^3$ and in Egaleo station being within the range of 25 μg/m$^3$ and 30 μg/m$^3$. As briefly mentioned some of the reasons are the outside influence of dust particles trapped within the platform level transferred either from the air or the passengers, the wagons do play the major role of the increase of PM2.5 emissions mostly from their breaks. This is showcased from the difference of the concentration of platform level of Argyroupoli and Egaleo station where in Egaleo station the blue subway line is much more constant in schedules with more wagons passing by and with the extra route of the Airport subway line that uses the same line as the blue line. Of course part of the reason of the increase is also to the fact that more people use the blue line and Egaleo station than the red line and Argyroupoli station. Finally the platform level is a space that has no effective way of scattering the emissions creating a trap effect of any emissions produced within that space.

### 7.3.2 A look on Patterns of drastic AQ changes

Below a graph is presented with the depiction of the air stream and its influence caused by wagons when they are decreasing their speed when they are approaching a station.

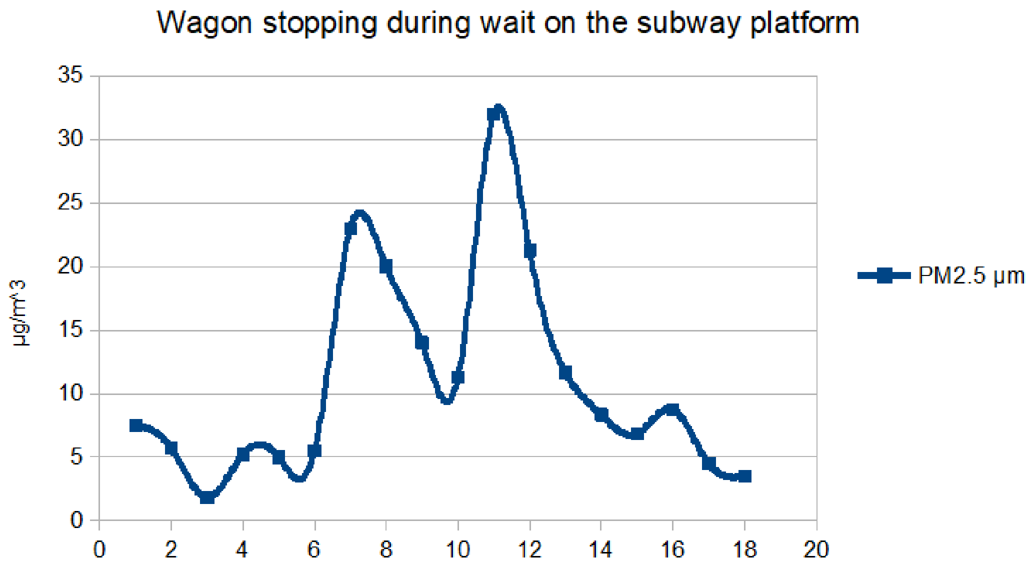



**Figure 30: Reported phenomenon of air strikes during a wagon stop while at the platform level.**

As we can see two major increases are taking place one being from data 6 through 9 which is the stream of air created by the wagon that uses its breaks to decrease its speed as it is getting closer tot he station and 10 through 13 is the moment the wagon is stopping on the station. The air created from the initial use of breaks is captured by the sensor after a short delay till the stream of air reaches the sensor.

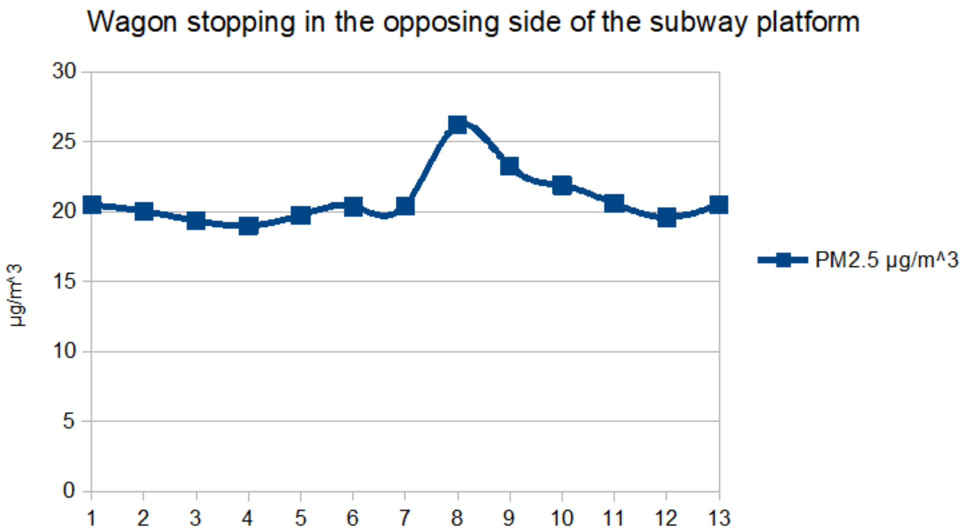



**Figure 31: Reported phenomenon of air strikes during a wagon stop while at the oposite platform of the wagon.**

Similarly the concentration is also affected by wagons stopping on the opposite side of the subway platform with a slight increase when the wagon stops. The wind mentioned previously, that subway wagons tend to create prior to their stopping is present in this graph too just in a lesser extend (value 5 through 7) mostly because the two sides of the platform are distant enough that such wind might not be completely monitored from the sensor.

Bellow a graph of PM2.5 concentration of the same station under different passenger capacity is presented.

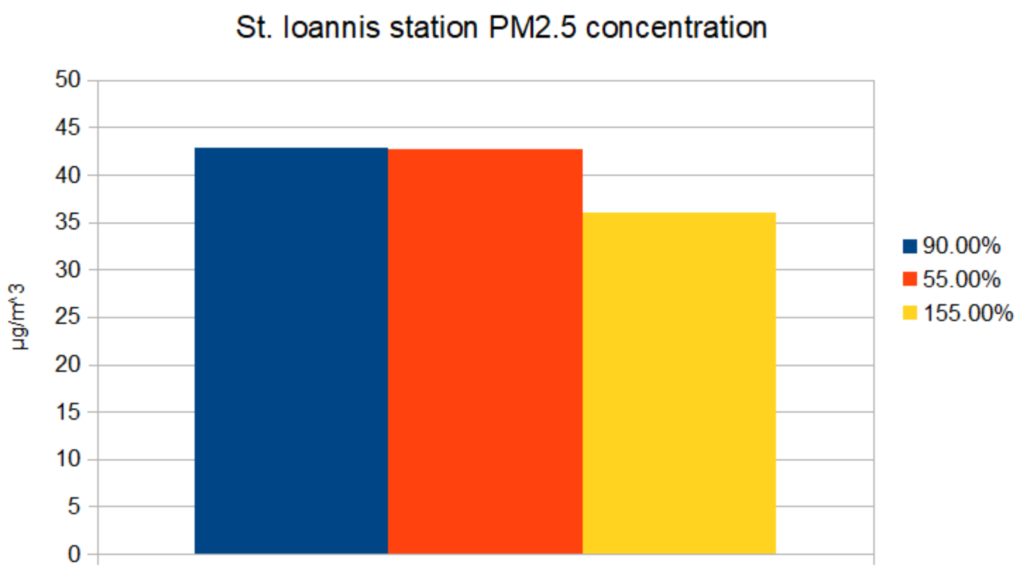



**Figure 32: Comparison of the average concentration of the same metro station at different passenger capacity at simillar conditions.**

Throughout the thesis the fact that passenger capacity has little effect compared to the passenger activity has been mentioned. On the graph above we can that the overall capacity shows too little in terms of the PM2.5 concentration and its influence. The data were used from three different days that shared similar characteristics in terms of humidity, temperature and air pressure provided from Purple Air sensor. The numbers used are the overall average concentration of these stations and the station used is St. Ioannis. In the first two cases the difference in passenger capacity is at the scale of 35% which is a significant amount of passengers, yet the overall PM2.5 concentration is identical to each other. In the contrary the third case has the highest passenger capacity of 155% and has a lower PM2.5 concentration that the other two cases, the passenger difference is 65% compared to the first case and 100% to the second case, yet the PM2.5 concentration has the same difference between the first and the second case of 6.6 μg/m$^3$.

### 7.3.3 A deeper look on the effect of age of Metro wagons

A phenomenon that was observed from the very first days of the monitoring routine was that the two age groups of the subway wagons had different levels of influence on the concentration of PM2.5. The old wagons are in service since 2000 and are assembled at 1999 and 1998 [7].

Bellow a graph showcases the different concentration of PM2.5 reported within the same route. The conditions are not identical but are similar with 1 ºC to 2 ºC difference and around 10% humidity difference, the data used was from day 10 and day 12 and the total passengers on board are the same throughout with 10% difference, with only exception the station of Dafni that in day 10 with the new wagon the total passenger rate is at 60% and at day 12 with the old wagon being 90%, at St. Ioannis the new wagon had 50% passenger rate and old wagon 75% and the last station that a notable difference on wagons is Ilioupoli station with 45% on the new wagon and 60% on the old wagon and on Alimos station both cases are at 40%. These differences are between 55 and 80.

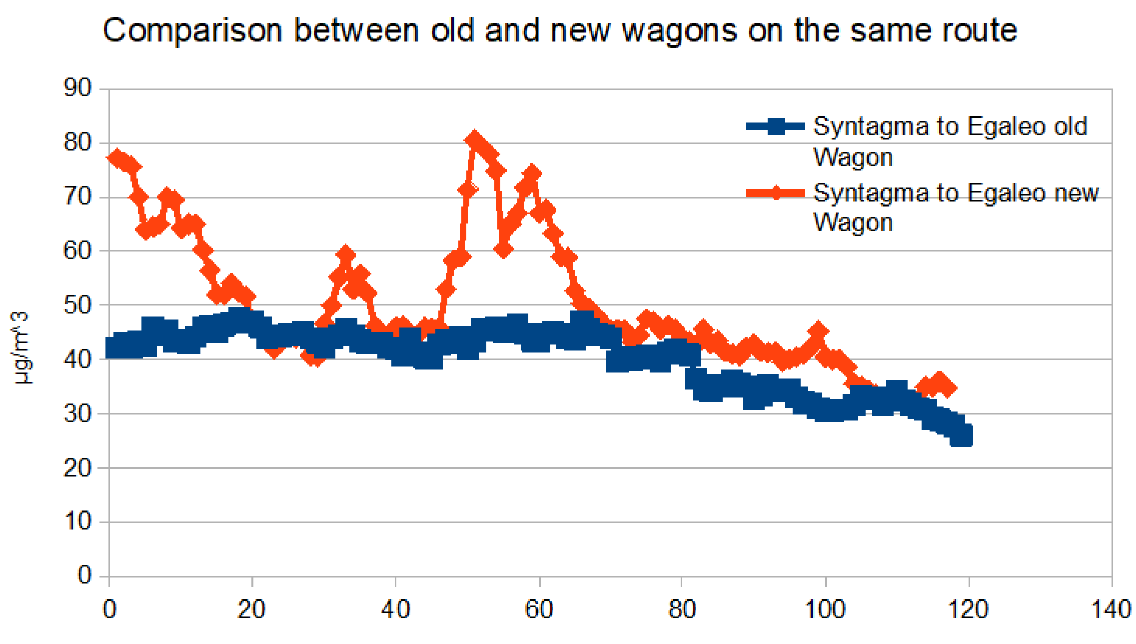



**Figure 33: Comparison between the route of Syntagma to Egaleo with old and new wagons at similar conditions.**

The main observation made throughout the value and with the live monitoring view PurpleAir provides was that older wagon are more unstable at the concentration during stations where the passengers activity is high with many fluctuations, in contrary the new wagon only reported steady increases on the concentration while the passenger activity was higher than expected. Another thing that was noted was that the concentration while at an old wagon was a lot more unstable compared to the newer wagons.

The assumption would be that the newer wagons are better isolated from the outside air leading to a better isolation of the inside air and thus a more stable concentration of PM2.5.

## 7.4 Brief look at the Metro graphs in comparison to Public Buses

Below will be presented graphs that compare the average concentration of PM2.5 in μg/m$^3$, within the 17 days of data collection, between the bus routes and metro routes.

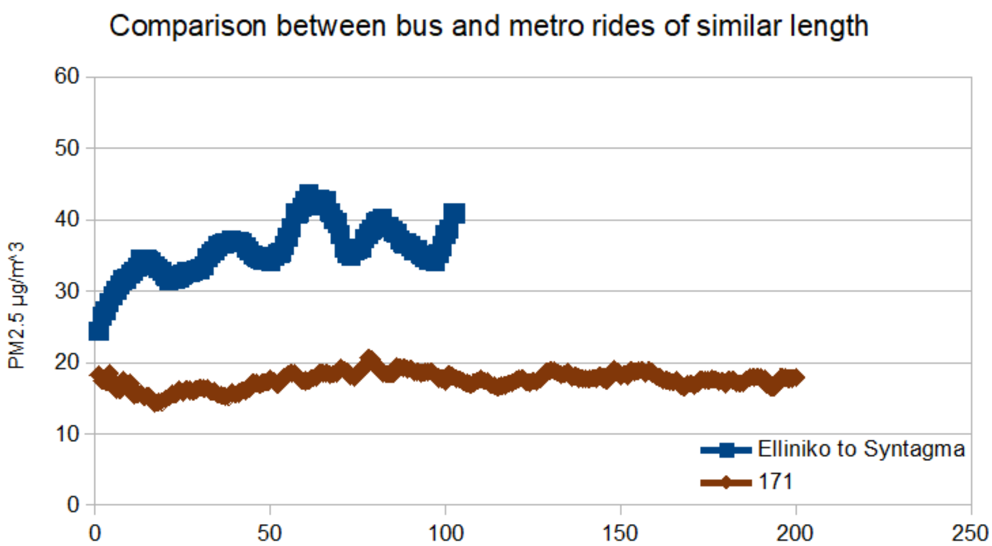



**Figure 34: Comparison of concentration of PM2.5 of metro and bus route of the 17 days data.**

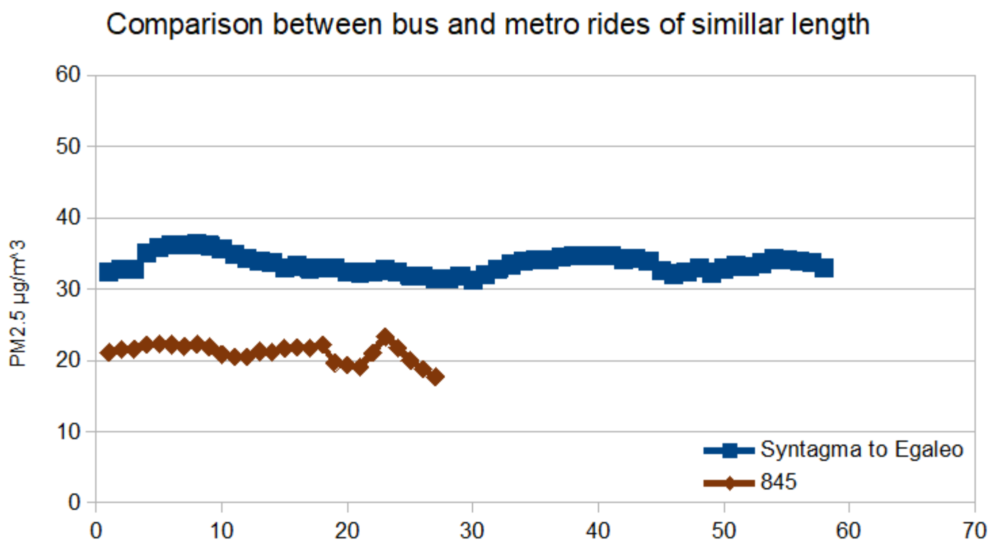



**Figure 35: Comparison of concentration of PM2.5 of metro and bus route of the 17 days data.**

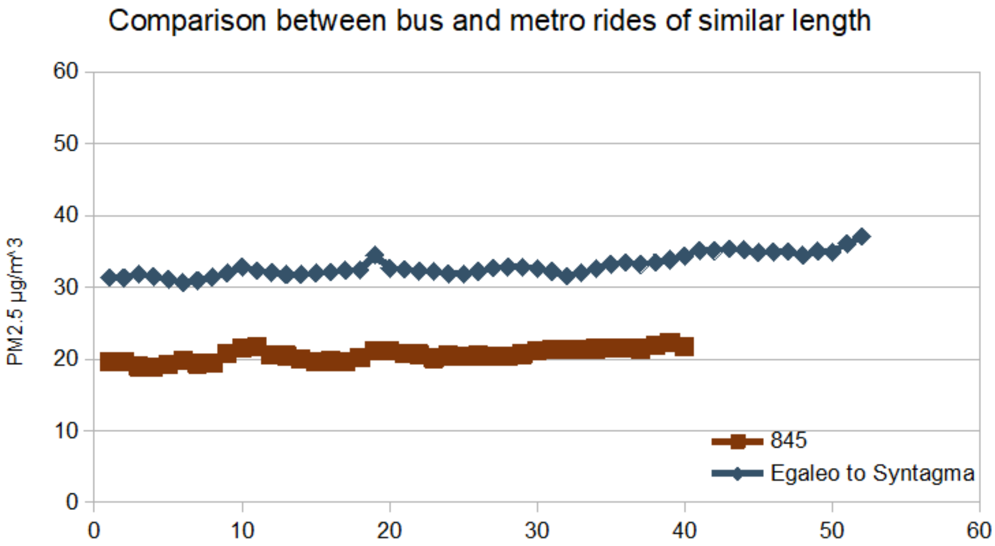



**Figure 36: Comparison of concentration of PM2.5 of metro and bus route of the 17 days data.**

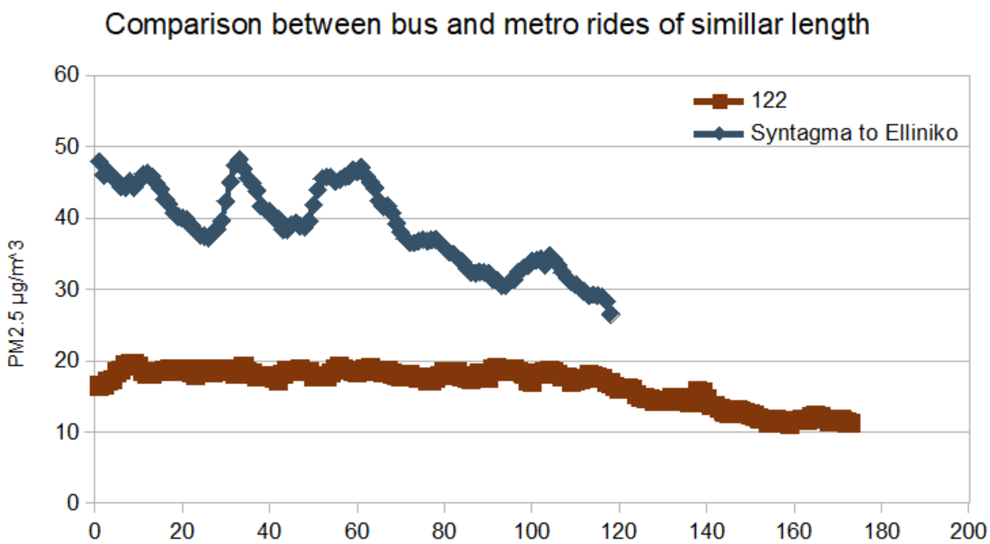



**Figure 37: Comparison of concentration of PM2.5 of metro and bus route of the 17 days data.**

As shown on the graphs above metro and bus as a mean of public transportation has an immense difference in Air Pollution exposure for the average passenger. Comparatively the route of Syntagma to Elliniko to the route of 122 is not representing much, due to the bus line being at a rather isolated suburban area with the Syntagma to Elliniko crossing a rather central area, but it still showcases how the metro can be a much more harmful for the health of the passengers compared to a regular bus. The route of 845 is a much more suitable route to compare to the route of blue line from Sintagma to Elliniko (and vice versa). Overall in each comparison we can spot a difference within the range of 10 μg/m$^3$ to 20 μg/m$^3$, which can be crucial for many passengers of either older age or groups of people with breathing issues, even though the concentration of 35 μg/m$^3$ can be expected while travelling through the center of Athens (considering the high density of private cars and traffic-heavy roads), metro can reach up to can surpass that number reaching up to 50 μg/m$^3$ in the case of the Syntagma to Elliniko case and up to 45 μg/m$^3$ in the case of Argyroupoli to

Syntagma, which can be harmful for even healthy groups of people if they use regularly and daily these routes.

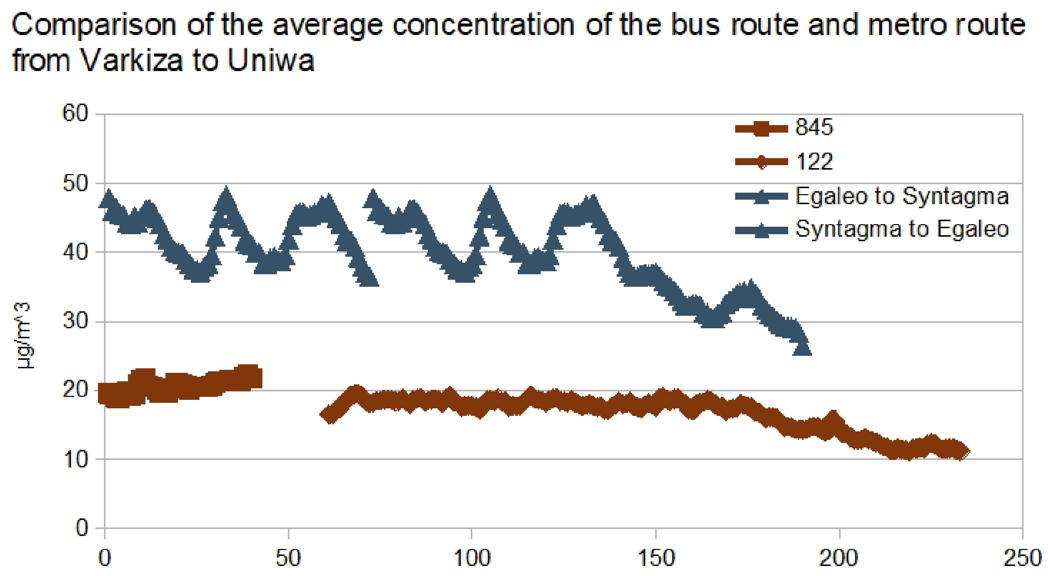



**Figure 38: Comparison of concentration of PM2.5 of metro and bus route of the 17 days data.**

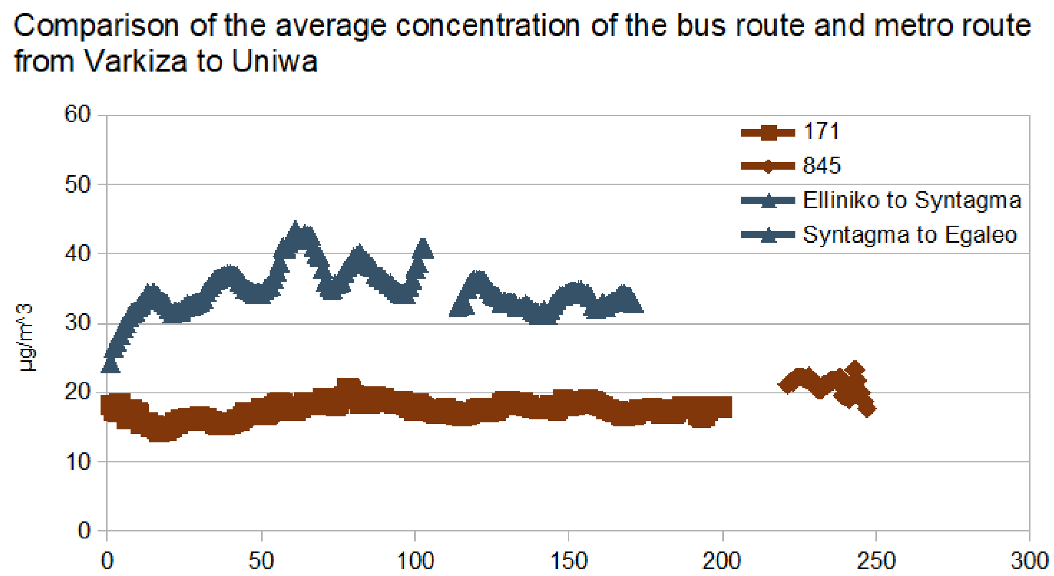



**Figure 39: Comparison of concentration of PM2.5 of metro and bus route of the 17 days data.**

As shown in the graphs above the overall exposure levels of the buses is relatively within risk-free levels, rarely surpassing the concentration of 20 μg/m$^3$. Metro can be a fast solution for transportation but the levels of concentration is worryingly high especially in the central stations. Even though things get better on the stations near Elliniko the concentration is still high and most likely much higher than the equivalent bus that could replace the metro route.

The metro route monitored in this thesis does cover the avenue of Vouliagmenis which is known for the intense traffic that can have throughout the day especially from the height of Alimos onwards, it is safe to assume than from that height onwards the equivalent bus that could replace the metro would also have higher concentration but based on the graphs above it would still be safer than the metro. Last thing to consider is even though the bus could have lower concentrations of

PM2.5 if the time required to get to Syntagma is double of the metro's, then the risk is even out, since even if the concentration is lowered if the time exposed at the concentration is doubled will most likely have the same effect.

## 7.5 Brief look at the AP exposure of an average walker in Athens

Bellow two graphs will be presented showcasing the difference between the PM2.5 concentration while walking in a central and suburban area (Egaleo and Varkiza). The data used for these graphs are the average concentration of 17 days under different hours and weather conditions.

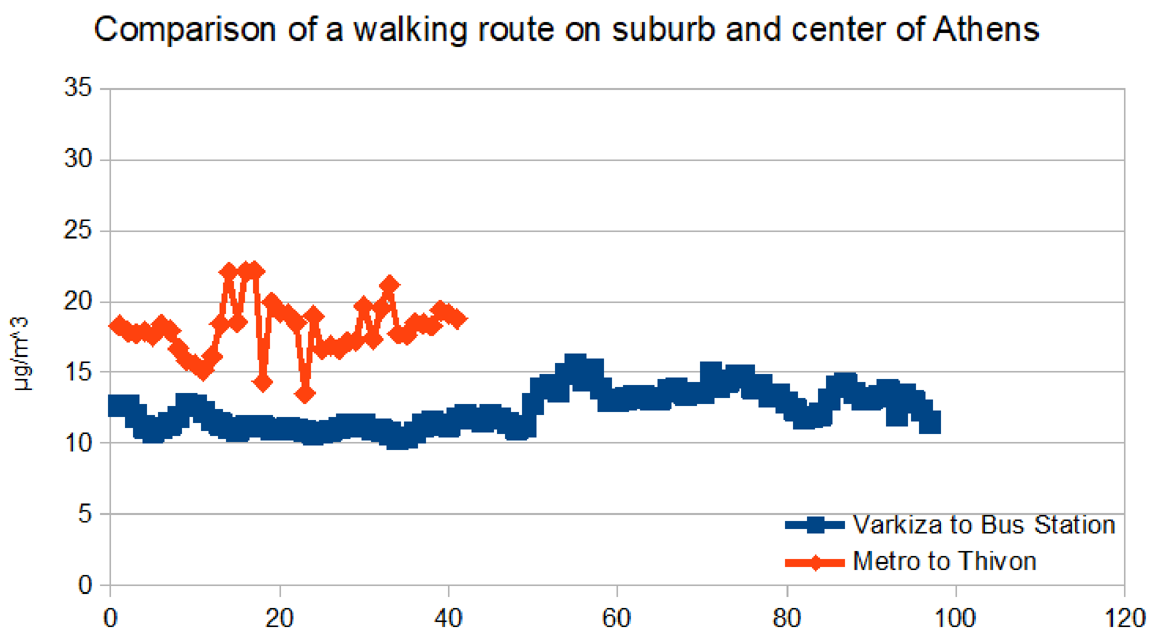



**Figure 40: Comparison of the concentration of PM2.5 of 17 days of data on central and suburb walking route.**

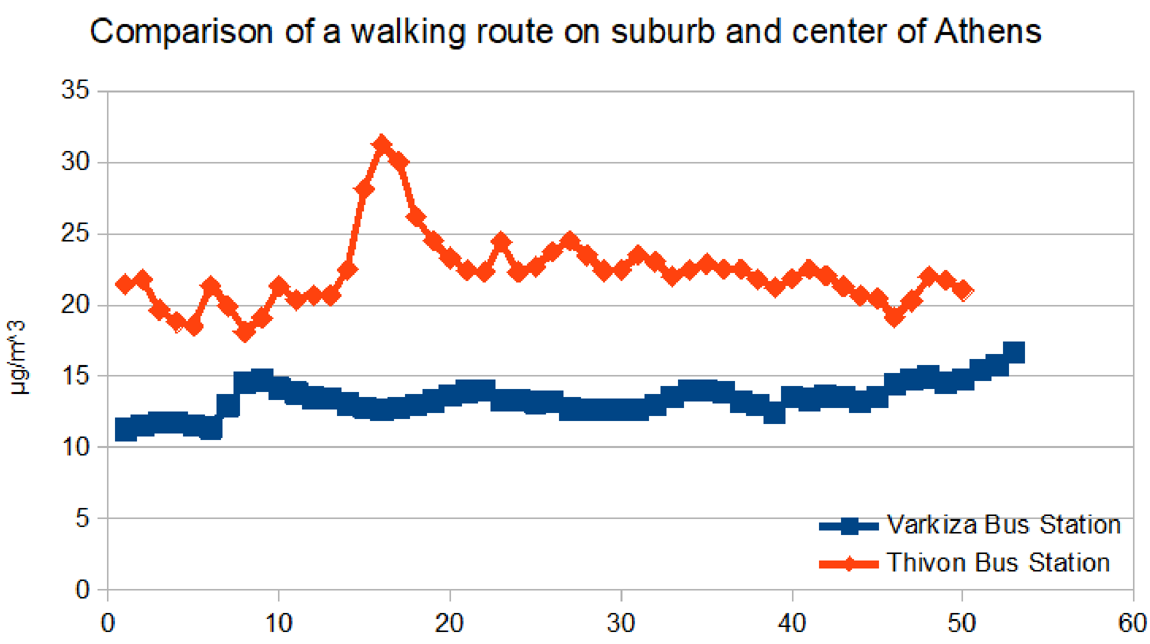



**Figure 41: Comparison of the concentration of PM2.5 of 17 days of data on central and suburb bus stations.**

Above we can see a simulation of the average exposure of someone who walk in the central area of Egaleo and suburban area of Varkiza.

The exposure on the area of Varkiza within the range of 10 μg/m$^3$ to 15 μg/m$^3$, which considering that the monitoring for these graphs took place while walking alongside with the Poseidonos street, could be considered normal and we could expect for a lower concentration the further we move from Poseidonos street.

The exposure showcased on Thivon street, even thought is seemingly high within the range of 20 μg/m$^3$ to 25 μg/m$^3$, considering the fact that is next to a high-traffic street and next to three avenue roads (Kifisos avenue, Petrou Ralli and Iera avenue as mentioned previously), is relatively average in terms of exposure. It wouldn't be ideal for someone to walk long distances with that concentration but given the vast options of public bus lines, the exposure is within an amount which shouldn't be worrying for most people.

Bellow an exposure during the same day under the same weather conditions (temperature, humidity and air pressure) within 1 hour difference (suburb sample collected around 13:00 and the central sample was collected around 14:00)

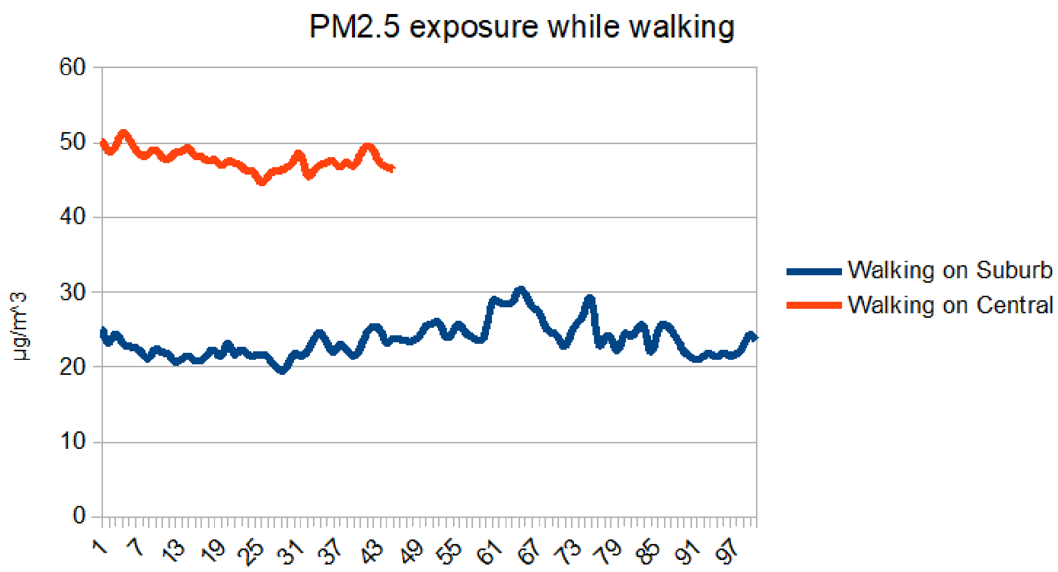



**Figure 42: Comparison of the concentration of PM2.5 on central and suburb walking route under simillar conditions.**

Exposure at the bus station on a suburb area and at a centric area, the sample was collected within 1,5 hour difference under the same weather conditions (suburb sample was collected around 13:00 and central sample was collected around 14:30) the traffic is around the same level with major difference being that in the suburb area little to no stops took place from the cars and the average speed was above 50km/h. In the central station due to nearby traffic lights major stops from cars took place and the average speed didn't surpassed 50km/h.

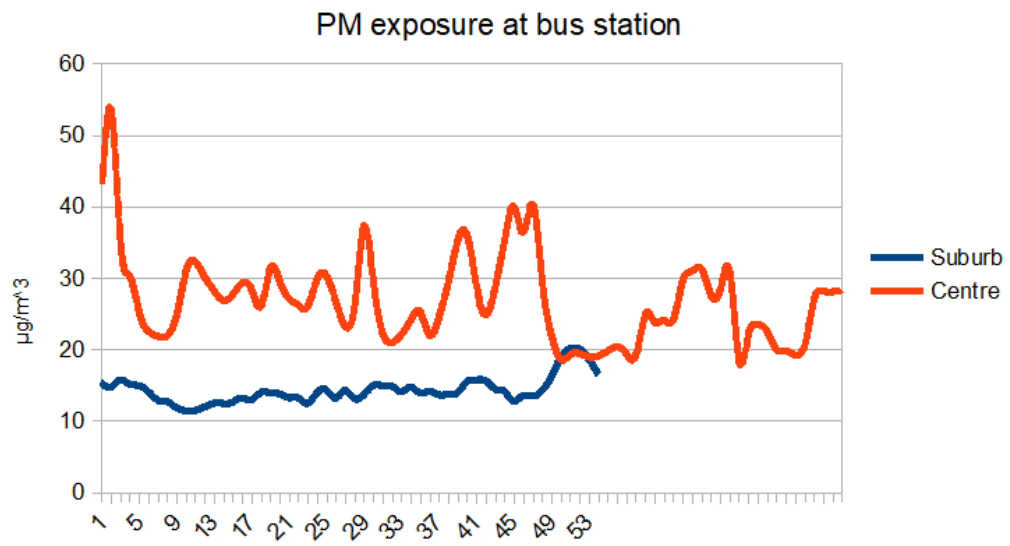



**Figure 43: Comparison of the concentration of PM2.5 on central and suburb while on bus stations under simillar conditions.**

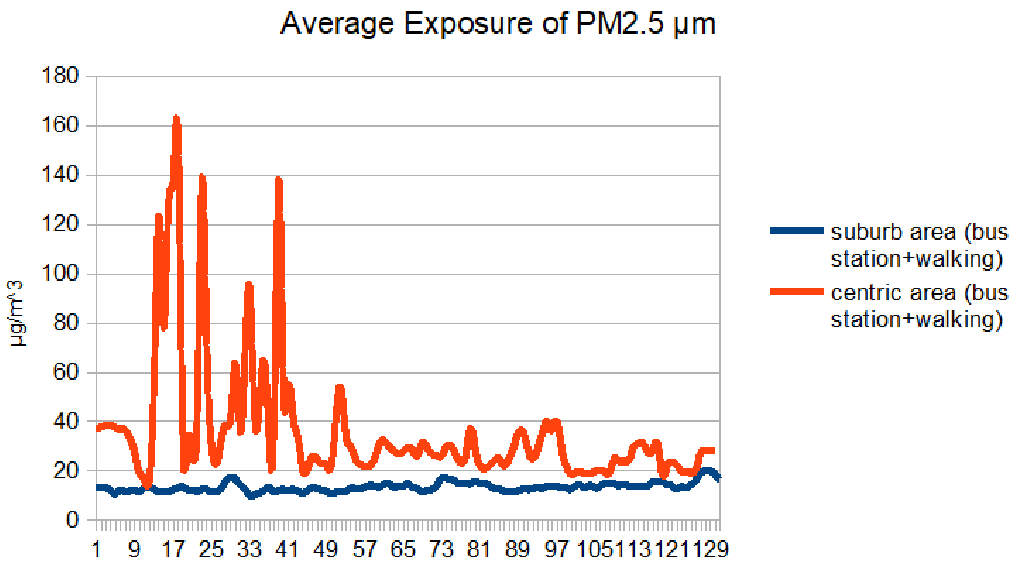



**Figure 44: Comparison of the concentration of PM2.5 on central and suburb while on bus stations and walking under simillar conditions.**

# 8 Conclusion

Within this thesis the goal was to primarily understand the value and the value of low-cost sensors and to further use them in an empirical study to create a conclusive idea of the subject studied. After the processing of the data obtained from the PurpleAir low cost sensor and the final results that were produced we can safely assume that low-cost sensors even if are not up to the standards of traditional sensors, are more than capable to be able to provide enough data to make important observation like in this case the worryingly high levels of concentration of PM2.5 within the Athenian metro subway network. Admittedly the low-cost sensor share some common technical limitations and do have some minor difficulties in demanding projects like the one in this thesis, but with the proper planning and preparation low cost sensors can be an option where budgets offers no alternative but a low cost sensor. Furthermore the results may not be completely accurate at the grade that other options offer, but the accuracy is high enough to provide a complete image of our study for a subject that no deeper research was done before and the results it offered were capable to even observe some rather unexpected phenomenons that play important role on conducting an overall conclusion.

## 8.1 Conclusion of the study

The primary study of this thesis was to track down the air pollution and air quality levels of the Athenian metro subway network and to represent a simulation of the weekly exposure an employee or a student is going through while using public transportation and most importantly the subway. The route that was used in this study consisted of two areas of vastly different geographical characteristics and it was showcased throughout the effects these characteristics had on the Air Pollution and the Air Quality passengers are exposed to. Outside of the subway this thesis was also able to delve deeper into the public buses as well as the routes that must be covered by foot for a passenger to get to the desired means of public transportation, even though the main focus was subway, it was possible with the data collected to make a clear comparison between the exposure of harmful PM2.5 concentration the different means host.

Throughout the showcase of the results it was clear that the Athenian subway has a worrying amount of PM2.5 concentration and it was further proven by the AQI levels the PurpleAir device reported. PurpleAir was accurate and reliable enough to also showcase some rather unexpected results such as the fact that during early hours of the morning, the metro station has a higher concentration on stations that are rather further away from the central stations rather than stations that are closer to the centre. PurpleAir also identified important factors that increases the concentration of PM2.5 further increasing the risk of groups of people that are vulnerable to such harmful pollution levels and it showcases possible factors that could be improved by either upgrading current equipment or changing some of the existing equipment within the subway to make it a safer mean of transportation. An example of such factor is the factor of the age of the wagons used in the subway, with older wagons consistently having higher levels of PM2.5 concentration and also having a higher rate of increasing the Air Pollution at the platform level when they are stopping on the platform. Another important distinction that was showcased from the data of PurpleAir was the importance of the activity of passengers (the amount of people embarking and disembarking the subway wagon) and the insignificance of the overall population the subway wagon may hosts, more specifically it showed that if the passengers activity is the same, yet the population of the wagon doubled there is high chance that the concentration be the same or even lower at the case of the higher passengers rate case. On top of that the data was also able to showcase the differences each level of the subway might host, with the upper level on the open air being slightly more harmful than the level of the ticket booth in the metro station and the level of the wagon platform being high in PM2.5 concentration to the extend that under specific scenarios and specific station might be risky for some target groups to be waiting there. Possibly the reason for something like that is because the platform level is isolated and the concentration of PM2.5 is difficult to be scattered, alongside with wagons travelling at high speeds causing the rested to the ground and walls dust particles to spread up in the air mostly on the level of the passengers. Ticket booth levels on metro station seem to be located and structured in a way that the different staircase exits create a natural air stream that recycles the air and scatters the emissions away from the space, causing it to have a cleaner air than the outside air.

Buses were presented to be possibly the optimal option for transportation when it comes to the Air Quality they offer. Admittedly the bus lines that were used throughout the study were not going through the same streets that metro is travelling through, but in every case the buses had a significantly lower PM2.5 concentration that in subway wagons, with no case of the bus hosting a higher Air Pollution level than a subway wagon.

Finally the overall exposure of Particulate Matter throughout the route of Varkiza to UNIWA and from UNIWA to Varkiza considering the AQI levels of all the 17 days combines, we could say that for an average person it is mostly safe for such a daily course, with mostly the AQI levels being below 100 with only short periods of time while using the metro surpassing levels of 100. For groups of people that have breathing issues although things can be different considering that a big portion of this course consists of exposure to levels of PM2.5 concentrations that are equivalent to higher than AQI of 50 and mostly around 80. For such people avoiding the subway is strongly suggested since the only public transportation that surpasses the AQI levels of 100 is the metro and the usage of protection from Particulate Matter is suggested.

Furthermore from the calibration tests Purple Air was the only truly portable sensor and still was able to deliver an above 90% linearity with a high precision sensor like TSI. Most of the phenomenons reported in this thesis was because of the practical design behind a low-cost sensor at a price that is equal to approximately 1/10 of the price of AQ Mesh and AQ Mesh was only able to deliver a 1.3% higher than Purple Air. Low-cost sensors are at the point that can be used for highly detailed practical and on the spot monitoring studies that can offer a complete image of the actual impact Air Pollution might has to people.

## 8.2 Additional comments

Considering all the data provided low-cost sensors can be possible solutions for many problems and challenges that aim at monitoring the Air Pollution and Air Quality of areas or spaces where budget is limited or the time required for the maintenance and frequent calibration of a traditional sensor is not possible. Even thought technical limitation are still present, the accuracy and the reliability that have been achieved are enough for detailed studies and research purposes as long as the accuracy needed is not too high. Finally such sensors can be used in great numbers to conduct studies for the coverage of long areas and distances where the purchase of a multitude of such sensors is preferred compared to the purchase of a high accuracy sensor.

Moving on the subject of Air Quality, we can comment that the Greek public transportation system provided is far from ideal, but still within the limits of being usable for everyday use. Given the conclusion we concluded a ventilation system is require in the lower levels of the subway station and can greatly increase the Air Quality on a rather isolated space where many factors exist to decrease the Air Quality and almost none exist to improve it. The replacement of all the old wagons would help the situation but only in a margin, most importantly the wagons should utilise an air recycling system that could be benefited by the use of PM filters and traps. Even though the study was mostly focused at Public Transportation and the Athenian metro, cigarette’s presence was strong in any situation that could influence this study, both in bus stops and walking routes cigarettes could greatly increase momentarily the data and even play a major role in the processing of the data. Even though unreasonably high or low measurements were not considered cigarettes were so persistent that their influence was consistent enough for the PM increase to be more than momentary, due to the high rate of smokers on the bus stations. Thus a legislation over the limitation of smoking or a campaign to combat smoking on public spaces would greatly increase the Air Quality that an average person is exposed to.

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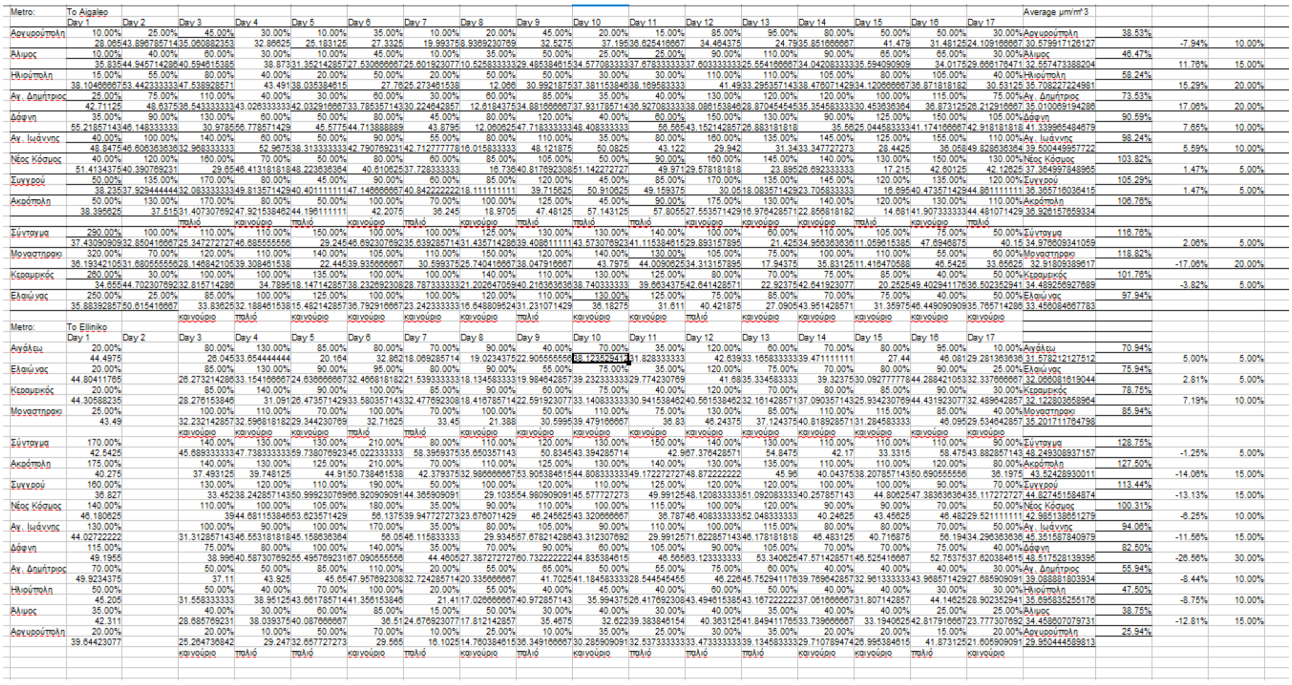
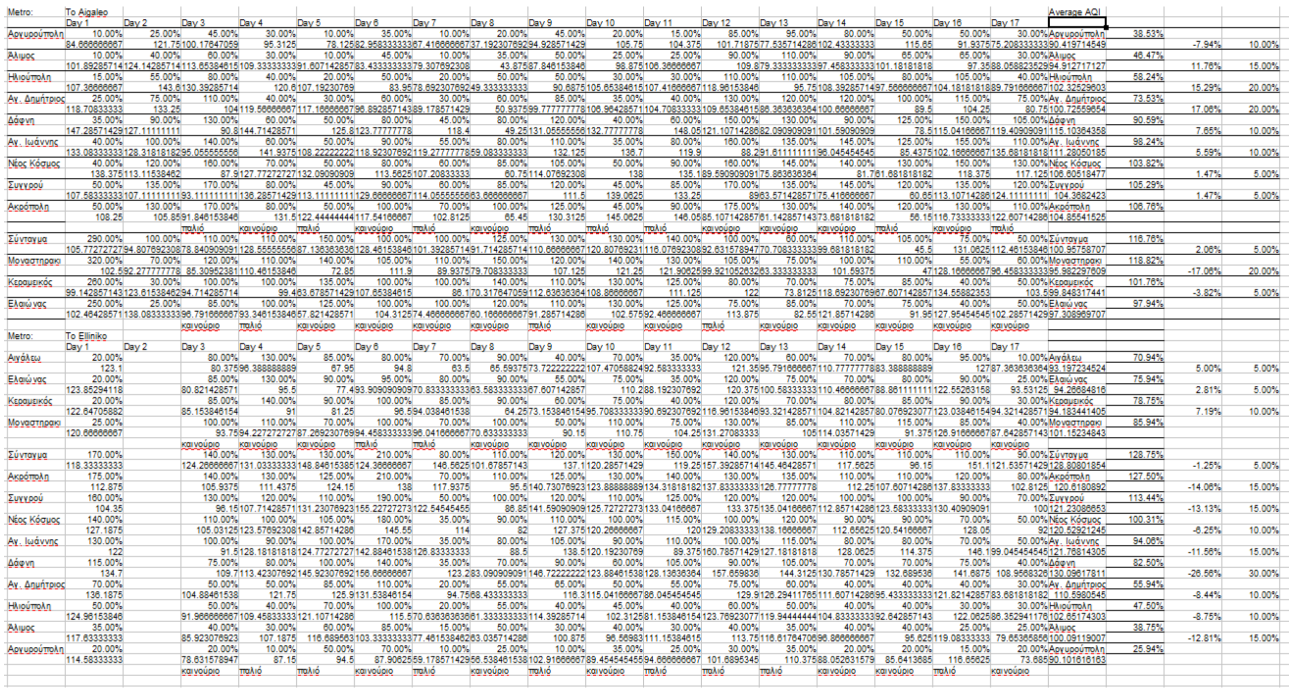
# Παράρτημα Α



| | Group 1 | Group 2 | Group 3 |
|---|---|---|---|
| Αργυρούπολη | | | |
| | 35.92378496 | 30.82368056 | 23.87475962 |
| Άλιμος | | | |
| | 36.38900065 | 32.87517685 | 27.57839652 |
| Ηλιούπολη | | | |
| | 41.39389286 | 34.63597317 | 30.17213333 |
| Αγ. Δημήτριος | | | |
| | 36.3242769 | 35.28441369 | 33.10380655 |
| Δάφνη | | | |
| | 34.62779022 | 48.31135702 | 41.02890595 |
| Αγ. Ιωάννης | | | |
| | 33.77448737 | 45.48146343 | 39.19438889 |
| Νέος Κόσμος | | | |
| | 27.9035474 | 43.75666652 | 41.04873598 |
| Συγγρού | | | |
| | 26.42453042 | 45.19498677 | 37.70001389 |
| Ακρόπολη | | | |
| | 25.16502098 | 46.96736554 | 38.99007222 |
| | | | |
| Σύνταγμα | | | |
| | 25.92197105 | 43.62442441 | 35.4647972 |
| Μοναστηρακι | | | |
| | 26.55533769 | 40.24997623 | 31.75514254 |
| Κεραμεικός | | | |
| | 34.32960394 | 39.80121459 | 28.30649132 |
| Ελαιώνας | | | |
| | 37.87920337 | 35.67304247 | 25.48799286 |
| Total Average | 32.50864983 | 40.20613394 | 33.36197207 |