National Observatory of Athens

Impact of cycling on Urban Air Quality

V. Assimakopoulou, N. Loumos, K.M. Fameli and D. Konsta
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Executive Summary

According to the IPCC there is unequivocal evidence that climate change is here affecting our everyday lives, our planet. The rising temperatures, the intensity and frequency of extreme events, the ocean acidification, the melting of the glaciers, the rising of sea level are all evidence of the changes occurring. It also widely accepted that emissions of greenhouse gases as a result of human activity are the main cause of this change.

The transportation sector contributes to almost 30% of energy related CO_2 emissions and is still growing despite mitigation measures (taxation, new engine technologies, alternative fuels etc) due to infrastructure works, rising income and so on. Avoided journeys and modal shifts due to behavioural change, together with other measures and changes in the built environment, offer high mitigation potential, (IPCC, 2018). It is clear from the above that cities play and will continue to play a crucial role in benefits such as improved local air quality, minimization of traffic congestion, improved health option, upgrade of commercial centres and more.

The transport sector is also a major contributor of classical air pollutants harmful to people's health, particularly in urban areas where the concentration of cars and the densely built environment create a dangerous combination. Adequate knowledge of the sources of pollution, the measures necessary to restrict them and the special characteristics of the urban area is a pre-requisite to developing effective mitigation policies, protecting human and environmental health. One of the main challenges found by the cities include how to effectively communicate air quality/climate change beneficial measures to the public and how to achieve the development/formulation of policies/laws across all administrative levels by taking advantage of platforms/funding instruments designed to support them such as Covenant of Mayors, EU Urban Agenda and so on, EEA (24/2018).

The main aim of the Cyclurban project was to focus on measures and actions to enhance cycling in municipalities by analyzing the special characteristics of their infrastructure, policies and procedures and by helping them formulate strategies. Within that frame, in the present report the impact of cycling on the urban air quality is analysed with the aid of indexes characterizing the air quality and comfort status as well as with the estimation on the reduction on GHG emissions. The methodology included the selection of typical municipalities located in the Attica Region, which were either characterized as urban traffic with no cycling paths or suburban/urban background with cycling infrastructure. Meteorological (temperature, relative humidity, wind) and air quality (NO_2, O_3) data were collected and processed with the aid of comfort and air quality indexes in order to assess the quality of the environment and the potential exposure of citizens to poor conditions. Moreover, road transport emissions scenarios were

developed and tested the scope being the assessment of the reduction of GHG and ozone precursors in the atmosphere.

The results clearly indicated that:

- The existence of cycling infrastructure, green spaces and less traffic is beneficial for the environment as it leads to better comfort conditions especially during the warm period of the year where high temperatures and high humidity prevail while ozone production is enhanced.
- In more centralized and high traffic areas the comfort and air quality conditions are burdened since the absence of open spaces and the concentration of road activities generate poor atmospheric conditions.
- Citizens are exposed to high levels of ozone mostly in areas where the traffic is not dense as it is a secondary pollutant that is created through the transportation of fresh/primary emissions of nitrogen oxides from central areas. It was found that even though some areas were characterized as urban background or suburban the fact that they are located within the Athens basin makes them vulnerable to high ozone concentrations.
- Citizens living in urban traffic areas are mostly exposed to higher levels of nitrogen dioxide as it is formed through the emission of nitrogen monoxide that is instantly transformed in dioxide. It is a pollutant characteristic of urban traffic areas and it is higher close to the source.
- Suburban or urban background areas with cycling paths and more green are in general facing less discomfort environmental conditions during the warm period of the year in comparison with those staying at more central locations. However, discomfort conditions prevail in almost all municipalities studied.
- The various emissions scenarios studied indicated that brave and severe traffic restrictions are needed to reduce significantly emissions of GHG and ozone precursors. It was found that an almost 50% reduction in all types of vehicles (passenger cars, high duty vehicles) would be more effective.
- In order to enhance cycling in the municipality and national level, measures to restrict traffic as well as citizen education actions are needed. Removing the habit of using a passenger car for every type of trip requires serious upgrade of the public transport and cycling/walking infrastructure as well as targeted promotional and educational activities towards citizens of all ages and categories.

Introduction

It is well recognized by organizations such as WHO, IPCC that urban areas contribute to climate change because of the concentration of anthropogenic activities that are both sources of greenhouse gases (GHG) and classical pollutants, such as carbon dioxide, carbon monoxide and nitrogen oxides that are precursors to ozone. The most important sector is transport and in this respect, it is accurate to say that climate change mitigation depends highly (but not only) on controlling the anthropogenic emissions from urban areas and more importantly those from the transport sector.

Cyclurban

On November 8, 2017, the European Commission (EC) published its regulatory proposal for post-2020 carbon dioxide (CO_2) targets for new passenger cars and light-commercial vehicles (vans). In contrast to previous vehicle CO_2 regulations, the new EC proposal does not specify CO_2 targets in absolute g/km terms but instead defines CO_2 reduction requirements in percentage terms. Under the EC proposal, average new-vehicle CO_2 emission levels would have to fall by 15% by 2025 and 30% by 2030.

Controlling the emissions from road transport is not simple as they depend on factors such as vehicle technology, fuel type, vehicle size and driver behaviour. Technical measures alone, in terms of technologies that directly reduce emission from road vehicles, are insufficient to meet compliance with urban air quality objectives. Thus, a logical solution would be a reduction in car use.

This can also facilitate accessibility to the major centers of interest and activities in urban areas. The majority of people in all European countries recognize this fact. Already in 1991, a representative sample survey conducted by the IUPT (International Union of Public Transport), carried out among 1 000 citizens in each member country of the European Union indicated that 83 % of Europeans on average agreed that public transport should be supported over private cars. Another survey conducted recently in France confirmed these findings.

Cycling is one of those modes of transport that can effectively help in climate change mitigation and improvement of local environmental conditions and consequently to a better quality of life. Technical improvements as well as infrastructure work have made modern bicycles efficient and convenient to use. It is important to note that more than 30 % of trips made with cars in Europe cover distances of less than 3 km and 50 % are less than 5 km. Enhancing bicycle use, along with other measures helps solve traffic and environmental problems in towns, while it represents a solution which fits perfectly into any general policy aiming to re-enhance the urban environment and improve the quality using few financial resources.

Further insight on urban environment and cycling

Healthier Urban living

Everyone is familiar with the huge drawbacks of using a car inside an urban environment, considering first and foremost the human health. Car traffic contributes to a considerable proportion of ambient air pollution in cities. Factors such as the car fleet, size, traffic conditions and lay out of the city play an important role. Cars' emissions consist mainly of CO_2 and other important greenhouse gases such as black carbon and air pollutants, of which the most important are particulate matter and nitrogen oxides (HEI, 2010). In figure 1, one may observe that road transportation is the most significant mode.

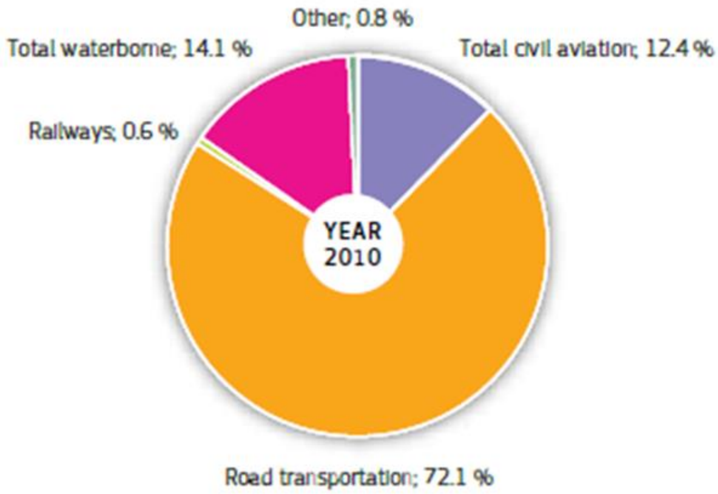

Figure 1: European Commission's results in transportation modes in 2010

Car Free day initiatives take place in every major city in Europe and they are a good precursor of the advantages of car free cities in general. The following image depicts steps towards car free policies, the importance of other forms of transportation like the bicycle and the benefits for the health of people living in urban environments.

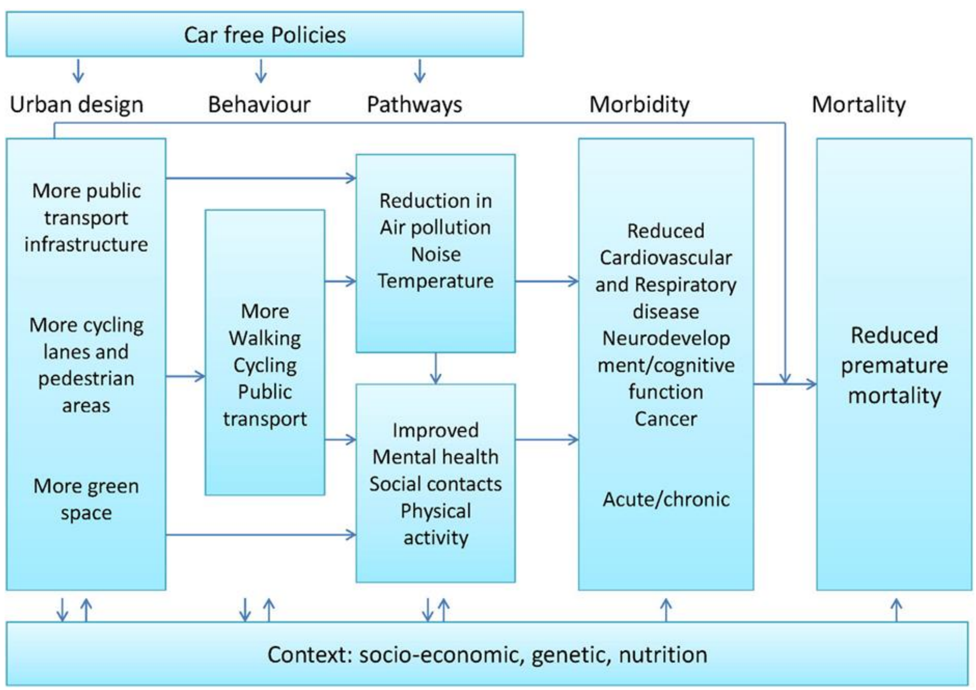

Figure 2: Initiatives of car-free cities: Implementation and Results (Mark J. Nieuwenhuijsen, 2016)

Measures taken by Airparif, which monitors city air quality in Paris, showed that levels of nitrogen dioxide dropped by up to 40% in parts of the city on Sunday 27 September 2015, when cars were banned. Another example of motorized traffic restriction is the London congestion zone, which resulted in a sustained reduction in vehicle numbers, thus reducing NO levels, while no impact was measured for PM10. Last example is the city of Milan and its congestion charging zone, referred to as the Ecopass area, which brings no significant difference in PM levels between the Ecopass area and outside (Ruprecht and Invernizzi, 2008). However, monitored black carbon (BC) reduced by 28%–40% in the charging area (as compared to outside). Likewise, car free Sundays implemented within the city also showed a 75%–78% reduction in BC. Black Carbon is considered the second largest contributor to climate change after carbon dioxide, thus its reduction through traffic restriction measures is important.

Climate change

R*adiative forcing* or *climate forcing*, as defined by the Intergovernmental Panel on Climate Change (IPCC), is the influence a given climatic factor has on the amount of downward-directed radiant energy impinging upon Earth's surface. Climatic factors are divided between those caused primarily by human activity (such as greenhouse gas emissions and aerosol emissions) and those caused by natural forces (such as solar irradiance). *Positive* forcing is exerted by climatic factors that contribute to the warming of the Earth's surface, whereas *negative* forcing is exerted by factors that cool it. There are four main mechanisms by which emissions from transport affect climate:

- by emission of direct greenhouse gases, mainly CO_2
- by emission of indirect greenhouse gases, i.e., precursors of tropospheric O_3 or gases affecting the oxidation capacity of the atmosphere, such as NOx, CO, and VOC
- by the direct effect of emission of aerosols or aerosol precursors, in particular black carbon (BC), organic carbon (OC), and sulfur compounds
- by the indirect effect of aerosols, which trigger changes in the distribution and properties of clouds.

The following figures depict the crucial role of CO_2 emissions from road transportation in radiative forcing (source: IPCC, 2005).

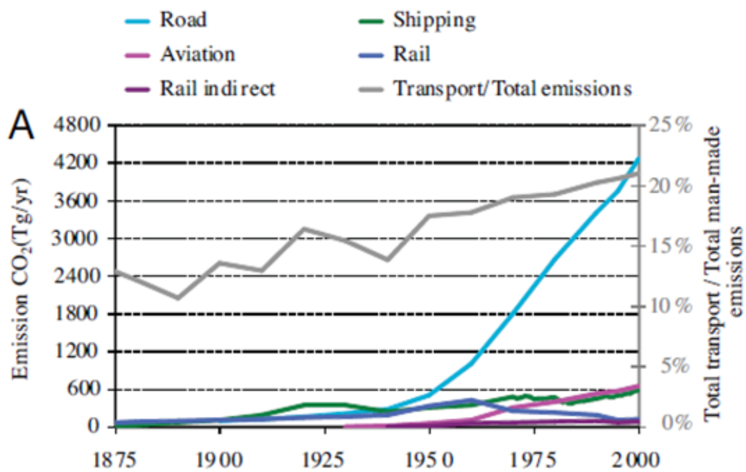

Figure 3.A: CO_2 emissions from all transportation modes

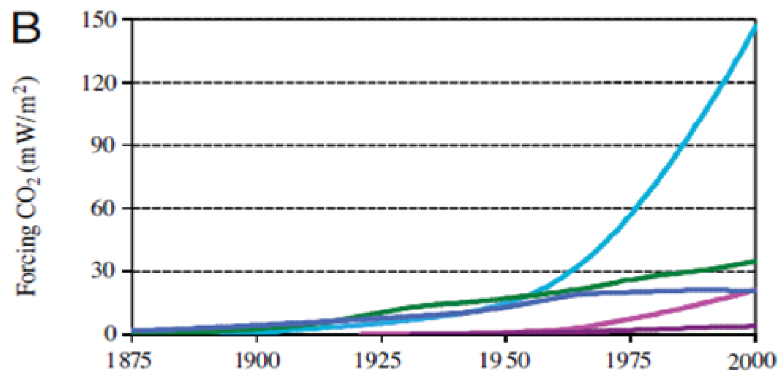

Figure 3.B: Radiative Forcing of CO_2 according to each mode

It is evident that CO_2 emitted from road transportation has the most remarkable ascending trend since 1950, something that depicts also the great effect road emissions have on climate. In order to be more specific the topic of radiative forcing, a few graphs can be borrowed from Jan's Fuglestvedt (2007) report:

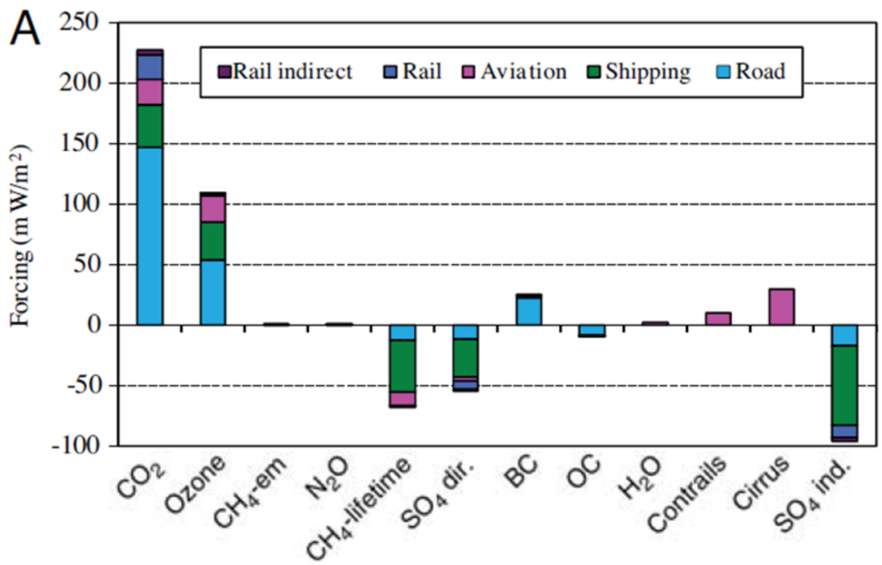

Figure 4.A: Global mean RF (mW/m2) for 2000 due to transport, relative to preindustrial times.

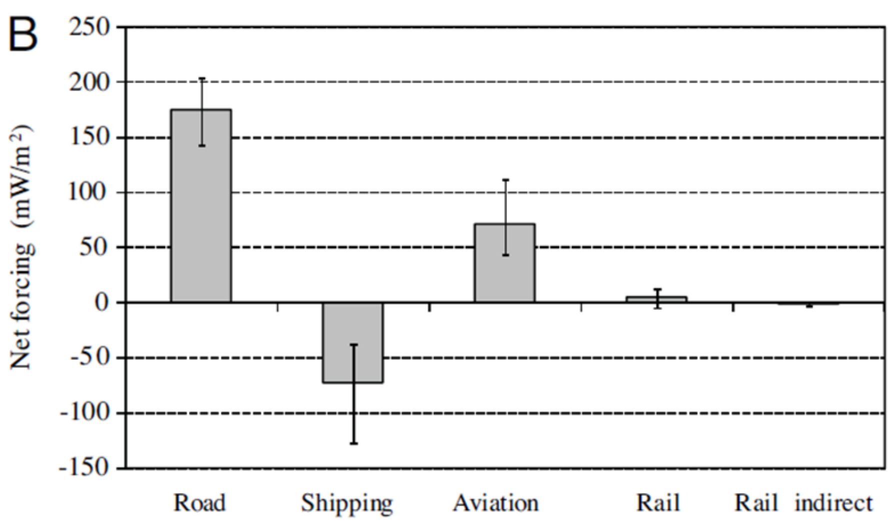

Figure 4.B: Global mean net RF (including all components in A) for 2000 due to transport, relative to preindustrial times, per sector.

It comes without question that through CO_2 and road emissions have the largest impact in radiative forcing, contributing the most to the global warming.

So, why cycling?

It is apparent that cycling effects cannot be actually measured, since very few cities in Europe have the infrastructure to support cycling along cities. However, anyone can see the benefits of ''why not a car'', therefore an easy and cheap solution to replace the car, is the bicycle. Fewer cars lead to less congestion, less traffic volume and a lot more space for people to move around the city easily. It also means lower noise and air pollution levels, thus healthier people who live more prosperous. Cycling is a very nice way to do your daily exercise that should be recommended for each and every individual. Last but not least, with all the above, somebody can have a happy life, because almost everyone gets angry at some point when he/she gets in front of the steering wheel in traffic congestion.

Someone would argue that people cannot always get to their jobs by cycling, if they work 10 km away from their home for instance. While cycling is not the solution to everything, since the infrastructure needs more expanding and better planning, but it can be used together with public transportation or help us reduce unnecessary commuting.

Cycling infrastructure

The importance of creating cycling infrastructure is related to the public perception of cycling as risky, since people prefer safe transportation than making a good impact at the environment and that is probably a main reason why cycling is still not so popular and preferable. A survey carried out in 2010 among UK adults found that 86% selected cycling as the mode most at risk of traffic accidents, as opposed to 2-7% for other modes (Thornton et al., 2010). A similar study in Portland (USA) revealed that there is significant potential for increasing cycling with a safer infrastructure stating that 60% of the residents would cycle if safety was increased, 7% are enthused and confident, less than 1% are strong and fearless, and a proportion are not interested in cycling at all (33%) (Geller, 2012).

The creation of new cycling infrastructure is usually directly correlated to an increase in modal shift. A 2003 cross-sectional study in the commuting behaviour of 43 cities in the United States revealed that every additional mile of bike lanes per square mile led to a 1 % increase in bicycle commuters (Dill and Carr, 2003). A study carried out in Dublin in 2012 revealed that the construction of segregated cycling lanes produced a 74.1% change in the opinion of residents on cycling safety, with 56.4% of the surveyed people actually considering shifting to cycling due to these new infrastructures (Caulfield et al., 2012).

All-in-all evaluation

Not every individual is keen on changing their mode of transportation and not every individual thinks only their own comfort and privilege. It is a matter of education as well, whether the children are taught to love their habitat, to preserve it and to make this world a better one. In any choice there are advantages and disadvantages. However, in the case of cycling, it is well recognized that the advantages can overrun the disadvantages and it is important to promote it effectively to attract even more people to this life-changing activity.

A few factors that make bicycle use appealing are:

- **Efficiency**: avoids traffic problems such as traffic jams, easy to park, enables door to door transport and is competitive with other modes of transport over certain distances
- **Flexibility**: no time or frequency restrictions
- **Economical**: no fuel expenses, the purchase and maintenance of the bicycle are economical

- **Ecological**: does not emit pollutants or greenhouse gases, hardly makes any noise and takes up little space
- **Healthy**: it is an active mode of transport that encourages people to exercise
- **Fun**: some users take pleasure in riding a bicycle

On the other hand, there are factors that in the most cases are proven crucial in the choice of modal shift and in the end inhibit bicycle use:

- **Distance**: distances to be travelled if they are too long
- **Danger**: perception of risk in relation to accidents or falls
- **Orography**: mountainous or hilly topography
- **Fitness**: poor physical condition.
- **Climate**: weather limitations such as rain, wind, low or high temperatures
- **Vandalism**: fear of the bicycle being stolen
- **Facilities**: need for complementary facilities for personal hygiene, bicycle parking area at the destination point, to keep the bicycle at home, etc
- **Comfort**: not as comfortable as other modes of transport

Impact of road transport to Climate Change

Transport is one of the key contributors to past and future climate change. Historical emissions from transportation contributed about 9% of the temperature change in 2000, while this share may increase to 20% in 2100. It is the second biggest source of greenhouse gas (GHG) emissions in the world, accounting for more than one fifth of all emissions. Progress in reducing these emissions is among the slowest of all sectors. Road transport is over 90% reliant on fossil oil and CO_2 emissions are still growing. They grew by 2.5% annually between 2010 and 2015 globally and are on track to become the largest GHG emitting sector, especially in developed countries. (UNFCCC) (Borgar Aamaas)

It is imperative to take actions now to achieve the goals that have been set in the Paris Agreement. In figure 5, eight key concepts towards the path of rendering the transport sector free of carbon are displayed. Every aspect has supporters and even more rivals. Maybe one of the most crucial parts of these initiatives is the reduction of unnecessary travel, simply because people are becoming more and more unwilling of shifting modes of transportation or sometimes even walk to their destination. Another part of the most importance is the supply chain matter. Surely globalization has made the economies of many countries flourish and has opened new dimensions in trading with people all over the world. However this is costly, not only when money is considered, but also regarding the emissions from the ways of transportation. Shipping, as the most preferable means of global transportation does not contribute so much in the GHG emissions as aviation does and secondly the high duty vehicles for inland transportation.

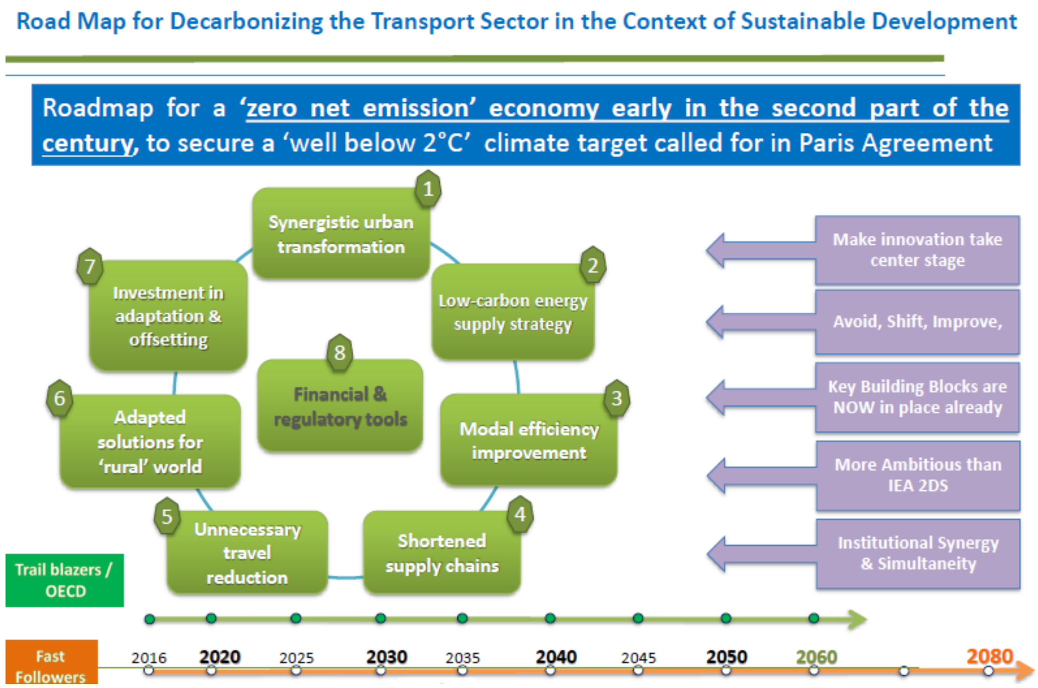

Figure 5: Ways to decarbonize transport sector (UNFCCC, 2018)

The case of Europe

Road transport is responsible for almost one fifth of Europe's greenhouse gas emissions. Emissions from vehicles also lead to high concentrations of air pollutants above EU standards in many of Europe's cities. GHG emissions from transport have increased and today, they are around 16 % above the levels of 1990. As emissions from other sources have decreased, the contribution that road transport makes to total EU emissions has increased by around half — from a 13 % share in 1990 to almost 20 % in 2013. Road transport remains an important source of some of the most harmful **air pollutants**. In particular, road transport is responsible for significant contributions to emissions of nitrogen oxides (NO_X) and 'primary' particulate matter (PM). Others, such as ozone and 'secondary' PM, form in the atmosphere after emissions of precursor pollutants, including NO_X and volatile organic compounds. The extent to which population and the environment are exposed to harmful levels of air pollution is a complex issue, dependent on how pollutants travel in the atmosphere, their mixing and how they react under different meteorological conditions. Since emissions from such sources are in direct connection with the people living in cities, the population is more exposed to them, in contrast to other sources like power plants in remote areas.

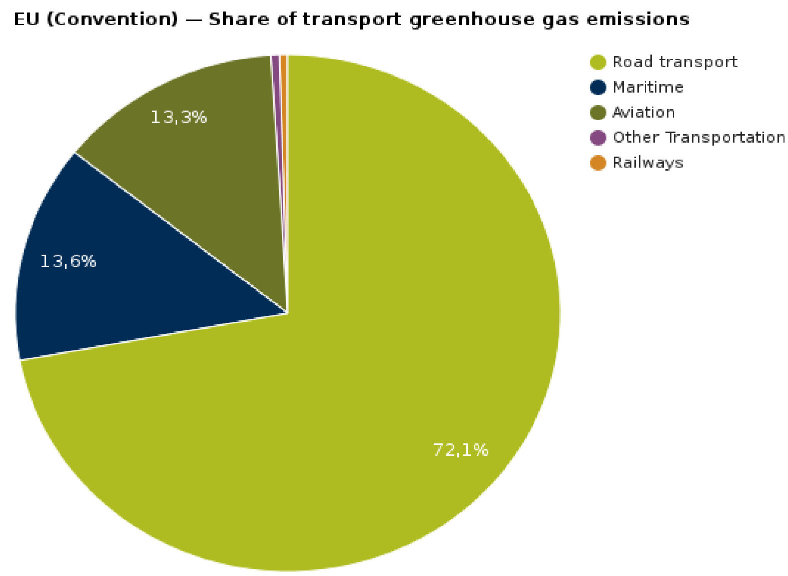

Figure 6.1: GHG emissions shares in the transportation sector in EU (2018)

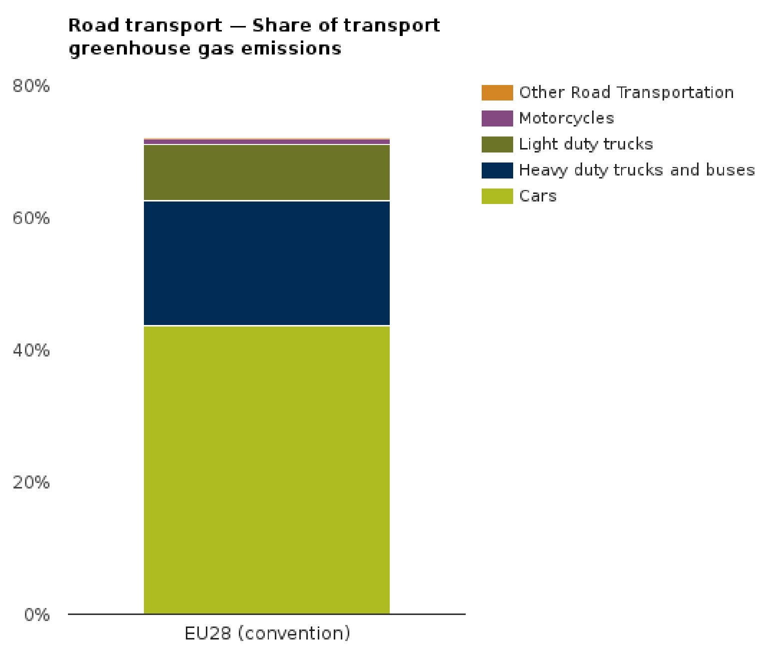

Figure 6.2: GHG emissions shares in the road transportation sector in EU (2018)

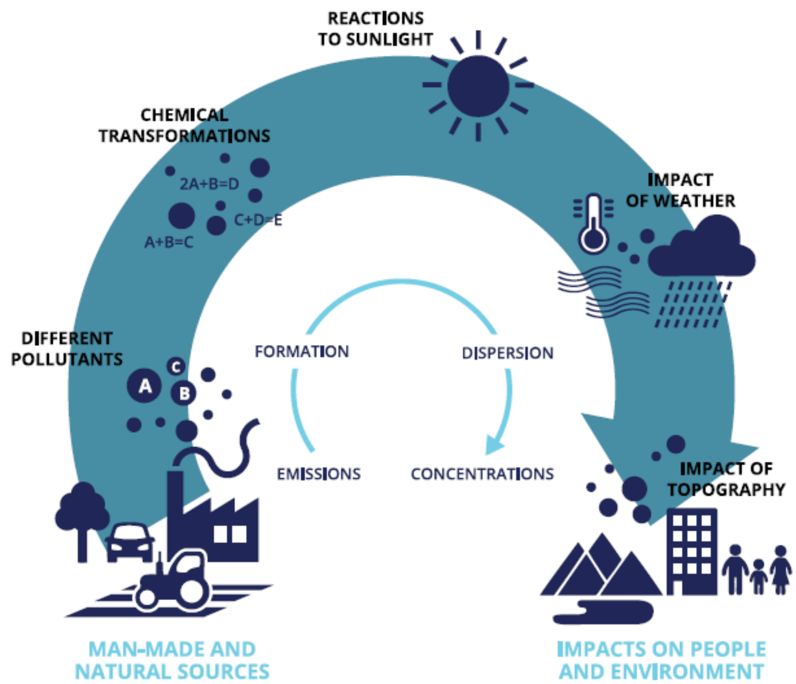

Figure 7: Pollutants circulation (EEA)

Air pollution

Road vehicles emit a variety of greenhouse gases and air pollutants. As well as being emitted from vehicle exhausts, certain pollutants are also released from brake and tire wear and from the evaporation of fuel. The **'regulated'** pollutants include:

- **Carbon dioxide** (**CO_2**): is the main product of fuel combustion in vehicle engines, along with water. CO2 is the most significant GHG influencing climate change, posing a threat to public health and the environment.
- **Hydrocarbons** (**HCs**): are produced from either incomplete or partial combustion and are toxic to human health. HCs and particularly the volatile organic compounds (VOCs), contribute to the formation of ground-level ozone and photochemical smog in the atmosphere.
- **Carbon monoxide** (**CO**): a product of incomplete combustion, which occurs when the carbon in the fuel is only partially oxidized, forming CO and not CO_2. It is colourless and odourless but highly toxic. Direct exposure to CO reduces the flow of oxygen in the bloodstream and is particularly dangerous to people with heart disease. Like HCs, CO also contributes to the formation of ground-level ozone and smog.
- **Particulate matter** (**PM**): is a product of incomplete combustion and a complex mixture of both primary and secondary PM. 'Primary' PM is the fraction of PM that is emitted directly into the atmosphere, whereas 'secondary' PM forms in the atmosphere following the release of precursor gases (mainly sulphur dioxide (SO_2), nitrogen oxides (NO_X), ammonia (NH_3) and some VOCs). In terms of its potential to harm human health, PM is one of the most important

pollutants, as it penetrates deep into the respiratory system and can cause or aggravate cardiovascular and lung diseases and cancer.

- **Nitrogen oxides** (**NO_X**): constitute a group of different chemicals that are all formed by the reaction of nitrogen — the most abundant gas in air — with oxygen. NO_X comprises colourless nitric oxide (NO) and the reddish-brown, very toxic and reactive nitrogen dioxide (NO_2). NO_X emissions also lead to the subsequent formation of 'secondary' PM and ground-level ozone in the atmosphere, and cause harm to the environment by contributing to the acidification and eutrophication of waters and soils.

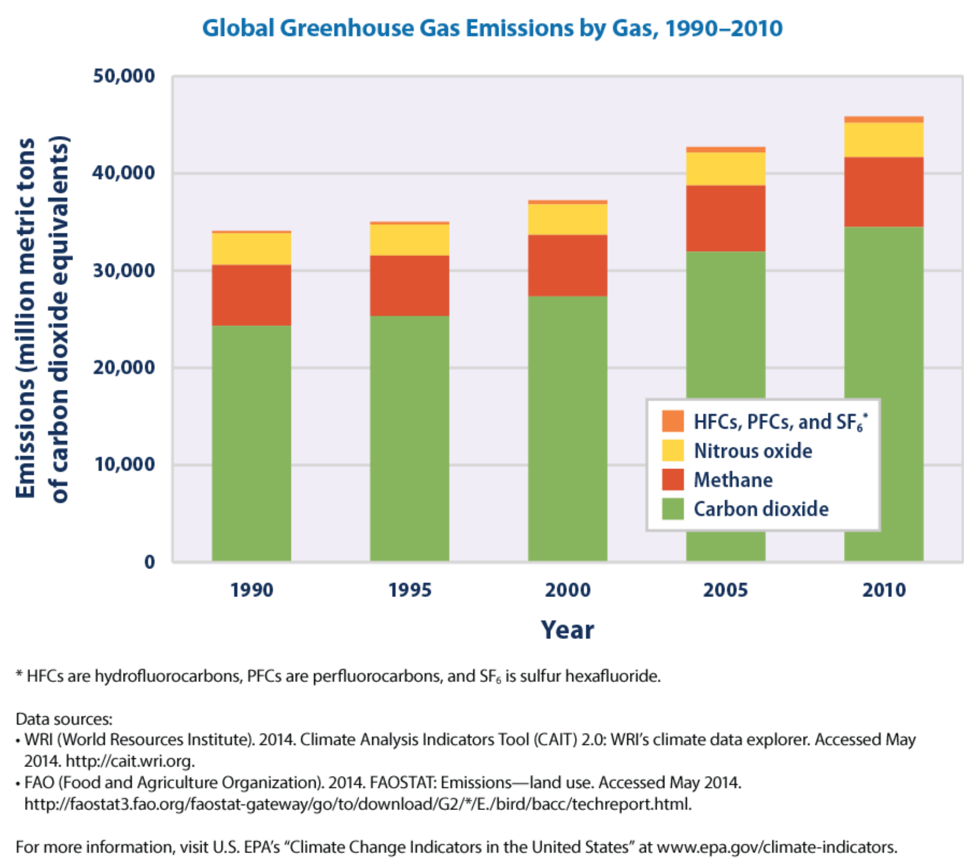

Figure 8: Emissions of GHG for the period 1990-2010

Pollutants emitted by vehicles that are **not currently regulated** by vehicle emission standards in the EU include: certain acidifying pollutants, such as NH_3 and SO_2 (although emissions of the latter are indirectly addressed via fuel quality legislation, which limits the amount of sulphur permissible in fuels); certain carcinogenic and toxic organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs), persistent organic pollutants (POPs), dioxins and furans; and heavy metals, such as lead, arsenic, cadmium, copper, chromium, mercury, nickel, selenium and zinc.

There are also these two very important greenhouse gases that have a huge impact on climate change, sometimes more considerable than the aforementioned.

Methane (**CH_4**) is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock and other agricultural practices and by the decay of organic waste in municipal solid waste landfills. Lastly, methane emissions are largely associated with leakage from the production of natural gas and the filling of compressed natural gas vehicles

Fluorinated gases: Hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride are synthetic, powerful greenhouse gases that are emitted from a variety of industrial processes. Fluorinated gases are sometimes used as substitutes for stratospheric ozone-depleting substances (e.g., chlorofluorocarbons, hydrochlorofluorocarbons, and halons). These gases are typically emitted in smaller quantities, but because they are potent greenhouse gases, they are sometimes referred to as High Global Warming Potential gases ("High GWP gases"). F-gas emissions generally come from air conditioners (including those in vehicles) and refrigerators.

Last but not least comes the **black carbon** and non-absorbing aerosols, emitted mainly during diesel engine operation, have short lifetimes in the atmosphere of only days to weeks, but can have significant direct and indirect radiative forcing effects and large regional impacts. (Ralph Sims)

Types of vehicle emissions

Vehicles emissions can be categorized into three groups:

- **Exhaust emissions** — the emissions produced primarily from the combustion of different petroleum products such as petrol, diesel, natural gas (NG) and liquefied petroleum gas (LPG). These fuels are mixtures of different hydrocarbons, i.e. compounds that contain hydrogen and carbon atoms. In a 'perfect' engine, oxygen in the air would react in a combustion process with all of the hydrogen in the fuel to form water and with all of the carbon in the fuel to form CO_2, and the nitrogen in the air would remain unaffected. In reality, no combustion process is 'perfect', thus vehicle engines emit many different pollutants in addition to water and CO_2. The amount of each pollutant emitted is very dependent on the type of fuel used, e.g. whether a vehicle is diesel or petrol powered, and engine technology.
- **Abrasion emissions** — the emissions produced from the mechanical abrasion and corrosion of vehicle parts. Abrasion is only important for PM emissions and emissions of some heavy metals. Significant levels of PM emissions can be generated from the mechanical abrasion of the vehicle's tires, brakes and clutch, the road surface wear or the corrosion of the chassis, bodywork and other vehicle components.
- **Evaporative emissions** — the result of vapors escaping from the vehicle's fuel system. Evaporative emissions are important for only VOCs. Petrol fuel vapor contains a variety of different HCs, which can be emitted any time there is fuel in the tank, even when the vehicle is parked with its engine turned off.

Carbon dioxide emissions from Europe's heavy-duty vehicles

In EU-28, HDVs (a mixture of different types of trucks, buses and coaches) are currently responsible for 27 % of road transport carbon dioxide (CO_2) emissions. Since 1990 these emissions have increased by 25% and they are projected to further increase. Society is greatly reliant on HDVs; they have a huge impact in logistics sector and contribute to Europe's societal and economic development. Without additional actions to curb CO emissions, the share of road transport CO emissions for which the HDV sector is responsible is set to increase from 27% in 2016 to 32 % in 2030. Such increases in emissions are not compatible with the EU's long-term policy objective of reducing GHG emissions from transport by at least 60 % by 2050.

The largest contributors to HDV CO emissions in the EU-28 are, by size, Germany, France, the United Kingdom, Italy, Spain and Poland. Since 1990 the countries mostly responsible for the increase in CO have been Germany (+14.9 million tonnes of CO (MtCO)), Poland (+9.9 MtCO) and Spain (+7.3 MtCO). Together, these three countries have accounted for more than two-thirds of the total increase in HDV CO emissions in the EU-28. (EEA, 2018)

It is not only transportation itself…

When someone is talking about transportation impact on the climate, one should not only consider the various means of transport and their footprint in the environment. One should also think about the way people travel. The climate impact of transportation is expected to differ with different travel behavior, both at the national level and for individual behavior. Surveys of travel behavior are performed on a regular basis in several countries like Germany, Switzerland, Norway and the USA. Linked with emission factors, the travel behavior is translated to emissions. The following factors can be considered:

1. Driving your car in an aggressive way makes you emit more pollutants to the environment.
2. Using cars for short distances.
3. Families or individuals with high income are responsible for almost 20% of the total climate impact. This can be attributed to the fact that, besides using cars of higher power, they also tend to use airplanes a lot more frequently, with aviation being after road transportation, the largest emitter and contributor to the climate change. (Borgar Aamaas)

GHG and Greek Road Transport

According to K.M. Fameli and V.D. Assimakopoulos (K.M. Fameli, 2015), despite the efforts through the years, the problem of GHG and road pollutants in general, still exists. The results revealed that about 40% of national CO_2, CO, VOC and NMVOC values and 30% of NOx and particles are emitted in Attica only, a place of approximately half the population of the whole country. The major part of CO (56.53%) and CO2 (66.15%) emissions was due to passenger cars (2010), while heavy duty vehicles (HDVs) were connected with NOx, PM2.5 and PM10 emissions with 51.27%, 43.97% and 38.13% respectively (2010).

Table 1
National total emissions (Gg) and emissions from road transport (Gg) for the year 2010 for Greece (as reported to CLRTAP in 2012 — WebDab — EMEP database).

2010	CO	NOx	NMVOC	$PM_{2.5}$
National total	526.53	321.62	184.38	62.81
Road transport	317.78	103.56	39.09	4.40
% contribution to total emissions	(60.35%)	(32.20%)	(21.20%)	(7.00%)

Table 1: Total National and Road emissions for Greece in 2010 (Fameli and Assimakopoulos, 2015)

Details are shown in the table 1 above, where the dominant pollutant is clearly the CO2 with over 50%.

According to UNFCCC report, in 2015, GHG emissions (without LULUCF - Land Use, Land Use Change and Forestry) amounted to 95.7 Mt CO2 eq showing a decrease of 9.64% compared to base year emissions and of 7.15% compared to 1990 levels. If emissions / removals from LULUCF were to be included then the decrease would be 8.25 % (from 100.9 Mt CO2 eq in 1990 to 92.6 Mt CO2 eq in 2015).

Carbon dioxide emissions accounted for 78.32% of total GHG emissions in 2015 (without LULUCF) and decreased by approximately 10.09% from 1990. Methane emissions accounted for 10.68% of total GHG emissions in 2015 and decreased by 6.31% from 1990, while nitrous oxide emissions accounted for 4.71% of the total GHG emissions in 2015 and decreased by 39.29% from 1990. Finally, f-gases emissions (from production and consumption) that accounted for 6.17% of total GHG emissions in 2015 were increased by 42.70% from 1995 (base year for F-gases). (UNFCCC, 2018)

An overview of GHG emissions for the time period 1990–2015 is presented in Table 1.1a and Table 1.1b, while emissions/removals per sector are presented in Table 1.2a and Table 1.2.b (National report, MEEN).

Table 1.1a Total GHG emissions in Greece (in kt CO_2 eq) for the period 1990-2002

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
A. GHG emissions per gas (excluding LULUCF)													
CO_2	83,375.36	83,350.94	84,915.80	84,229.45	86,391.99	86,945.64	89,098.55	93,804.20	98,624.77	97,941.65	102,982.30	105,368.98	105,011.40
CH_4	10,906.61	10,919.21	11,013.98	11,038.71	11,148.72	11,303.20	11,471.76	11,419.64	11,640.53	11,634.36	11,628.86	10,937.64	11,023.64
N_2O	7,423.22	7,289.30	7,134.00	6,575.73	6,458.52	6,662.98	6,835.07	6,675.00	6,602.04	6,560.21	6,328.64	6,204.93	6,161.18
HFC	1,182.82	1,400.08	1,149.07	2,032.44	2,712.11	4,157.38	4,820.17	5,166.49	5,767.51	6,721.15	5,261.83	4,781.39	5,090.07
PFC	190.26	191.19	187.74	112.94	70.31	62.85	53.73	125.64	155.48	105.31	122.26	84.10	88.29
SF_6	2.93	3.02	3.11	3.20	3.29	3.42	3.51	3.56	3.60	3.69	3.81	3.88	4.06
Total	**103,081.19**	**103,153.73**	**104,403.70**	**103,992.47**	**106,784.94**	**109,135.47**	**112,282.79**	**117,194.53**	**122,793.94**	**122,966.37**	**126,327.70**	**127,380.92**	**127,378.64**
B. GHG emissions/removals from LULUCF													
CO_2	-2,245.82	-2,418.51	-2,513.10	-2,979.19	-2,721.86	-2,975.06	-2,389.37	-2,082.05	-2,016.03	-2,647.14	-2,339.38	-2,630.66	-2,903.34
CH_4	62.18	30.91	91.27	81.38	75.92	43.05	26.07	57.40	156.40	11.92	206.51	27.78	3.79
N_2O	5.62	3.30	8.73	8.52	8.35	5.94	5.04	8.18	16.73	5.34	21.65	7.41	5.93
Total	**-2,178.02**	**-2,384.30**	**-2,413.10**	**-2,889.29**	**-2,637.59**	**-2,926.07**	**-2,358.25**	**-2,016.48**	**-1,842.91**	**-2,629.89**	**-2,111.21**	**-2,595.48**	**-2,893.62**
C. GHG Emissions from International Transport													
CO_2	10,580.51	9,569.44	10,762.45	12,332.40	13,393.29	14,004.40	12,530.32	12,475.75	13,767.30	12,829.23	14,018.48	13,513.65	12,342.00
CH_4	17.09	15.33	17.62	20.62	21.76	23.02	20.54	20.62	23.27	20.63	23.94	23.62	21.19
N_2O	257.70	251.00	308.49	343.27	379.47	439.16	363.52	362.02	366.45	342.03	365.90	316.01	285.45
Total	**10,855.29**	**9,835.77**	**11,088.56**	**12,696.30**	**13,794.52**	**14,466.58**	**12,914.38**	**12,858.38**	**14,157.02**	**13,191.89**	**14,408.32**	**13,853.28**	**12,648.64**

Table 1.1b Total GHG emissions in Greece (in kt CO2 eq) for the period 2003-2015

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
A. GHG emissions per gas (excluding LULUCF)													
CO_2	109,083.18	109,530.03	113,925.07	112,464.91	114,582.59	111,112.52	104,340.56	97,342.98	94,531.70	91,417.80	81,722.58	78,657.96	74,962.94
CH_4	11,118.17	11,154.41	11,235.08	11,295.52	11,144.59	11,092.07	10,746.91	10,972.53	10,793.89	10,595.13	10,387.06	10,312.84	10,218.43
N_2O	6,085.75	6,088.43	5,924.21	5,763.70	5,864.10	5,632.82	5,267.02	5,469.46	5,228.73	4,796.77	4,499.27	4,485.00	4,506.46
HFC	4,733.36	4,927.91	5,077.45	2,722.45	3,245.14	3,710.35	3,964.12	4,388.67	4,661.66	5,061.78	5,650.22	5,758.13	5,902.68
PFC	89.28	87.86	91.51	87.21	103.04	118.95	91.35	129.44	110.53	147.77	172.56	134.63	119.52
SF_6	4.06	4.26	6.16	7.98	9.46	7.18	5.02	5.86	5.13	5.05	5.15	4.92	5.06
Total	**131,113.78**	**131,792.90**	**136,259.48**	**132,341.78**	**134,948.92**	**131,673.90**	**124,414.97**	**118,308.93**	**115,331.64**	**112,024.30**	**102,436.85**	**99,353.49**	**95,715.10**
B. GHG emissions/removals from LULUCF													
CO_2	-2,632.47	-2,609.09	-3,388.93	-3,463.86	-2,086.45	-3,310.91	-3,377.93	-3,351.26	-3,440.73	-3,431.62	-1,890.55	-461.70	-3,159.71
CH_4	5.32	13.47	10.49	20.81	319.28	43.24	45.82	16.27	17.75	43.48	15.99	9.39	10.77
N_2O	6.54	7.87	7.87	9.26	34.49	12.36	12.75	9.98	9.94	12.34	9.56	8.62	8.51
Total	**-2,620.60**	**-2,587.75**	**-3,370.57**	**-3,433.79**	**-1,732.67**	**-3,255.30**	**-3,319.36**	**-3,325.00**	**-3,413.04**	**-3,375.80**	**-1,865.00**	**-443.69**	**-3,140.44**
C. GHG Emissions from International Transport													
CO_2	13,304.19	13,474.19	11,815.09	12,727.53	13,103.79	12,862.32	11,147.83	11,373.02	11,652.07	9,727.87	9,382.76	8,878.27	8,657.31
CH_4	21.91	22.17	19.89	21.52	22.09	21.68	18.35	19.06	19.56	16.00	15.09	13.22	12.52
N_2O	275.48	267.53	223.68	235.55	227.13	216.42	196.01	206.56	195.71	167.63	171.56	160.30	172.75
Total	**13,601.58**	**13,763.90**	**12,058.66**	**12,984.61**	**13,353.01**	**13,100.42**	**11,362.19**	**11,598.64**	**11,867.34**	**9,911.50**	**9,569.40**	**9,051.78**	**8,842.57**

Table 1.2a Total GHG emissions in Greece (in kt CO_2 eq) for the period 1990-2002

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Energy	76,869.62	77,006.70	79,019.75	78,659.44	80,886.43	80,949.77	83,167.51	87,703.96	92,427.63	91,883.56	96,678.36	99,120.02	98,946.99
IPPU	11,226.96	11,163.40	10,577.36	11,028.32	11,636.59	13,569.65	14,338.11	14,835.60	15,552.78	16,389.35	15,176.38	14,575.50	14,768.63
Agriculture	10,120.79	10,144.10	9,868.57	9,314.84	9,119.26	9,465.84	9,527.64	9,443.03	9,418.75	9,346.04	9,124.74	9,109.03	9,132.75
Waste	4,863.82	4,839.52	4,938.02	4,989.87	5,142.66	5,150.20	5,249.53	5,211.94	5,394.79	5,347.42	5,348.23	4,576.37	4,530.27
Total [1]	**103,081.19**	**103,153.73**	**104,403.70**	**103,992.47**	**106,784.94**	**109,135.47**	**112,282.79**	**117,194.53**	**122,793.94**	**122,966.37**	**126,327.70**	**127,380.92**	**127,378.64**
LULUCF	**-2,178.02**	**-2,384.30**	**-2,413.10**	**-2,889.29**	**-2,637.59**	**-2,926.07**	**-2,358.25**	**-2,016.48**	**-1,842.91**	**-2,629.89**	**-2,111.21**	**-2,595.48**	**-2,893.62**
Index per sector													
Energy	100.00	100.18	102.80	102.33	105.23	105.31	108.19	114.09	120.24	119.53	125.77	128.95	128.72
IPPU	100.00	99.43	94.21	98.23	103.65	120.87	127.71	132.14	138.53	145.98	135.18	129.83	131.55
Agriculture	100.00	100.23	97.51	92.04	90.10	93.53	94.14	93.30	93.06	92.34	90.16	90.00	90.24
Waste	100.00	99.50	101.53	102.59	105.73	105.89	107.93	107.16	110.92	109.94	109.96	94.09	93.14
Total [2]	**100.00**	**100.07**	**101.28**	**100.88**	**103.59**	**105.87**	**108.93**	**113.69**	**119.12**	**119.29**	**122.55**	**123.57**	**123.57**

1) Emissions / removals from *Land Use, Land Use Change and Forestry* are not included in national totals

2) *Land Use, Land Use Change and Forestry* is not included

Table 1.2b Total GHG emissions in Greece (in kt CO_2 eq) for the period 2002-2015

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Energy	102,830.84	103,324.48	107,136.64	105,852.07	108,071.31	105,227.91	100,268.60	93,080.53	91,901.25	88,118.94	77,766.86	74,323.39	71,022.38
IPPU	14,532.25	14,673.33	15,425.62	12,739.51	13,173.76	12,987.41	11,185.12	11,662.02	10,320.48	11,140.73	11,861.99	12,232.95	11,896.29
Agriculture	9,099.06	9,139.04	8,936.41	8,839.92	8,971.78	8,715.16	8,497.16	8,815.94	8,574.71	8,446.56	8,380.53	8,294.91	8,309.97
Waste	4,651.63	4,656.04	4,760.81	4,910.28	4,732.08	4,743.41	4,464.09	4,750.44	4,535.19	4,318.07	4,427.47	4,502.23	4,486.46
Total [1]	**131,113.78**	**131,792.90**	**136,259.48**	**132,341.78**	**134,948.92**	**131,673.90**	**124,414.97**	**118,308.93**	**115,331.64**	**112,024.30**	**102,436.85**	**99,353.49**	**95,715.10**
LULUCF	**-2,620.60**	**-2,587.75**	**-3,370.57**	**-3,433.79**	**-1,732.67**	**-3,255.30**	**-3,319.36**	**-3,325.00**	**-3,413.04**	**-3,375.80**	**-1,865.00**	**-443.69**	**-3,140.44**
Index per sector													
Energy	133.77	134.42	139.37	137.70	140.59	136.89	130.44	121.09	119.55	114.63	101.17	96.69	92.39
IPPU	129.44	130.70	137.40	113.47	117.34	115.68	99.63	103.88	91.93	99.23	105.66	108.96	105.96
Agriculture	89.90	90.30	88.30	87.34	88.65	86.11	83.96	87.11	84.72	83.46	82.81	81.96	82.11
Waste	95.64	95.73	97.88	100.96	97.29	97.52	91.78	97.67	93.24	88.78	91.03	92.57	92.24
Total [2]	**127.19**	**127.85**	**132.19**	**128.39**	**130.92**	**127.74**	**120.70**	**114.77**	**111.88**	**108.68**	**99.37**	**96.38**	**92.85**

1) Emissions / removals from *Land Use, Land Use Change and Forestry* are not included in national totals

2) *Land Use, Land Use Change and Forestry* is not included

The dominance of CO_2 emissions is shown in the tables above. What is also interesting is the fact that there is a decreasing trend from 2007 and onward. Presumably, this is a result of the economic crisis that hit Greece and the rest of the world in 2008. At that time on, people gradually started not to use their cars for transportation. Many people got rid of their automobiles as well. That is the most possible explanation to such drastic decline and it is shown at figure 9 too. Of course, it is also the new EURO engine cars, which contribute to the protection of the environment through their better technology.

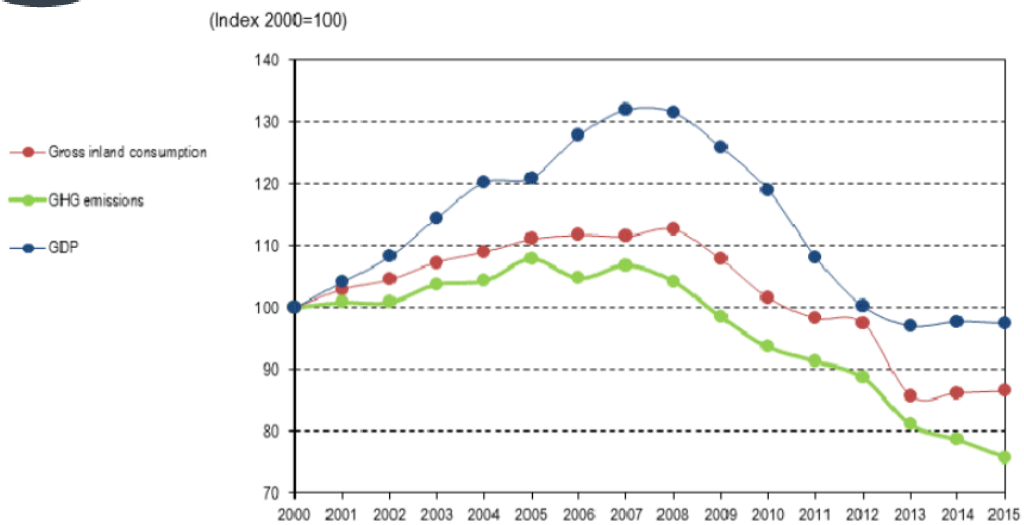

Figure 9: Greece's GHG emissions in reliance with its GPD (Report on the State of the Environment, MEEN 2016)

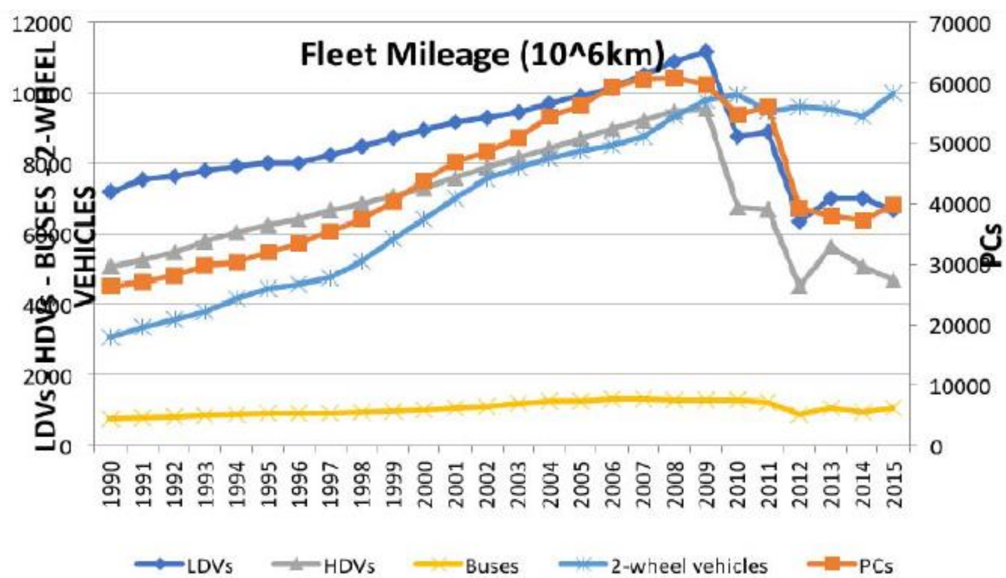

Figure 10: Greek fleet mileage for different types of vehicles (Report on the State of the Environment, MEEN 2016)

Passenger cars are by far the most usable mode of transportation. Yet again there is the difference between the pre-crisis period and the after-crisis, where every mode except the 2-wheel vehicles, showed a decline. Probably the 2-wheel vehicles became more popular because of their low cost of acquisition and lower cost of individual transportation.

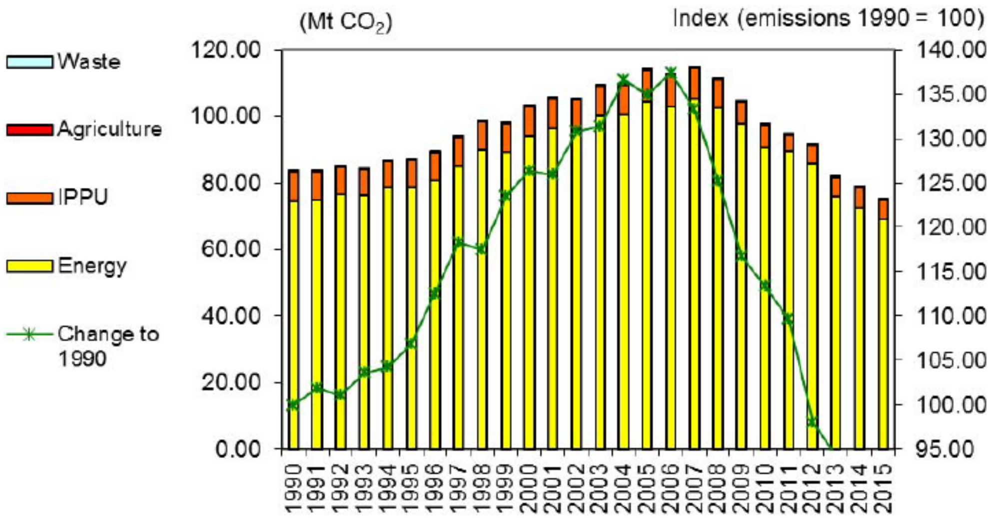

Figure 11: Carbon Dioxide (CO_2) emissions by sector (Report on the State of the Environment, MEEN 2016)

Methodology

The main aim of the present work is to study the effect of cycling on the local air quality, climatic conditions and emissions of CO_2 and NOx. It was done by selecting two municipalities: The first one is a suburban area, with a significant percentage of green spaces, cycling infrastructure, traversed by highways, with low traffic zones and a commercial centre (e.g. Vrilissia). The second one is a densely built up area, located in the urban centre, with almost no free green spaces, metro and bus stations, traffic congestion conditions and no cycling infrastructure.

For the selected municipalities:

- Air quality data regarding the pollutants NO_2 and O_3 were collected from the Ministry of the Environment Air Quality Monitoring Network, for the years 2012, when one of the hottest summers in Attiki took place, and for the years 2015 & 2016.
- Temperature, relative humidity, wind speed and direction were collected from the National Observatory of Athens meteorological network (www.meteo.gr) for the period 2015-2017.

The data collected were used to compute the Daily Air Quality index (**DAQx**), the bioclimatic comfort index from the data taken from the Ministry and to compute the Discomfort Index (**DI**) from the data taken from National Observatory of Athens meteorological network. The lower the values of the index the better conditions prevail, so one can understand that in terms of traffic produced pollutants such as NOx the conditions are expected to be worse in a highly trafficked area.

Indexes adopted

There are many indices to monitor and assess the quality of the local urban environment, each one with different input needs and output. According to the data collected it was decided to use the aforementioned two indices (DAQx and DI). Below, there is a short literature review of other indices that exist. These indices could be calculated with reference to Temperature and Relative Humidity and with reference to various pollutants.

Concerning the first group, indexes measured with Temperature and Relative Humidity, those particular were found:

1. **Discomfort Index**: According to the result taken by the calculations, the number of the class depicts the conditions that an average man should feel. The desired class is the first one, where the ambient condition of the environment is comfortable. (Anastasia Poupkou, 2011)

$$\mathrm{DI}(^{\circ}\mathrm{C}) = T_h - 0.55(1 - 0.01\mathrm{RH_h})(T_h - 14.5)$$

where **T_h** is the mean hourly value of the air temperature in degrees Celsius and **RH_h** is the corresponding hourly value of the relative humidity as a percentage. The classes of the DI index are the following shown in figure 14:

Table 1 Classes of the Discomfort Index

Class number	DI (°C)	Discomfort conditions
1	$DI<21$	No discomfort
2	$21 \leq DI<24$	Less than half of the population feels discomfort
3	$24 \leq DI<27$	More than half of the population feels discomfort
4	$27 \leq DI<29$	Most of the population suffers discomfort
5	$29 \leq DI<32$	Everyone feels severe stress
6	≥ 32	State of medical emergency

Figure 14: Classes of the Discomfort Index

2. **HUMIDEX**: This index provides an indication of a citizen's perception of the outdoor air as a consequence of a lack of evaporation of perspiration during hot and humid weather. The equation calculating Humidex is the following:

HUMIDEX = T + (0.5555) * (e - 10.0)

where **T** = air temperature (°C) and **e** = actual vapour pressure (hPa). The classes of the index are

HUMIDEX range (°C)	Degree of comfort
Less than 29	Comfort
30–34	Some possible slight discomfort
35–39	Some possible moderate discomfort
40–45	Possible strong discomfort
46–53	Possible very strong discomfort
Over 54	Danger of death; imminent heat stroke

Tab. 2: HUMIDEX scale (after Baum et al., 2009)

Figure 15: Humidex index range (Hana Středová, 2015)

If the result of the calculations is below 29, then people have the feeling of comfort. However, index values from 40 and above indicate there is a serious sense of discomfort and vulnerable groups of people must be protected.

3. **Effective Temperature**: mainly used to estimate the phenomenon of the Urban Heat Island, it is calculated by a little more complicated equation:

$$ET = 37 - \frac{37 - T}{0.68 - 0.0014 \cdot f + \frac{1}{1.76 + 1.4 \cdot v^{0.75}}} - 0.29 \cdot T \cdot (1 - 0.01 \cdot f)$$

Figure 16: Equation for the calculation of Effective Temperature

where: **t** is air temperature (ºC), **f** is relative air humidity (%) and **v** is wind speed exceeding 0.2 m·s^(-1) at 2 m above ground level. Finally, the classes of the ET index are:

- very cold (below 3.1 ºC)
- cold (3.2-7.1 ºC)
- cool (7.2-11.2 ºC)
- comfortable (11.3-14.9 ºC)
- warm (15.0-18.9 ºC)
- hot (19.0-21.8 ºC)
- very hot (above 21.8 ºC) (Małgorzata Czarnecka, 2014)

As far as the second group of indexes is concerned, the ones that are calculated with the data from pollutants like NO_2 and O_3, the one and only reliable index that was also used, is the Daily Air Quality Index or DAQx for short. Impact-related air quality indices are very rare, because it is difficult to quantify the impacts of a mixture of air pollutants, which is typical of the ambient air, on wellbeing and health of people in a graded way. Below it is the classification of the index taken from the reference above:

Table 2: Assignment of ranges of specific air pollutant concentrations to DAQx values and DAQx classes inclusive of classification names (according to MAYER et al., 2002a, b).

NO_2 ($\mu g/m^3$)	SO_2 ($\mu g/m^3$)	CO (mg/m^3)	O_3 ($\mu g/m^3$)	PM_{10} ($\mu g/m^3$)	*DAQx value*	*DAQ class*	*classification*
0–24	0–24	0.0–0.9	0– 32	0.0–9.9	$\leq$1.4	1	very good
25–49	25–49	1.0–1.9	33–64	10.0–19.9	1.5–2.4	2	good
50–99	50–119	2.0–3.9	65–119	20.0–34.9	2.5–3.4	3	satisfying
100–199	120–349	4.0–9.9	120–179	35.0–49.9	3.5–4.4	4	sufficient
200–499	350–999	10.0–29.9	180–239	50.0–99.9	4.5–5.4	5	poor
$\geq$ 500	$\geq$ 1000	$\geq$ 30.0	$\geq$ 240	$\geq$ 100	$\geq$ 5.5	6	very poor

Figure 17: Classes of the DAQx index for various pollutants

DAQx is calculated for each air pollutant – according to the EPA index AQI – by:

$$DAQx = \left[\left(\frac{DAQx_{up} - DAQx_{low}}{C_{up} - C_{low}}\right) * (C_{inst} - C_{low})\right] + DAQx_{low}$$

Figure 18: DAQx calculation equation

where **Cinst** .: daily maximum 1-h concentration of NO2, SO2, and O3, daily highest 8-h running mean concentration of CO or daily mean concentration of PM10, **Cup**: upper threshold of specific air pollutant concentration range (Table 2), **Clow**: lower threshold of specific air pollutant concentration range, **DAQxup**: index value corresponding to Cup, **DAQxlow**: index value corresponding to Clow (HELMUT MAYER, 2004). It is quite accurate, easy to calculate and provides with good results. The first class indicates a good ambient environment, while the last two classes depict a bad environment.

COPERT application

The European model COPERT was used in order to measure road transport air emissions in urban areas and to simulate various scenarios in which different fleet mixtures with various speed tests serve as inputs. It is a widely used program, especially in the countries of Europe like Italy (Salvatore Saija, 2002), Spain (Rafael Borge, 2012), Ireland (StephanLeinert, 2013), Denmark (Katerina Papagiannaki, 2009) and many more.

The road transport sector emissions were calculated using the top-down approach based on the EMEP/ CORINAIR methodology (EEA, 2016). Within that frame the model COPERT 5.1 was applied for the estimation of annual emissions for Attica for the year 2016. COPERT is user-friendly software

(Gkatzoflias et al. 2012, Katsis et al. 2012) and it is officially proposed from the United Nations Framework Convention on Climate Change (UNFCCC) (IPCC, 2006). The methodology allows the estimation of emissions from five main vehicle classes: Passenger Cars (PCs), Light Commercial Vehicles (LCV), Heavy Duty Trucks (HDT), buses and motorcycles. These are then distinguished according to the fuel type used (gasoline, diesel, liquid petroleum gas, compressed natural gas, hybrid gasoline), the EU Directives to which they conform in terms of emissions (PRE ECE, ECE 15/00-01, Euro 1, Euro 2, etc.) and the engine capacity (e.g. <1.4lt, 1.4-2.0lt, >2.0lt for passenger cars, <3.5t or >3.5t for commercial vehicles).

Model performance

Generally total emissions are calculated by means of the following equation, for each vehicle category (EEA, 2013b):

$$E_{total} = E_{hot} + E_{cold} \qquad (1)$$

where E_{total} is the annual total emissions (g) of any pollutant for Attica, E_{hot} is the emissions (g) during stabilized (hot) engine operation and E_{cold} is the emissions (g) during transient thermal engine operation (cold start).

Since engine operations determine vehicle emissions a distinction was made between urban (peak and off peak), rural and highway driving conditions (e.g. for gasoline PCs the share was considered to be 44% (14%-30%), 42% and 14% for urban (peak-off peak), rural and highway driving conditions respectively). Moreover, different speed values were attributed to vehicle categories for each driving condition (e.g. PCs speed values of 19 km/h, 30 km/h, 60 km/h and 90 km/h correspond to the urban peak, urban off peak, rural and highway driving conditions). The necessary activity data (share of driving condition and mean travelling speeds in different driving conditions) as well as the information needed for vehicles technology splitting were collected in the framework of the FLEETS project (Ntziachristos et al. 2008) and are provided by EMISIA SA for Greece (www.emisia.com).

Road traffic emissions depend on: 1) the distance traveled (km); 2) the fuel used (e.g. diesel, gasoline); 3) velocity (km/h) or road type; 4) the engine capacity and 5) the emission standards (e.g. Euro 4). Therefore, the formula to be applied for the calculation of hot emissions of pollutants yields:

$$E_{hot;\, i,\, k,\, r} = N_k \times M_{k,r} \times e_{hot;\, i,\, k,\, r} \qquad (2)$$

where $E_{hot;\, i,\, k,\, r}$ is the annual hot exhaust emissions of the pollutant i (g), produced by vehicles of technology k driven on roads of type r, N_k is the number of vehicles (veh) of technology k in operation in the period concerned, $M_{k,r}$ is the mileage per vehicle (km/veh) driven on roads of type r by vehicles of technology k and $e_{hot;\, i,\, k,\, r}$ is the emission factor in (g/km) for pollutant i, relevant for the vehicle technology k, operated on roads of type r.

Cold-start emissions are attributed mainly to urban driving (and secondarily to rural driving), as it is expected that a limited number of trips start at highway conditions. Cold-start emissions are introduced into the calculation as additional emissions per km using the following formula:

$$E_{cold;\, i,\, j} = \beta_{i,\, k} \times N_k \times M_k \times e_{hot;\, i,\, k} \times (e^{cold} / e^{hot}|_{i,k} - 1), \quad (3)$$

Where $E_{cold;\, i,\, k}$ is the cold-start emissions of pollutant i (for the reference year), produced by vehicle technology k, $\beta_{i,\, k}$ is the fraction of mileage driven with a cold engine or the catalyst operated below the light-off temperature for pollutant i and vehicle technology k, N_k is the number of vehicles (veh) of technology k in circulation, M_k is the total mileage per vehicle (km/veh) in vehicle technology k and $e^{cold} / e^{hot}|_{i,k}$ is the cold/hot emission quotient for pollutant i and vehicles of k technology.

The β-parameter depends upon ambient temperature t_a (for practical reasons the average monthly temperature can be used), and the pattern of vehicle use — in particular the average trip length l_{trip}. A value of 12.4 km has been established for the l_{trip} value.

Input - Output data

Table 4 presents the input data required for the COPERT compilation. Fleet composition data were provided by the National Statistical Service of Greece (Hellenic Statistical Authority). Moreover, new vehicle registrations were obtained from ACEA, the Association of Motor Vehicle Importers Representatives (AMVIR), the Hellenic Statistical Authority, Eurostat and the International Council on Clean Transportation (ICCT, 2011). The fleet composition for the Attica is presented in Table 5 for the years 2010 and 2016. Gasoline (G) PCs remain rather stable the last six years with a slight decrease in G > 2.0 lt while diesel, hybrid, CNG and LPG PCs increased. This is due to the fact that there is a trend in withdrawal of PCs with cylinder capacity above 2.0 lt and in buying diesel, CNG and LPG PCs thanks to the taxation policy. The meteo.gr provided the necessary mean minimum and maximum monthly temperature profiles as well as the humidity values required by COPERT (Table 6). The annual total fuel consumption for each fuel type was provided by the Greek Ministry of Environment. Less reliable information concerning the annual mileage for each vehicle type were used considering that old vehicles travel fewer kilometers (Symeonidis et al. 2003).

Table 4. Input data used in the inventory and the sources that provided these data

Input data	**Source**
Vehicle fleet composition per vehicle type	National Statistical Service of Greece
New vehicle registrations	European Automobile Manufacturers (ACEA) Association of Motor Vehicle Importers Representatives (AMVIR) National Statistical Service of Greece International Council on Clean Transportation
Minimum and maximum monthly mean	www.meteo.gr

temperature profiles and humidity values	
Annual fuel consumption	Ministry of Environment and Energy

Table 5. Vehicles fleet composition in Attica for the years 2010 and 2016.

	2010%	**2016%**
PC	**74.09**	**73.32**
Gasoline PCs	*98.80*	*94.08*
Diesel PCs	*0.96*	*5.91*
LPG, CNG	*0.10*	*0.12*
Hybrid Gas	*0.14*	*0.25*
LCV	**6.05**	**5.77**
HDT	**1.49**	**1.53**
Buses	**0.34**	**0.32**
Two-wheelers	**18.03**	**19.05**
Total	100	100.00

The emission estimation methodology covers exhaust emissions of CO, NOx, NMVOC, CH_4, CO_2, N_2O, NH_3, SOx, exhaust PM, PAHs and POPs, dioxins and furans, and heavy metals contained in the fuel (lead, arsenic, cadmium, copper, chromium, mercury, nickel, selenium and zinc). NOx emissions are further split into NO and NO_2. PM is also divided into elemental carbon and organic carbon as a function of vehicle technology. A detailed speciation of NMVOCs is also provided, and this covers homologous series such as alkanes, alkenes, alkynes, aldehydes, ketones and aromatics compounds.

Impacts of input parameters on Attica emissions

In order to estimate the effects of different input parameters on emissions calculated by COPERT for the Attica region seven scenarios were constructed concerning the vehicles fleet, the fleet of PCs in particular and the length of the trip and the maximum and minimum monthly temperatures. The reference year for the scenarios process was 2016 so changes were made for that year's inputs. More specifically, the nine scenarios were:

- ***Scenarios A & B.*** In order to estimate the possible benefits due to the decrease in PCs all diesel and gasoline PCs were reduced by 30% and 50% respectively.
- ***Scenarios C & D.*** The influence of the oldest engine technologies (Euro standards 1, 2, and 3) on emissions was examined with the reduction of all Euro 1, 2 and 3 PCs by 30% and 50% respectively.
- ***Scenarios E & F.*** The two-wheelers fleet effect on emissions was estimated by decreasing their number by 30% and 50%.

- ***Scenarios G & H.*** The effect on emissions from the reduction of all vehicles by 30% and 50% was estimated.

- ***Scenario I.*** The mean monthly minimum and maximum temperatures increased by 2^0C in order to analyze the sensitivity of calculations with respect to the temperature.

Results – Vehicle emissions and impact of traffic reduction scenaria

Table 6 shows the emissions per vehicle type for the year 2016 for Attica. It is obvious that PCs contribute most to the total road traffic emissions of CO, NMVOC and CO_2. Approximately 37.9% of CO and 59.1% of CO_2 emissions come from gasoline PCs while diesel PCs are responsible only for 0.2% of total CO emissions and 6.2% of CO_2 emissions. Motorcycles also play a significant role to CO and NMVOC emissions (45.9% and 46.7% respectively) since they are economic and efficient and consequently very popular to use in urban Athens traffic conditions. The vehicle category that dominates in NOx, $PM_{2.5}$ and PM_{10} emissions is HDTs with 54.4%, 43.9% and 37.6% respectively, which is attributed to the diesel engines and the old engine technology. The second larger contribution to this group of pollutants comes from PCs, namely 20.2% for NOx, 31.6% for $PM_{2.5}$ and 40.0% for PM_{10}. Motorcycles have a small contribution to NOx (4.8%), $PM_{2.5}$ (11.2%) and PM_{10} (10.1%) emissions. LCVs use both gasoline and diesel fuel and as a consequence the emissions percentages do not vary among pollutants, the percentage of CO is the highest, 10.7%. Buses contribute to NOx by 15.0% and particles emissions (7.9%- $PM_{2.5}$, 6.9% - PM_{10}).

Table 6. Annual emissions per vehicle category in ktonnes.

2016	CO (ktonnes)	NOx (ktonnes)	$PM_{2.5}$ (ktonnes)	CO_2 (ktonnes)
PCs	**30.5979**	**5.0551**	**0.2996**	**5,549.7672**
Gasoline	**30.3788**	**3.3048**	**0.2561**	**5,003.0903**
Diesel	**0.1707**	**1.7447**	**0.0422**	**528.7992**
Gas Hybrid	**0.0268**	**0.0029**	**0.0008**	**10.5555**
LPG Bifuel	**0.0197**	**0.0025**	**0.0004**	**6.6184**
CNG Bifuel	**0.002**	**0.0002**	**0.**	**0.7038**
LCVs	**8.591**	**1.4045**	**0.0495**	**449.8606**
HDTs	**3.3028**	**13.6103**	**0.416**	**1,522.8392**
Buses	**0.8166**	**3.7557**	**0.0754**	**433.8376**
Two-wheelers	**36.7927**	**1.1891**	**0.106**	**506.4056**
Total	80.1009	25.0147	0.9465	8,462.7102

The results from the scenarios A – I estimates are presented in figures 19-21 for the pollutants CO, NOx, NMVOCs, $PM_{2.5}$, PM_{10} and the greenhouse gas CO_2. The emissions for 2010 and 2016 are also presented as reference for comparison.

Regarding scenarios A & B, CO_2, PM_{10}, CO and NMVOCs emissions were mainly affected (reduced) by the reduction of PCs - 32%, 20%, 19% and 19% reduction for scenario B respectively, compared with the initial 2016 ones. The influence of reducing Euro 1, 2, 3 PCs (scenarios C & D) was the decrease of CO, NMVOCs and CO_2 emissions by maximum 14% (scenario D). Small was the impact of the reduction of two wheelers on NOx, PM and CO_2 emissions while CO and NMVOCs were reduced by 23% in scenario G. On the other hand, the sharp change of the total vehicles fleet revealed that HDTs and old engine technologies can affect the total emissions for all pollutants and CO_2 and measurements should be taken towards that direction. In scenario I the increase of the ambient mean maximum and minimum temperature led to a small decrease in all emissions but CO and NMVOCs were mainly affected by 3.3% and 2.8% respectively.

Table 8. Emissions for the years 2010, 2016 and from the development of the scenarios for Attica.

	Emissions (ktonnes)				
		CO	**NOx**	**$PM_{2.5}$**	**CO_2**
2010		91.21	25.54	1.03	7,992.62
2016 - base case		80.10	25.01	0.95	8,462.71
2016 - scenarios					
A	*All PCs -30%*	70.92	23.50	0.86	6,797.79
B	*All PCs -50%*	64.80	22.49	0.80	5,687.84
C	*Euro 1, 2, 3 PCs -30%*	73.08	24.28	0.91	7,713.16
D	*Euro 1, 2, 3 PCs -50%*	68.40	23.79	0.88	7,213.46
E	*Two wheelers -30%*	69.06	24.66	0.91	8,310.79
F	*Two wheelers -50%*	61.70	24.42	0.89	8,209.51
G	*All vehicles -30%*	48.00	17.39	0.64	5,878.67
H	*All vehicles -50%*	3.92	1.61	0.06	485.46
I	*Temperature +2^{0}C*	77.42	24.98	0.94	8,431.00

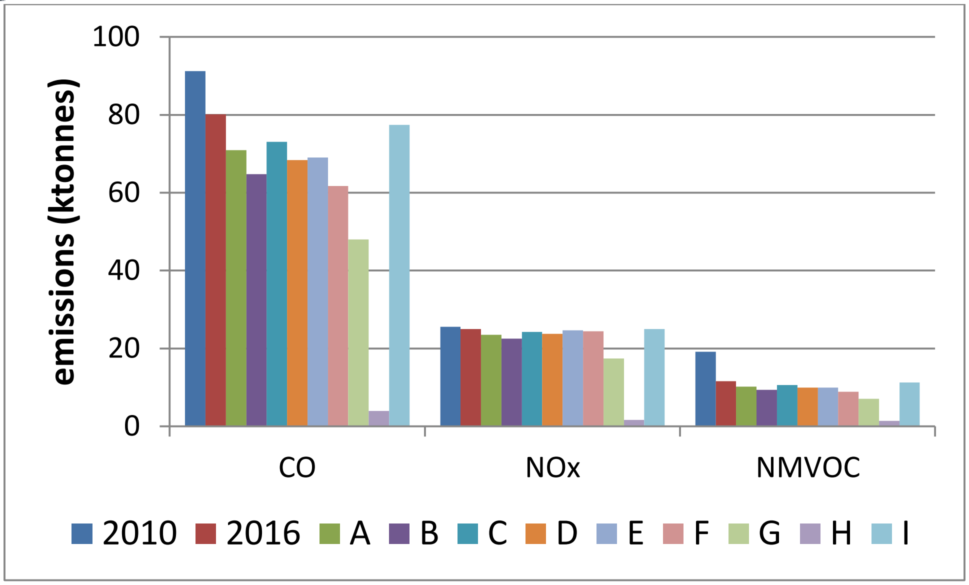

Figure 19: CO, NOx and NMVOCs emissions for the years 2010, 2016 and emissions scenarios.

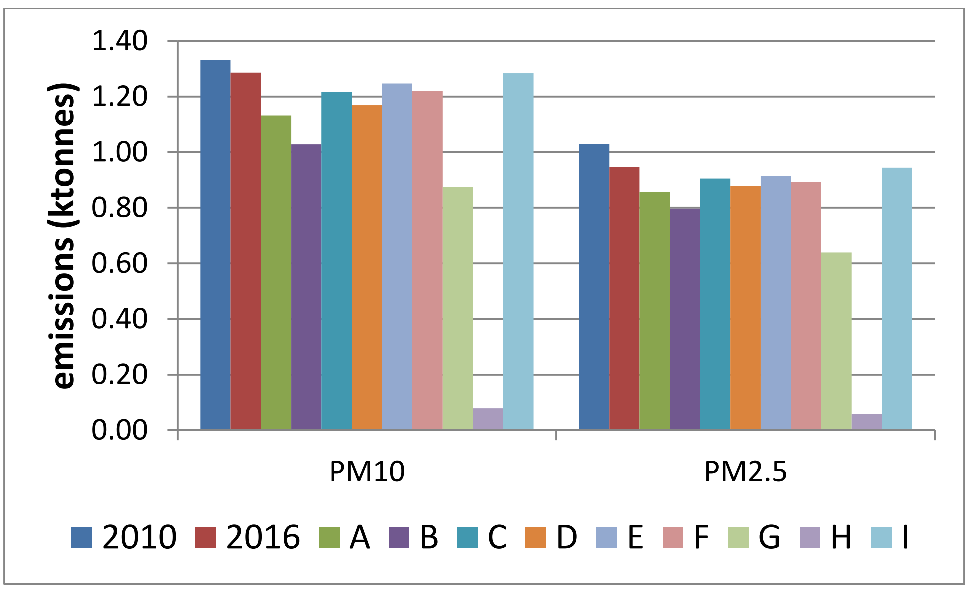

Figure 20: PM_{10} and $PM_{2.5}$ emissions for the years 2010, 2016 and emissions scenarios.

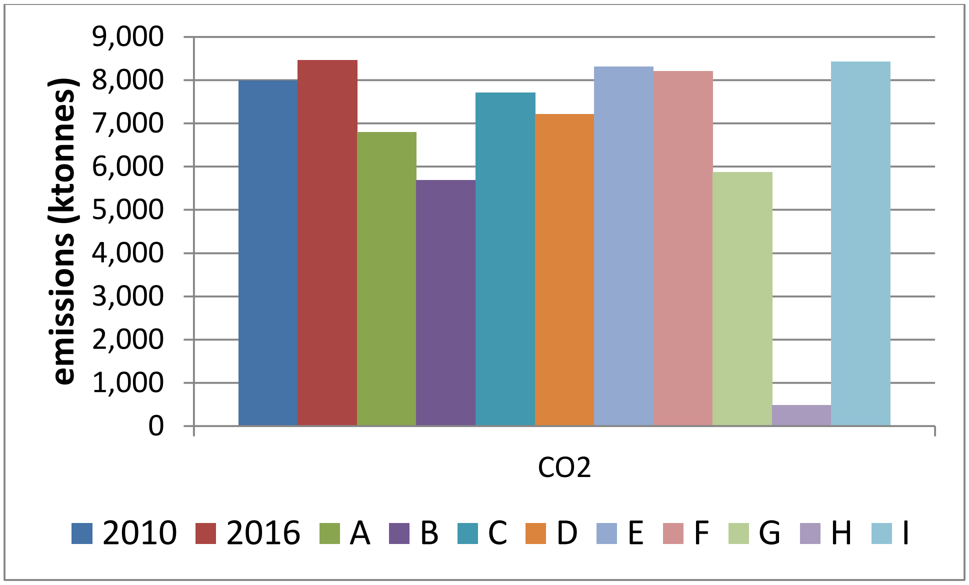

Figure 21: CO_2 emissions for the years 2010, 2016 and emissions scenarios.

Results: Comfort and air quality indexes and impact of location

The analysis of the results from the computation of indexes DAQx and DI, in order to assess the environmental conditions that people live in two different areas described above, is presented in this section. Regarding the Discomfort Index (DI), the data collected came from different areas of the Athens basin where Athens, Koridallos, Patisia, Ampelokhpoi and Nea Smurni are the worst cases examined (urban, traffic, densely built, minimum cycling paths), while Penteli, Vrilisia and Agia Paraskeui are the suburban areas with more green spaces, cycling paths, low traffic conditions.

As for the DAQx, the general impression is that some places like Nea Smurni, its ambient environment is considered as poor. There were measured high values of both NO2 and ground level O3 pollutants. However, there is a clarification here that needs to be made. Tropospheric, or ground level ozone, is not emitted directly into the air, but is created by chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC). This happens when pollutants emitted by cars, power plants, refineries, chemical plants, and other sources chemically react in the presence of sunlight. Therefore, ozone is most likely to reach unhealthy levels on hot sunny days in urban environments, but can still reach high levels during colder months. Ozone can also be transported long distances by wind, so even rural areas can experience high ozone levels and that is exactly the case here. While there are places in the Atiiki area that are not so densely populated, thus less cars are moving into the area, high volumes of ozone are measured, simply because it is created in these areas by the transportation of NOx and VOCs via the wind or it is transported itself by the wind to these areas. For instance, Marousi and Agia Paraskeui are example of high ozone pollution.

Discomfort Index

In the figures below some of the results and the basic differences among the different types of environments are depicted. In some stations like Penteli, temperature and relative humidity present satisfactory values, which make people living close to the region feeling comfortable. These results were expected, as Penteli is a located on a mountainous area. On the other hand, there are areas like Nea Smurni, where the comfort conditions are poor. Nea Smurni is in the south of the Athens basin and it suffers from high temperatures and high percentages of humidity, merely because of the lack of green spaces as well as being densely populated.

In the figures below, the graphs presented show on the horizontal axis the index class, i.e., the comfort or discomfort of the people according to the temperature and the relative humidity. The frequency of appearance of each class of DI is depicted on the vertical axis. The higher the class value, the more discomfort is felt. In areas like Athens and Nea Smurni, more than half of the population would probably feel more discomfort around 40 times in the year of 2015, which is double the frequency at the Vrilisia municipality. Penteli's results are significantly lower and the same is observed in the years 2016 and 2017, with the latter being slightly worse and the reason might be, that every year, Greece is suffering from more extreme winters and summers.

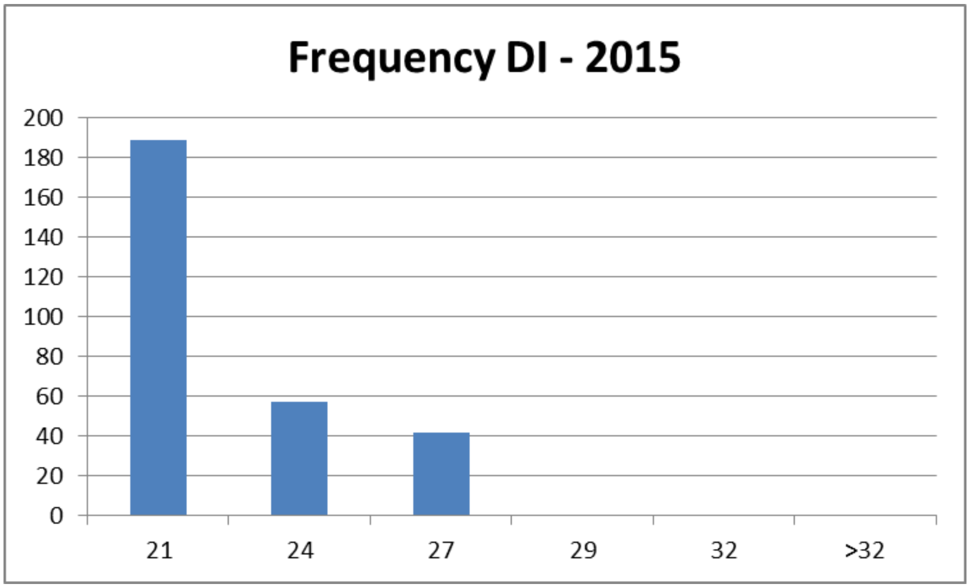

Figure 22: Nea Smurni annual frequency of DI

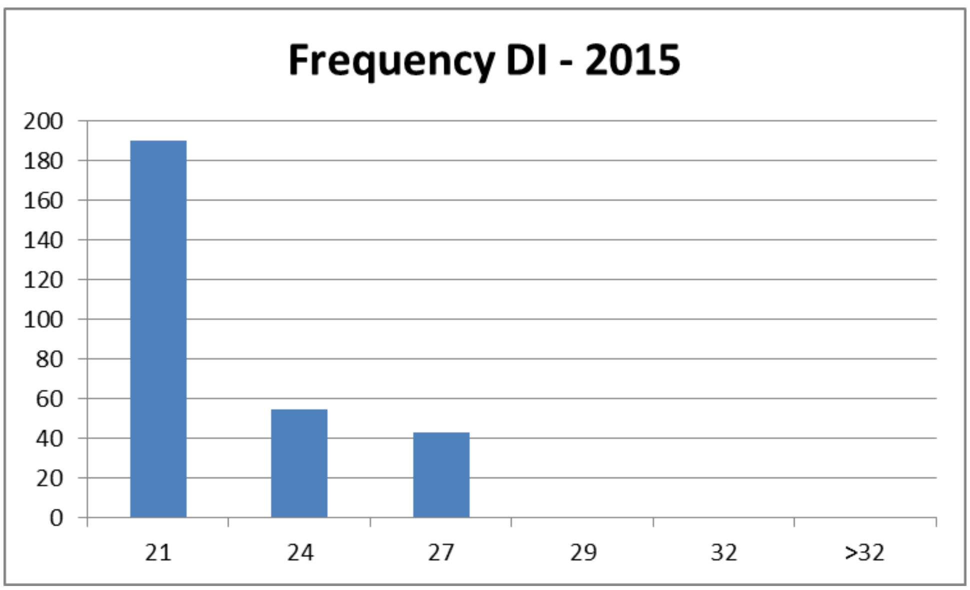

Figure 23: Athens annual frequency of DI

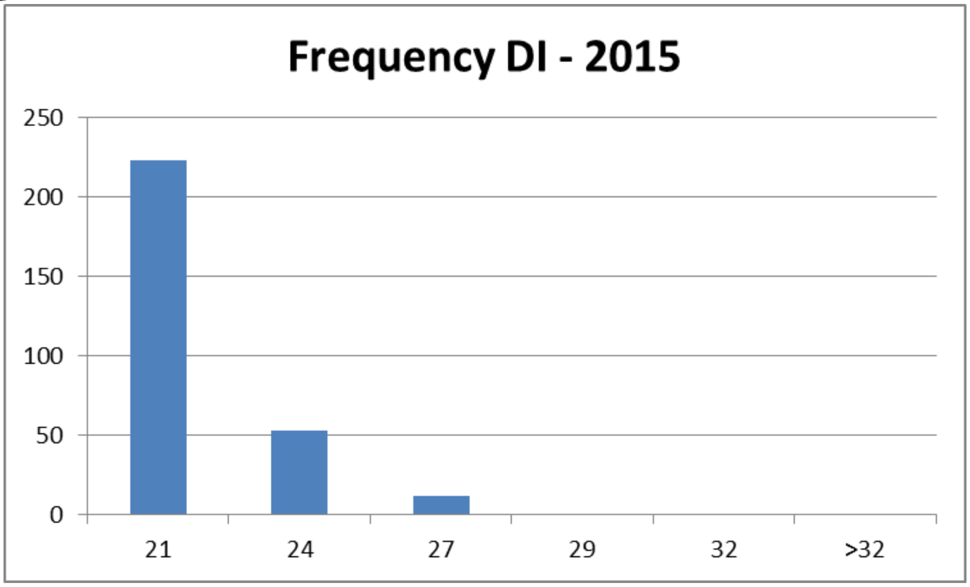

Figure 24: Penteli annual frequency of DI

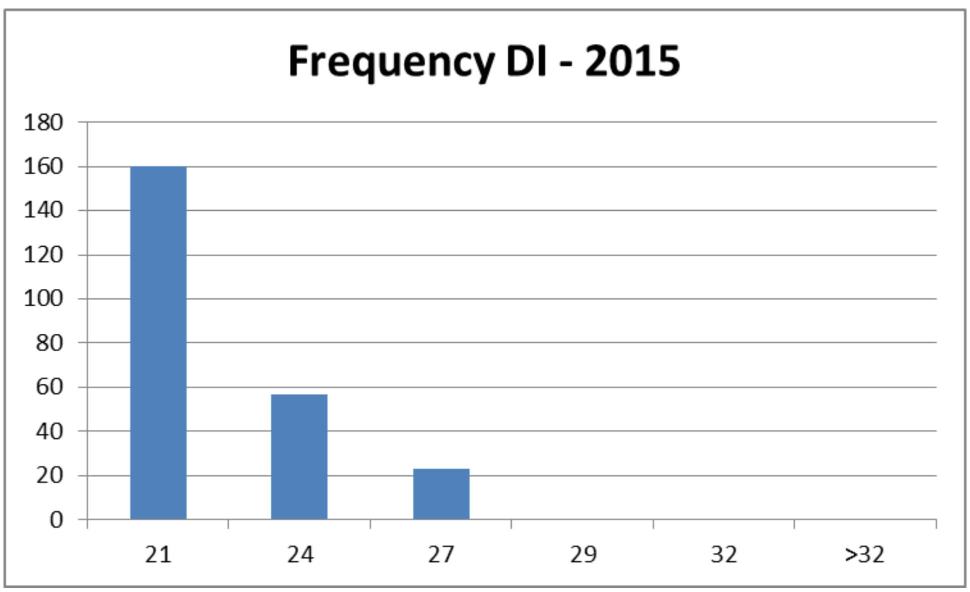

Figure 25: Vrilisia annual frequency of DI

Following this analysis, it was thought of importance to study the monthly variation of the index in order to give to the reader a more comprehensive view of the discomfort people may suffer and what are the months that this phenomenon is at its peak. From the previous frequency graphs, it was shown that worst class of the index achieved in the year of 2015 was the 24-27. The following figures exhibit the frequency results, with their peak being at 26-27. As can be seen, during the winter months the lower class index appeared and with the exception of 2015 the summer months presented the highest values, where September is the third month with the most discomfort observed.

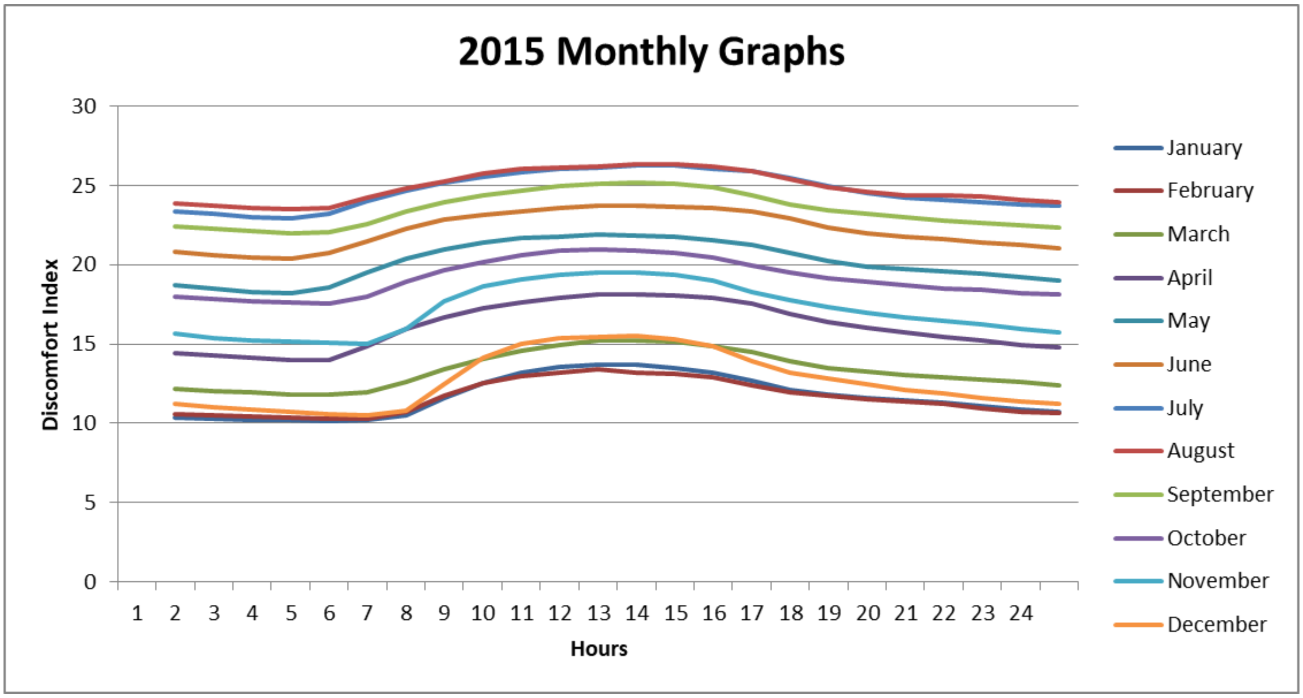

Figure 26: Monthly representation of DI in Nea Smurni in 2015

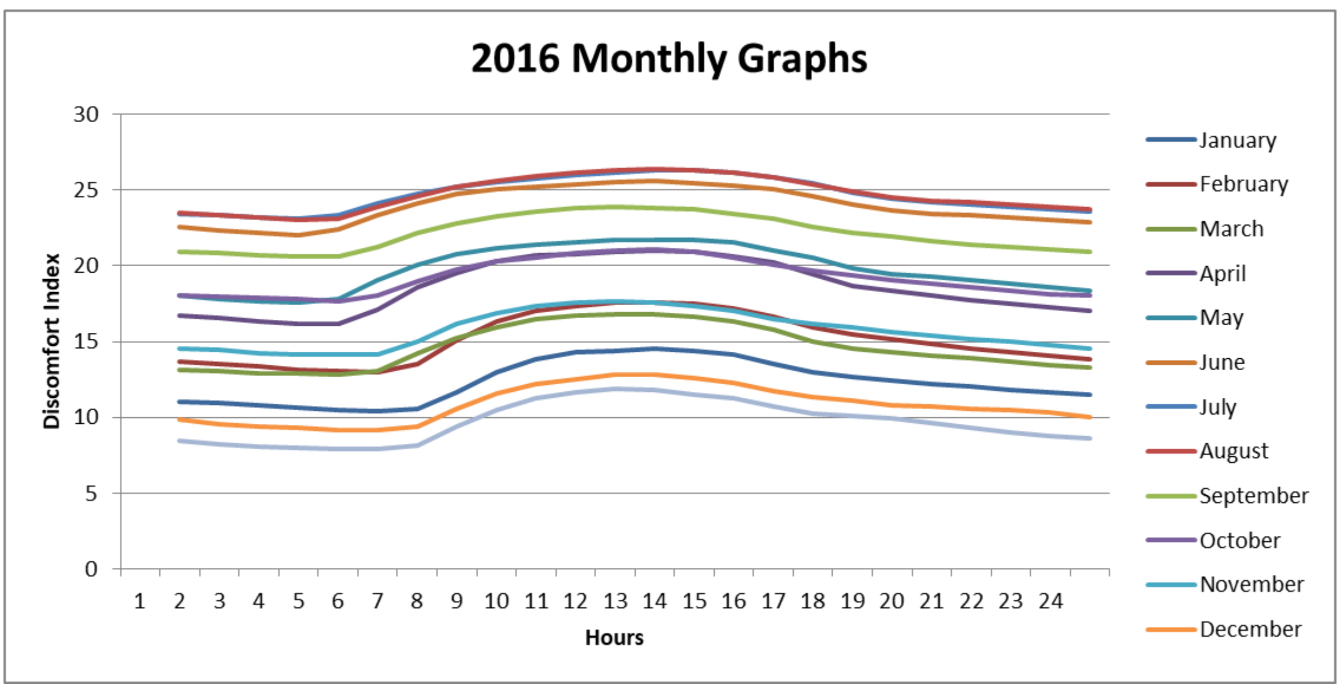

Figure 27: Monthly representation of DI in Nea Smurni in 2016

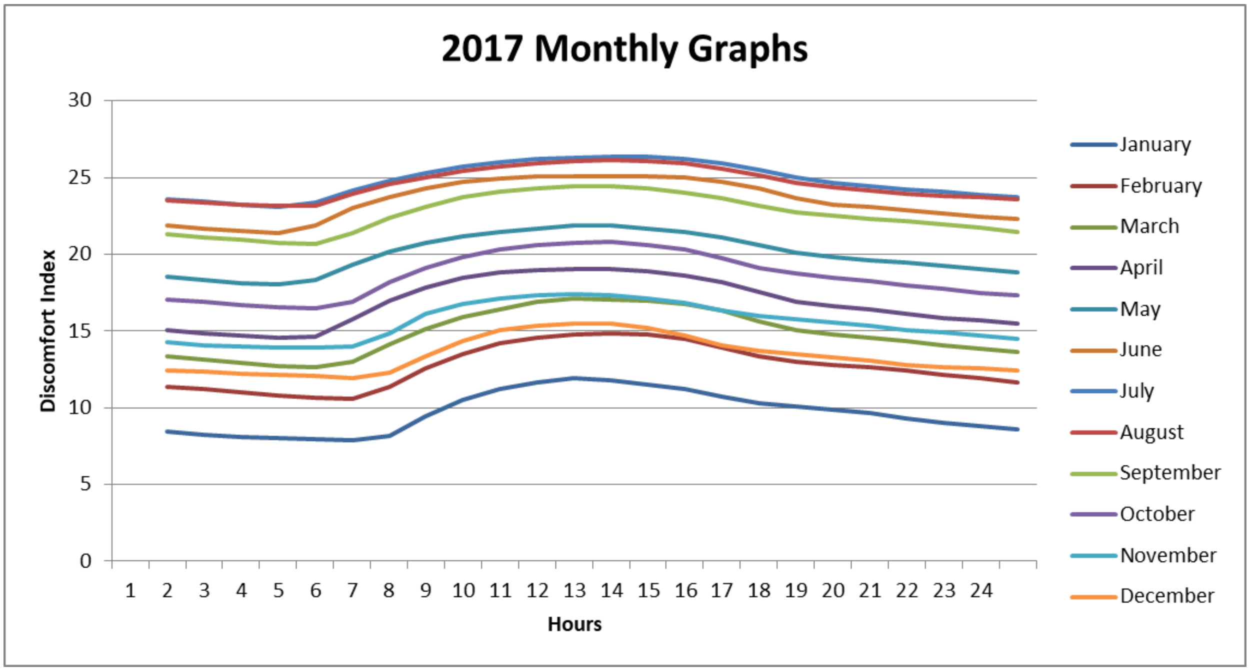

Figure 27: Monthly representation of DI in Nea Smurni in 2017

Similar results are observed for the case of Penteli. Same months are on the bottom and on top, the same exemption is observed also in 2015 for the DI. The only difference is the peak. Now it is below 25, even for the summer months.

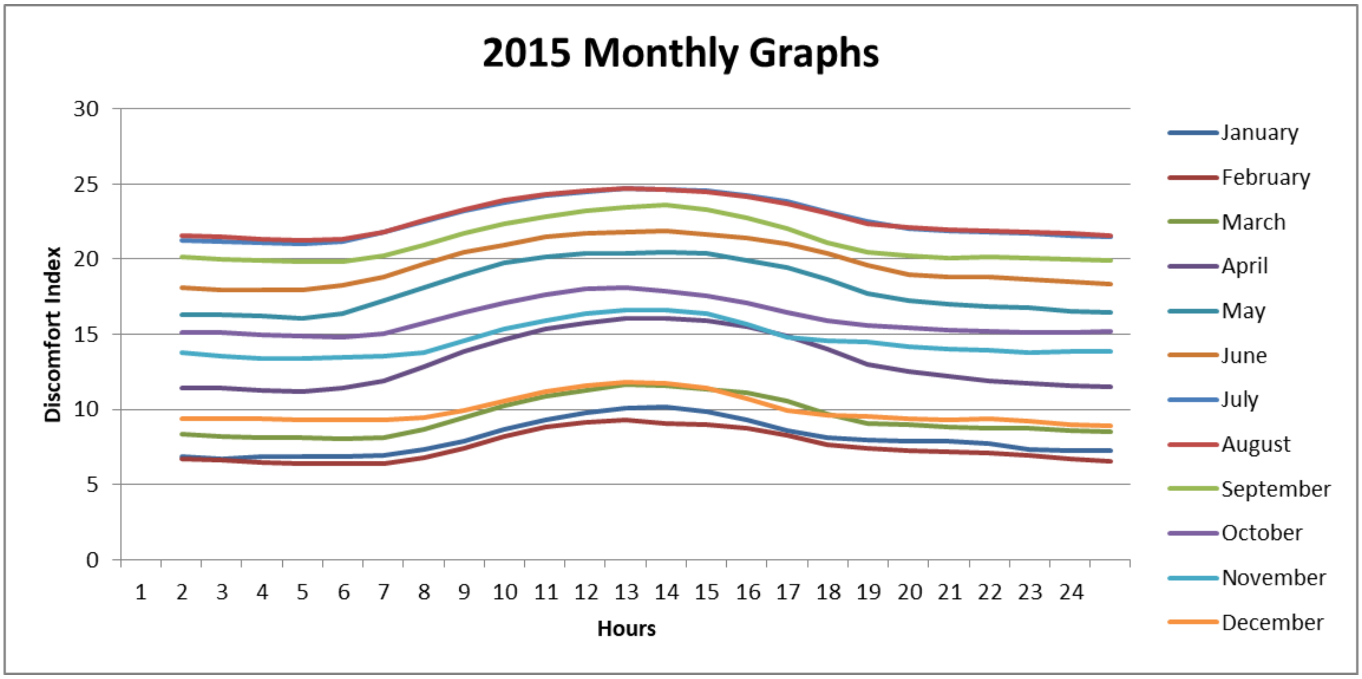

Figure 28: Monthly representation of DI in Penteli in 2015

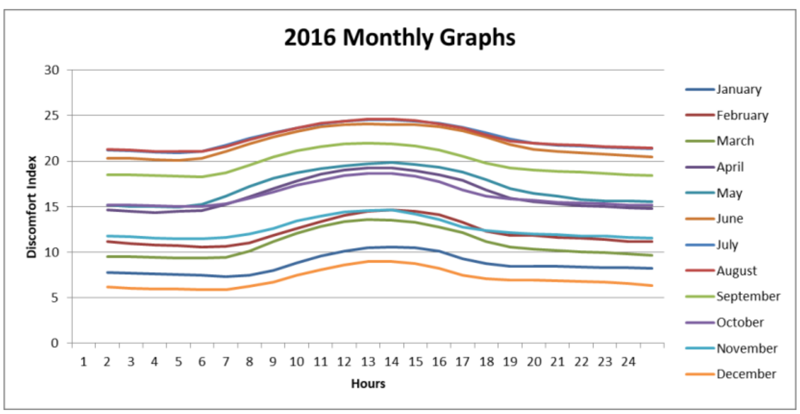

Figure 29: Monthly representation of DI in Penteli in 2016

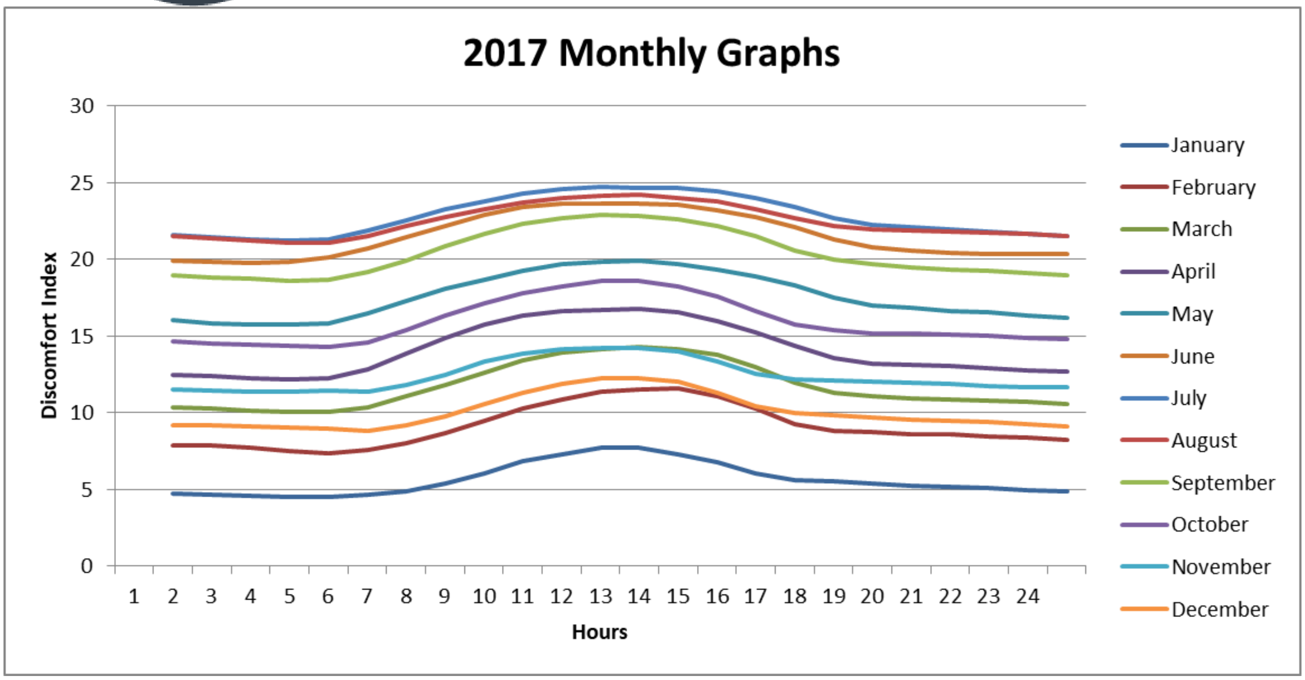

Figure 30: Monthly representation of DI in Penteli in 2017

The last noteworthy fact about the Discomfort Index is the hourly fluctuation of the average temperature and average relative humidity. In figure 31, the Nea Smurni case is depicted. The upper graphs are the relative humidity curves and the lower are these of temperature. In 2015, it was observed that the highest relative humidity appeared in contrast to the other years. Besides that, the differences are minimal, not only in Nea Smurni itself, but also in contrast to Penteli's results, which are shown in figure 32.

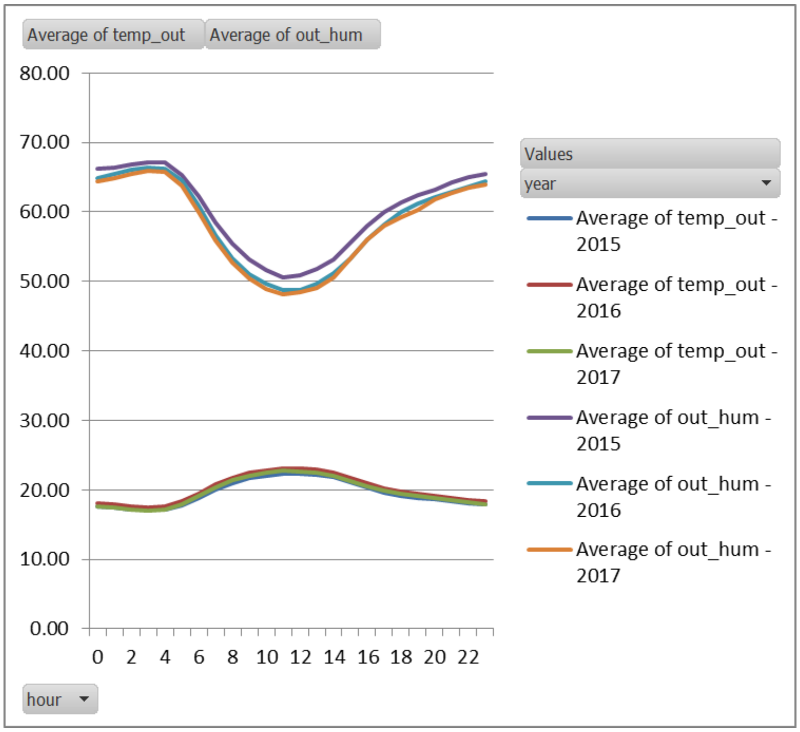

Figure 31: Nea Smurni's hourly variation of Relative humidity and Temperature in the years 2015-2017

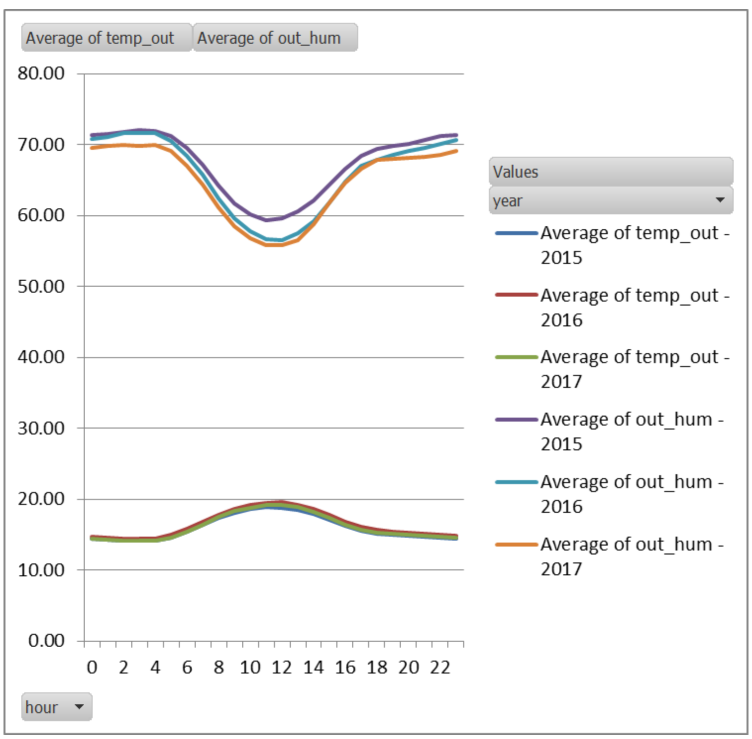

Figure 32: Penteli's hourly variation of Relative humidity and Temperature in the years 2015-2017

Daily Air Quality Index (DAQx)

This is probably a critical index, as it has to do with pollutants that are harmful for people's health both in central and suburban locations. It must be noted here that ozone (O_3) is a secondary pollutant that is created, after transport of primary pollutants emitted from highly trafficked areas (NOx, VOC) to suburban locations rich in oxygen and with low traffic conditions. Thus, one region may have low NO_2 concentrations but high O_3 or the other way around. What is expected is that, in high density areas, NO_2 is usually high. Under favourable weather conditions, sunlight, clear skies, low wind conditions high values of ozone are observed and pollution episodes take place. The case of Nea Smurni computed DAQx is presented in figures 33 and 34, where the frequency of appearance of DAQx different classes of values, in the same logic as the DI. Here again the X axis depicts the classes and the Y axis is the frequency of appearance of all selected years. The most frequently appearing class is the 3.4 one and this means that on average citizens of the area are exposed to 50-99μg/m^3 of NO_2 and 65-119μg/m^3 of O_3, respectively. The ground level ozone levels are especially high and dangerous. The annual variation of DAQx (O_3) for all selected years is depicted in Figure 35, where one may observe that in general the highest classes appear during the summer (warm) period of the year. Another important feature is that in 2016 the values were fluctuating significantly, which is connected with the cooler and windier weather conditions at that time.

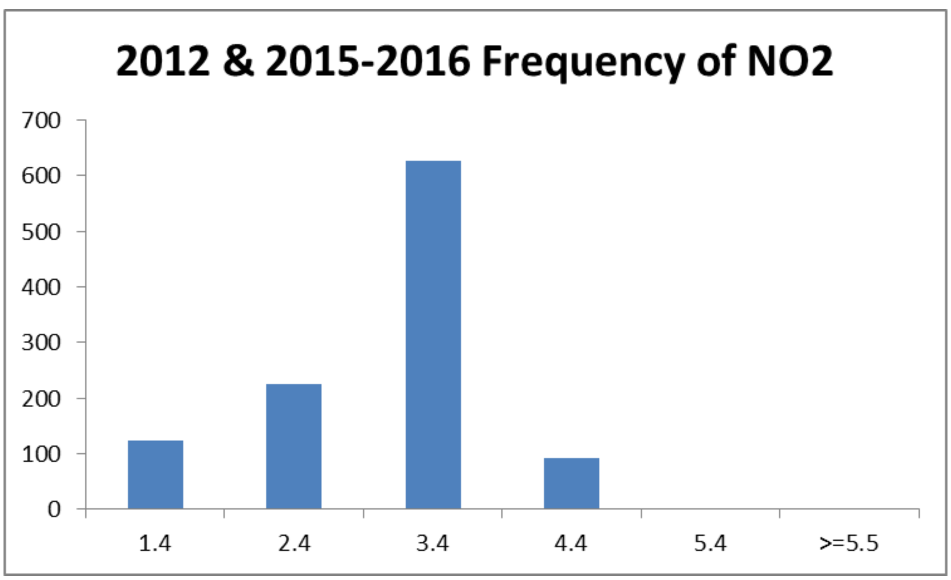

Figure 33: Nea Smurni annual frequency of DAQx for NO_2

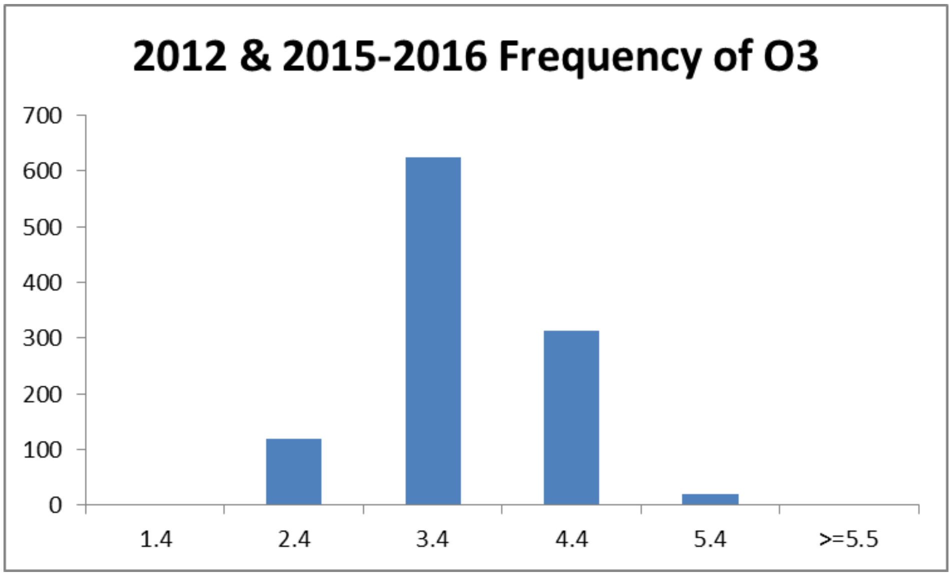

Figure 34: Nea Smurni annual frequency of DAQx for O_3

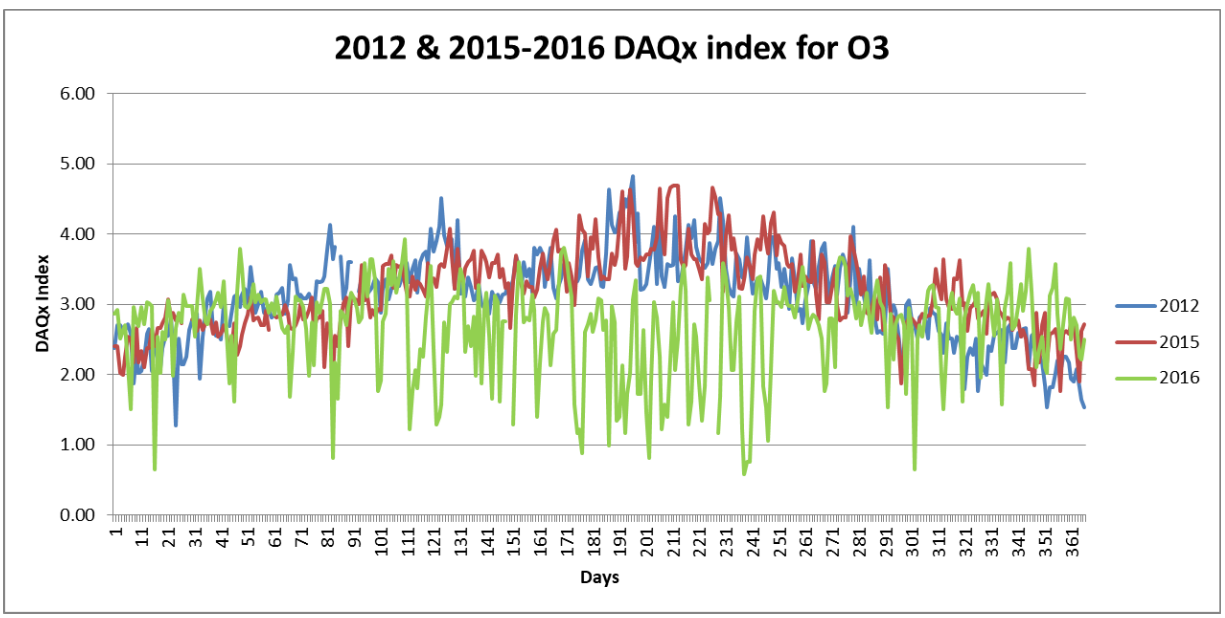

Figure 35: Annual presentation of DAQx for O3 in Nea Smurni

Observing the monthly and seasonal data, one can see the periods when the pollution reaches a peak. More specifically, regarding NO_2, the index is higher in the autumn, winter and spring time which may be attributed to higher traffic at these periods. In the summer, when traffic is less dense the index takes lower values as expected. Only in 2012 spring surpassed autumn in the third class. The reason why is probably the fact that most of the citizens in the summer move away for holidays, therefore less cars are moving in the area. Also, concerning spring, maybe more people decide to take the public transport, once the weather gets a little better. So, pollution of NO_2 is worse in winter and autumn and that is something that needs to be tackled.

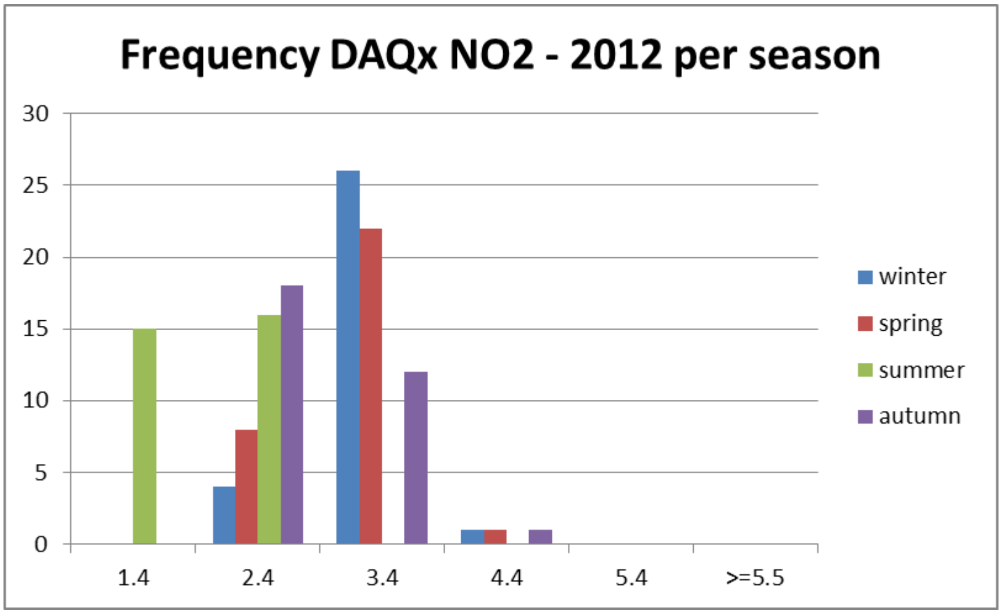

Figure 36: Frequency of DAQx for NO_2 per season in 2012 in Nea Smurni

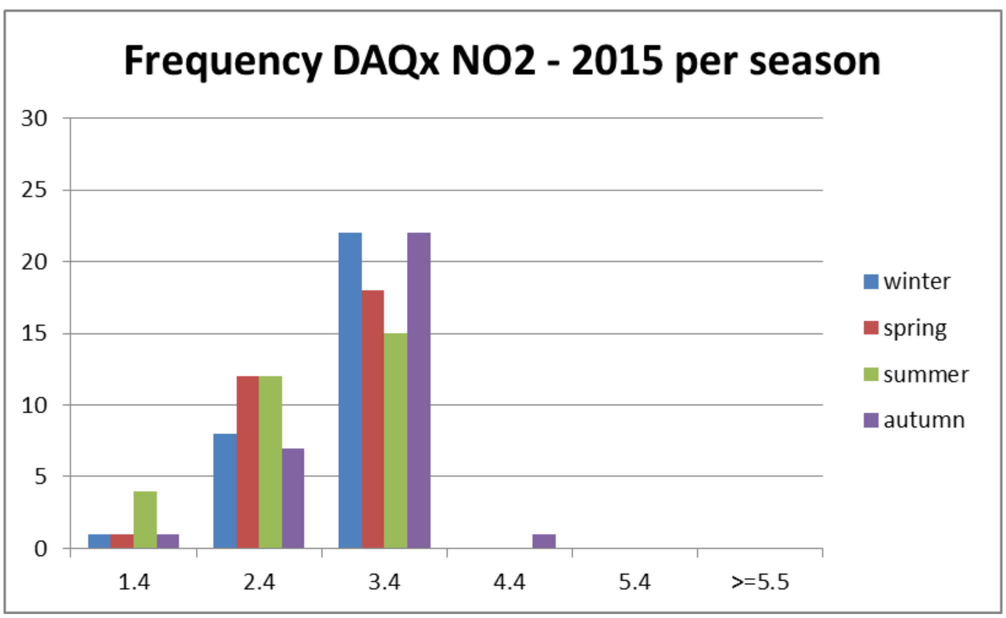

Figure 37: Frequency of DAQx for NO_2 per season in 2015 in Nea Smurni

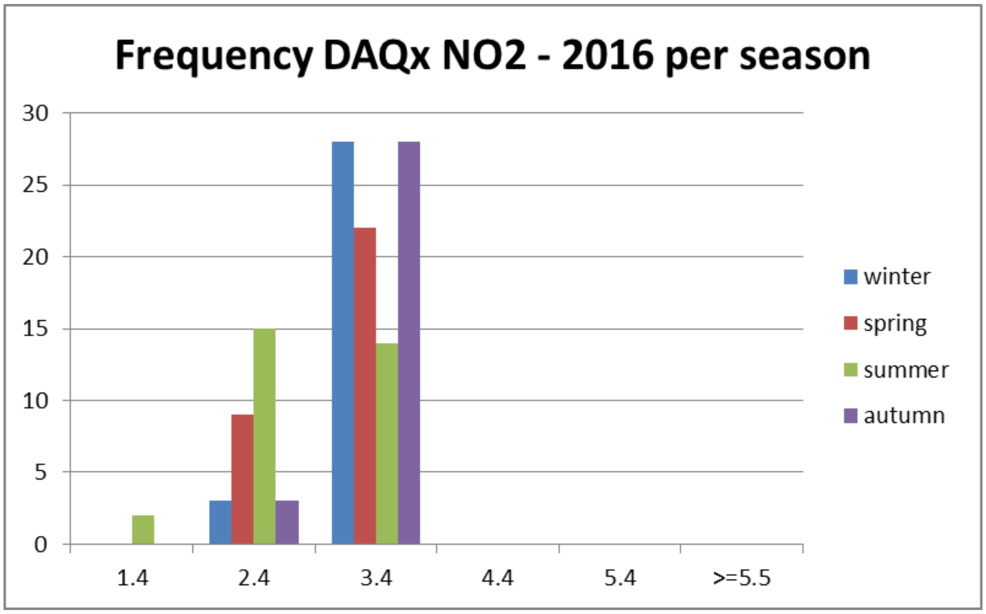

Figure 38: Frequency of DAQx for NO_2 per season in 2016 in Nea Smurni

Regarding ground level ozone, as discussed above, the worst conditions apply mostly in summer, when the circumstances are right for ozone production. The worst conditions appear in spring, summer and autumn as expected and in fact the index takes higher values as compared with NO_2 indicating that ozone pollution is a problem for an urban background area close to the city centre that is densely built. These measurements may depict not only regional pollution, but also pollution transported from other regions. Overall it is a very bad situation for people's health in the municipality of Nea Smurni and the reduction of cars is imperative.

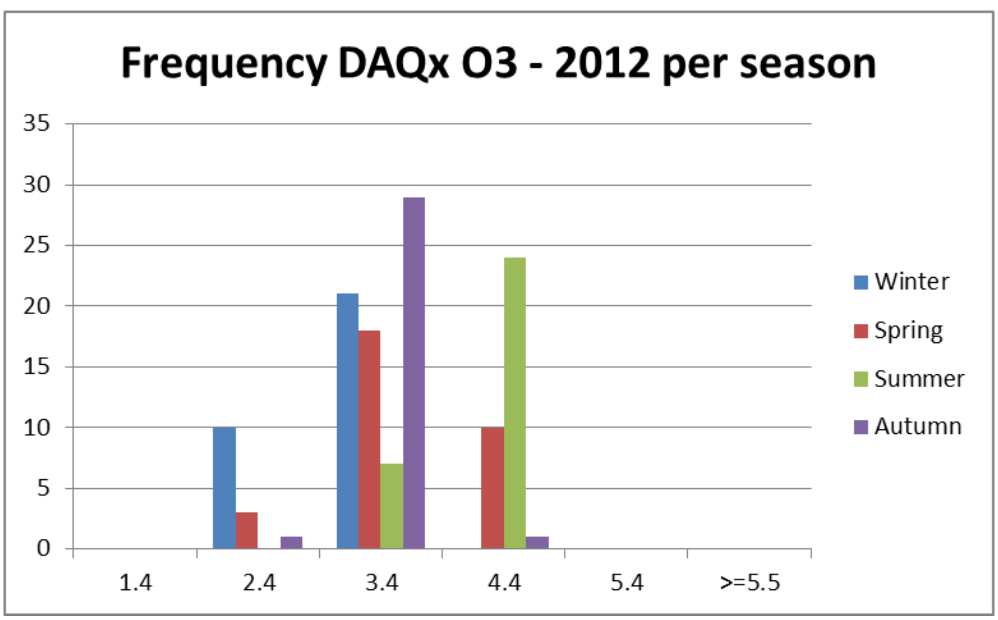

Figure 39: Frequency of DAQx for O_3 per season in 2012 in Nea Smurni

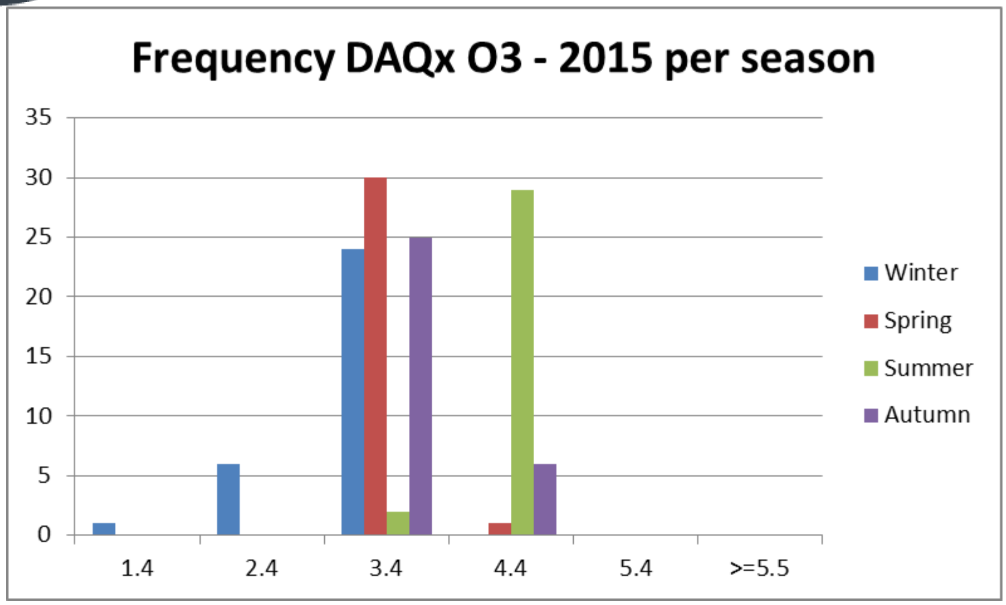

Figure 40: Frequency of DAQx for O_3 per season in 2015 in Nea Smurni

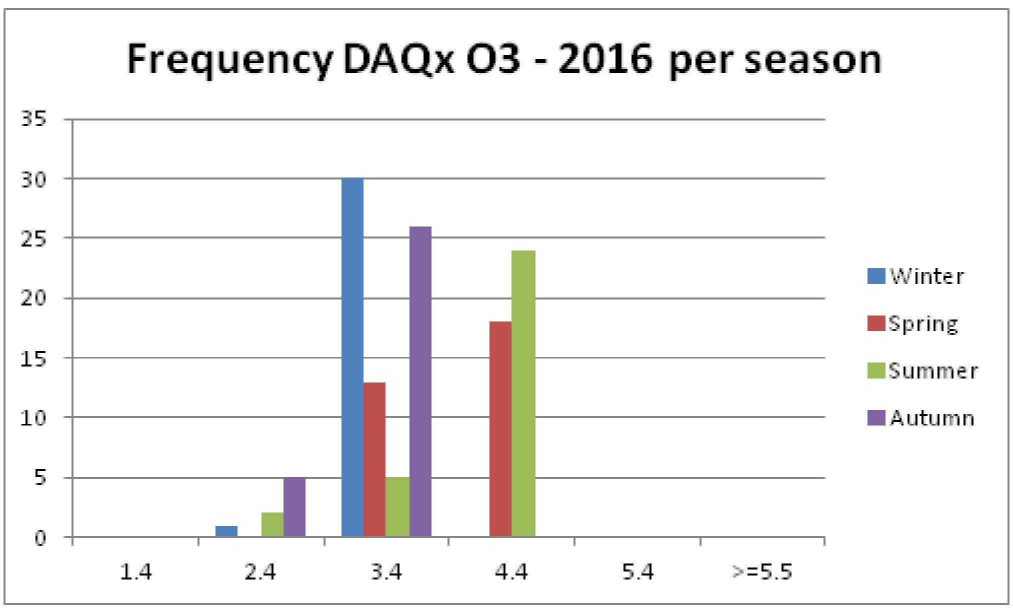

Figure 41: Frequency of DAQx for O_3 per season in 2016 in Nea Smurni

Taking into consideration a totally different region, the municipality of Agia Paraskeui, the results about NO_2 are not surprising at all. Less NO_2 pollution is measured due to lower density of population, thus fewer cars. As opposed to Nea Smurni the index takes smaller values in general. On the other hand ground level ozone index values are quite similar to Nea Smurni and the reason is the transportation of precursor pollutants NOx and VOCs and their transformation into ozone. Figure 43 depicts the situation unfolded in the years monitored. From this it may be concluded that traffic affects not only the location where it takes place but remote areas where primary emissions are less.

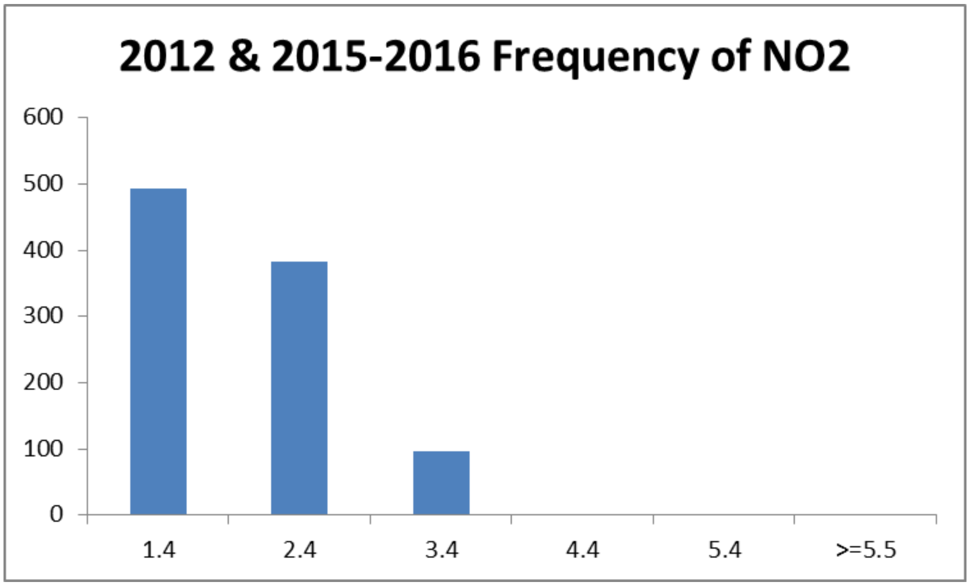

Figure 42: Agia Paraskeui annual frequency of DAQx for NO_2

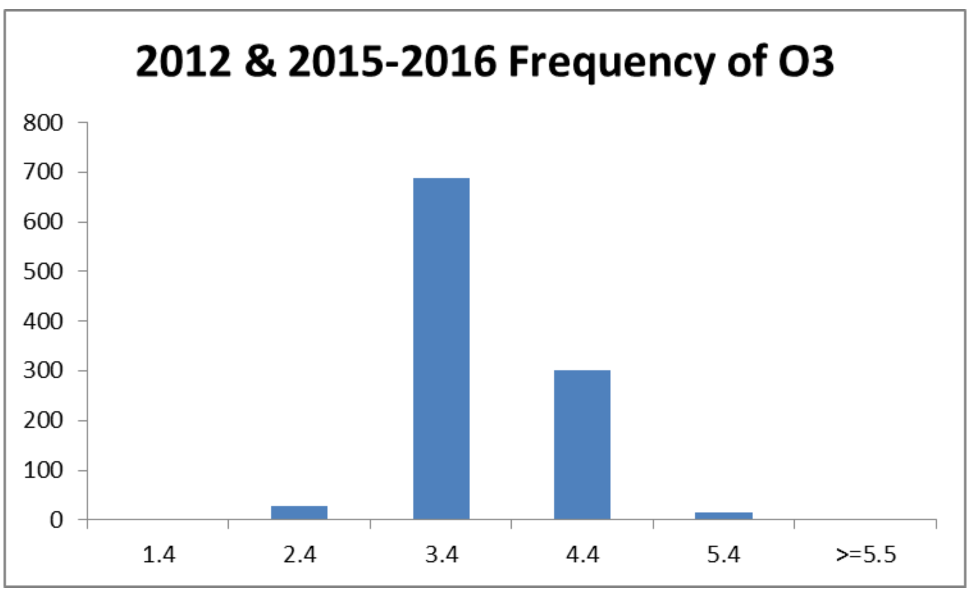

Figure 43: Agia Paraskeui annual frequency of DAQx for O_3

Taking a closer look at the seasonal graphs, as done with Nea Smurni as well, regarding the NO_2 one may observe the lower index values indicating once again the importance of less traffic emissions , the existence of more green spaces and the lower population density.

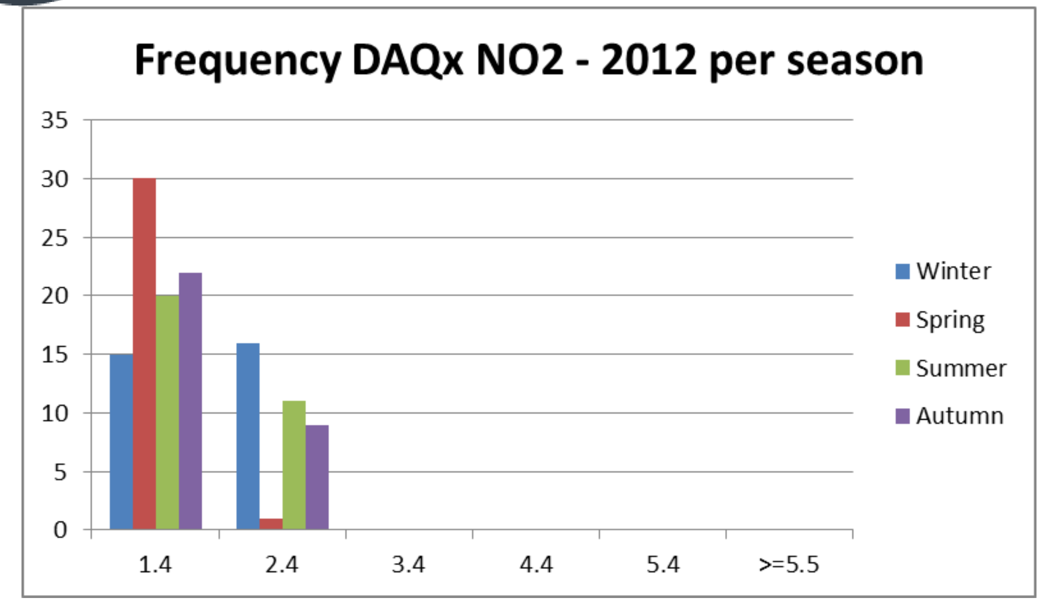

Figure 42: Frequency of DAQx for NO_2 per season in 2012 in Agia Paraskeui

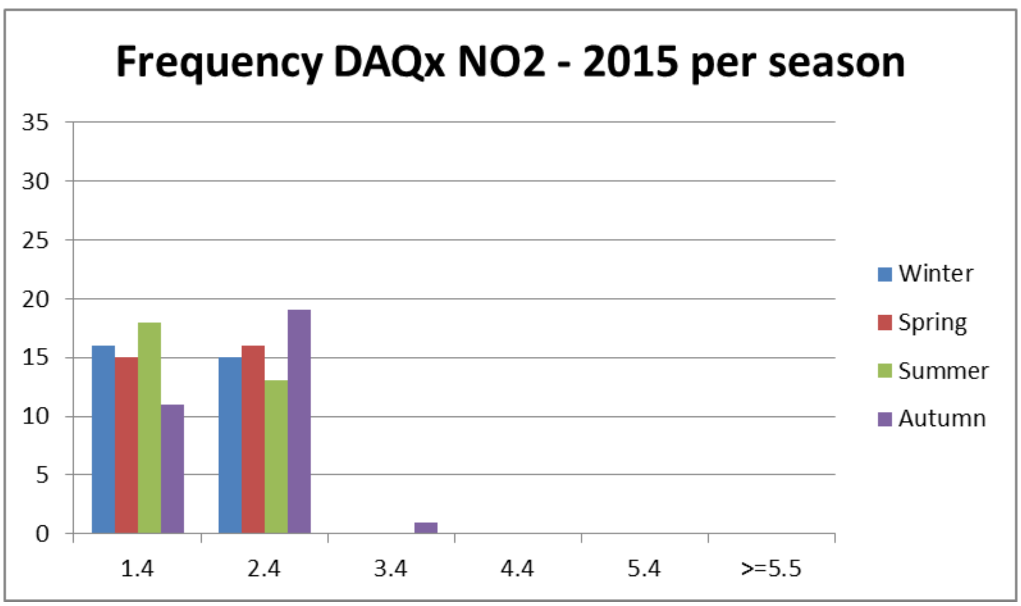

Figure 43: Frequency of DAQx for NO_2 per season in 2015 in Agia Paraskeui

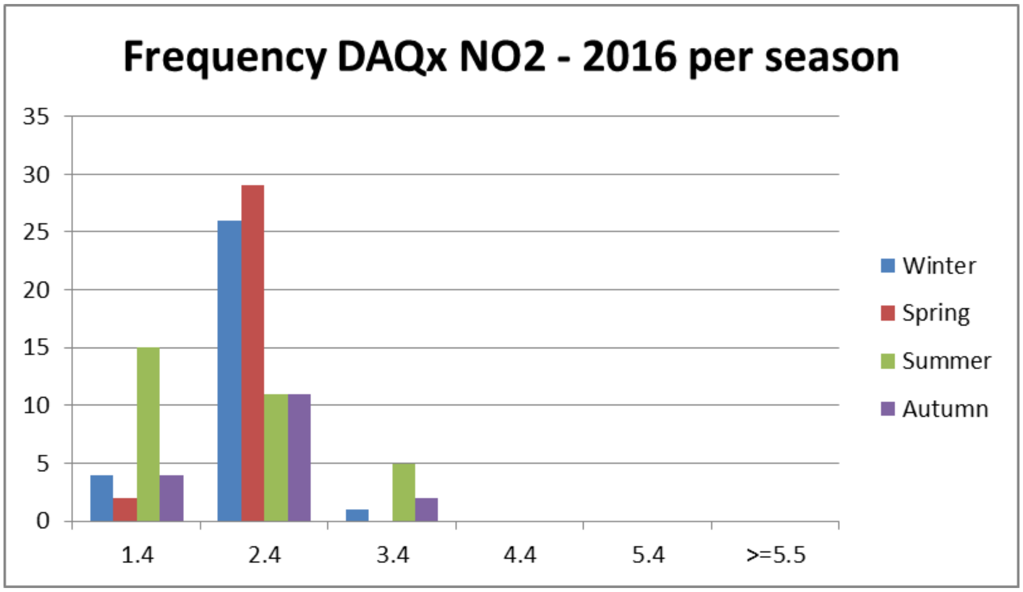

Figure 44: Frequency of DAQx for NO_2 per season in 2016 in Agia Paraskeui

In figure 45, it is clear that the annual fluctuation of the ozone index followed that of Nea Smurni with the exception of 2016, which in this case closely tracks the slope of the other two years. Some peaks are even higher than Nea Smurni, indicating the lower traffic conditions (i.e., less primary pollutants emissions that acts as ozone sinks) that aid with the development of higher ozone levels.

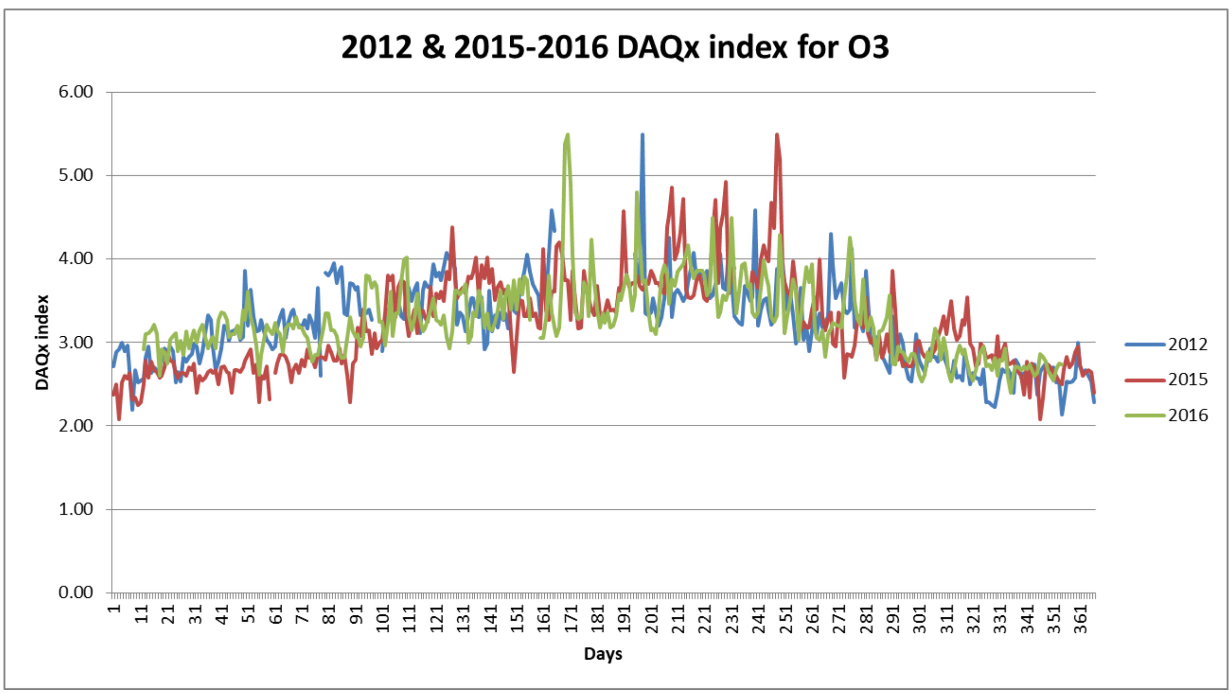

Figure 45: Annual presentation of DAQx for O_3 in Agia Paraskeui

Taking a look at the seasonal graphs, one can see the intensity of the phenomenon not only in summer as expected but also in winter and autumn. In general, it is accepted that higher temperatures lead to higher ozone levels which is closely connected with climate change. Surely the most intense pollution is in the summer at 2015 and 2016 and in spring at 2012, however what is surprising is the winter and autumn class, which is considered dangerous as well. This may be attributed to the higher than normal temperatures, the clear skies, the strong temperature inversions and the biomass burning for heating.

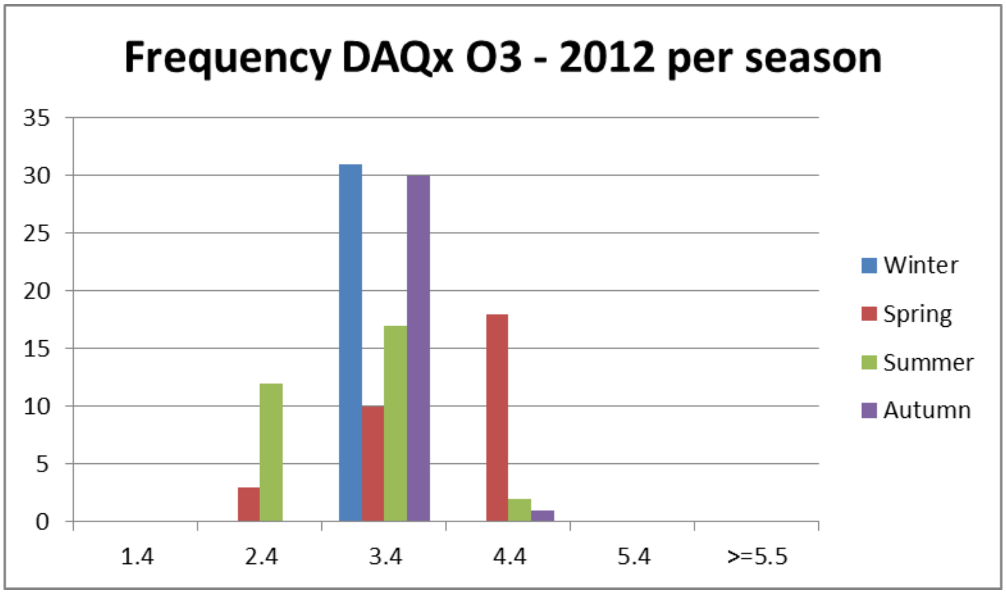

Figure 46: Frequency of DAQx for O_3 per season in 2012 in Agia Paraskeui

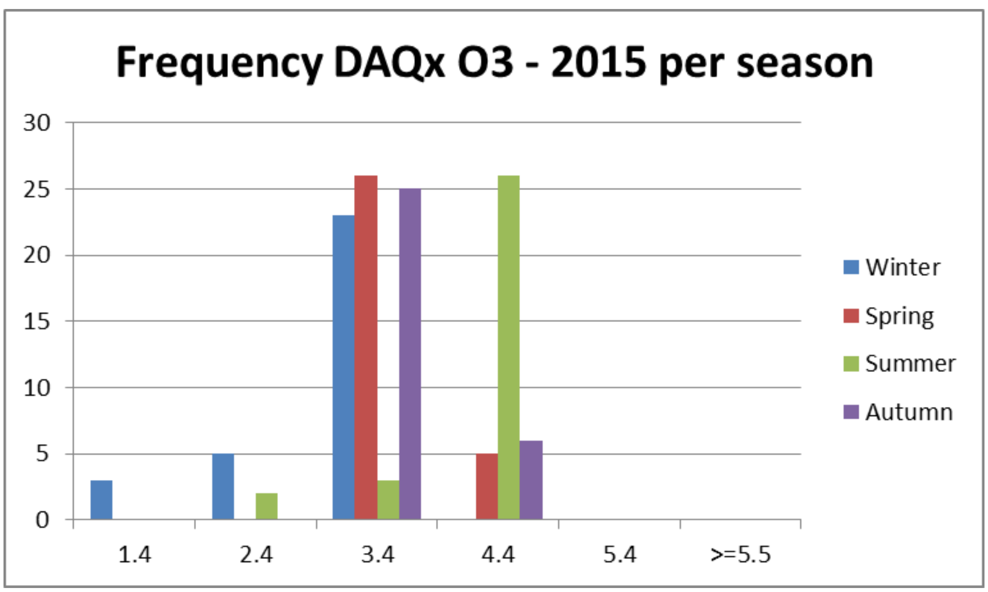

Figure 47: Frequency of DAQx for O_3 per season in 2015 in Agia Paraskeui

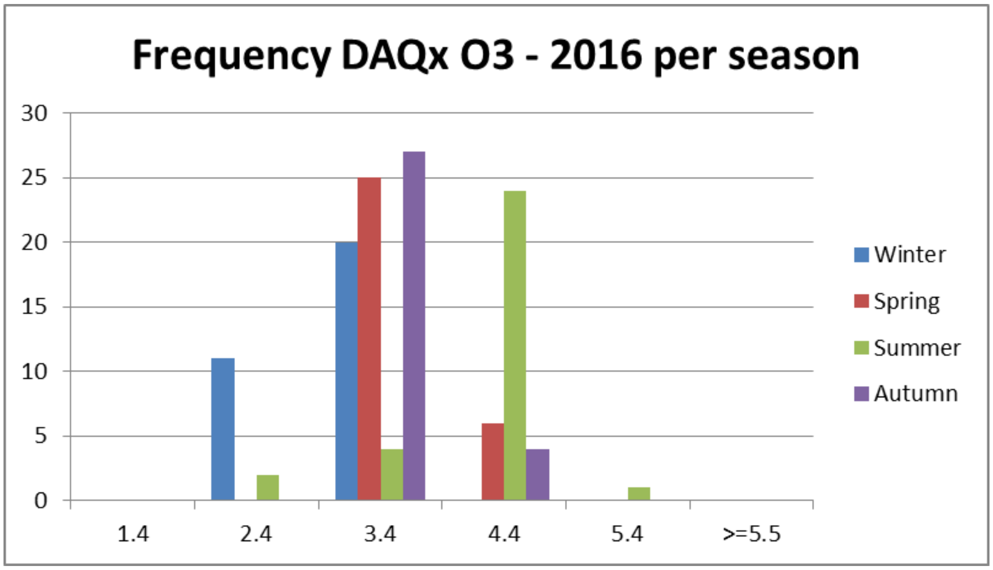

Figure 48: Frequency of DAQx for O_3 per season in 2016 in Agia Paraskeui

Concluding Remarks and Future Work

So far it seems that cycling as well as cycling infrastructure may help improve the living conditions for the citizens. Moreover, areas with high traffic, less green/open spaces are more burdened as regards air quality, environmental comfort conditions and emissions of harmful pollutants. Identification of the street geometrical characteristics, the air quality and bioclimatic comfort indexes may help in characterizing/categorizing municipalities and pointing out their needs and challenges.

The main aim of the present work was to assess the impact of cycling on urban air quality with the aid of air quality, meteorological and emissions data. The reduction of CO_2, NOx and other pollutants emissions from traffic under different mobility scenarios proved that an efficient way to tackle urban air pollution and climate change would be through the encouragement of alternative, sustainable modes of transport. So far the transport sector keeps growing and is still dependent on fossil fuels.

The results presented underline the importance of making people aware of the dangers in their health and the environment and make them aware of their personal responsibilities with regards to climate change, of the effective ways to tackle the issue and push their municipalities/local governments to take action. Make the districts less dense with cars, build infrastructures for bicycles and invest in new ways of commuting. This eventually will have an impact on health, the climate and the economy.

Bibliography

Anastasia Poupkou, P. N. (2011). Climatology of Discomfort Index and Air Quality Index.

Borgar Aamaas, J. B.-K. (n.d.). The climate impact of travel behavior: A German case study with illustrative mitigation options. *2013*.

EEA. (2018). Carbon dioxide emissions from Europe's heavy-duty vehicles.

EEA, E. E. (n.d.).

Hana Středová, T. S. (2015). Smart tools of urban climate evaluation for smart spatial planning.

HELMUT MAYER, L. M. (2004). Air stress and air quality indices.

IPCC. (2018). *https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter8.pdf.*

K.M. Fameli, V. (2015). Development of a road transport emission inventory for Greece and the Greater Athens Area: Effects of important parameters.

Katerina Papagiannaki, D. D. (2009). Decomposition analysis of CO2 emissions from passenger cars: The cases of Greece and Denmark.

Małgorzata Czarnecka, J. N.-L. (2014). Intensity of Urban Heat Island and Air Quality in Gdańsk during 2010 Heat Wave.

Rafael Borge, I. d. (2012). Comparison of road traffic emission models in Madrid.

Ralph Sims, R. S. (n.d.). IPCC - ch. 8 Transport.

Salvatore Saija, D. R. (2002). A methodology for the estimation of road transport air emissions in urban areas of Italy.

StephanLeinert, H. B. (2013). Co-benefits? Not always :Quantifying the negative effect of a CO2-reducing car taxation policy on NOx emissions.

UNFCCC. (n.d.).

UNFCCC. (2018). *Annual Accounts, management report and audit report 2018 #inditex.*

UNFCCC. (2018). *HELLENIC REPUBLIC - MINISTRY OF ENVIRONMENT AND ENERGY.*