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ASSESSMENT OF THE URBAN VEHICLE TRAFFIC AND GREENHOUSE GAS EMISSIONS: THE CASE OF THE MUNICIPALITY OF PADUA

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Abstract

Transportation is crucial issue for our society, having its importance in convenience and connectivity, however it comes with its consequences. This thesis investigates the potential impact of traffic emissions on urban air quality and public health for the on-road sector, by analyzing the case study of the Municipality of Padua (North-east Italy). To perform estimation of traffic emissions, a bottom-up approach was adopted, and a vehicle emission model was developed by using data from the national databases about number and type of vehicles, emission factors, fleet composition and transport activity. A further model was then considered to be more accurate; it implied the use of traffic monitoring detectors to count the number of vehicles entering the city. Data were then analyzed but, due to relevant gaps in data collection, estimation on emission was partially compromised. Results indicate that traffic accounts for about a quarter of Padua's total emissions is one of the predominant contributors to urban air pollution. The model's predictions were validated against air quality monitoring data, showing strong correlation and reliability. The findings highlight the model's potential as a decision-support tool for urban planners and policymakers. Possible alternatives and solutions were listed to meet Europe's 2035 net-zero emission goals. Including behavioral change by enhancing car sharing and public transport, and a transition to different types of vehicles, such as electric vehicles (EVs) or e-fuel based. Future demand of electrical energy will surely increase and, to reduce indirect emissions generated by burning fossil fuels in its production, a transition to renewable, nuclear and sustainable energy is essential.

1. Introduction

1.1 Climate Change and Traffic Pollution

In the 21st century, the fast evolution of vehicles has transformed the way we travel through the world, these means of transport are part of our daily lives and are also a crucial aspect for global economies. As societies strive for greater convenience and connectivity, the vehicular landscape has encountered a profound metamorphosis (De et al., 2022), however this remarkable progress can't be considered without its consequences, indeed, one of the most pressing challenges facing contemporary society is the intensifying issue of air pollution and the continuous increasing of temperatures causing global warming. Road traffic is widely considered to be the main source of pollution in most urban areas (Inkinen & Hämäläinen, 2020), some studies show how air quality has a damaging impact on human health and on the environment, producing approximately 1.2 million deaths each year worldwide seeing particulate matter (PM) emissions as the leading cause (Bo et al., 2017). The natural greenhouse gas is primarily a function of the concentration of water vapor, CO_2, CH_4 , N_2O and O_3, in general, human emitting greenhouse gases include water vapor, CO_2, CH_4, N_2O, and other trace gases in the atmosphere. Specifically, in the transportation sector, the main components of vehicle exhaust emissions include carbon monoxide (CO), nitrogen oxides (NO_x), total hydrocarbons (THC), and PM, but the most dangerous particles are those responsible for greenhouse effect such as carbon dioxide (CO_2). However, it is known that the era of thermal engine will soon come to an end and in the future the road environment will be mainly formed by electric vehicles, this is one of the most significant goals for the European Parliament, indeed, the sale of petrol and diesel cars will be banned from 2035 to reach carbon neutrality by 2050 (European Parliament, 2023). The direct consequence is that many climate-altering gases will decrease dramatically in the atmosphere, but the complete impact is delayed due to fleet inertia. Studies show that accelerating the pace of electrification positively impacts the carbon footprint, but a ban by 2035 is insufficient to meet national transport sector policy targets, necessitating either an earlier ban (such as in 2025) or an increased use of biofuels (Morfeldt et al., 2021). The Intergovernmental Panel on Climate Change (IPCC) completed the Synthesis Report for the Sixth Assessment Report in March 2023, and it concludes that the primary cause of the rising global temperatures is the increasing emissions of CO_2. It warns that surpassing a 1.5 °C rise is highly probable under scenarios with higher emissions. Climate change presents a significant danger to both humanity and the environment, requiring rapid and coordinated action, in fact, to achieve sustainability the decisions made in the upcoming years will have long-term effects. Human activities, especially the release of greenhouse gases, are identified as the main accelerators of global warming, with unequal contributions from various nations, regions, and individuals. The main issue is that current policies fall short of the necessary reductions, and financial support is insufficient to meet mitigation objectives. Continuing or increasing the levels of greenhouse gas emissions will lead to more global warming, rising adverse consequences, surpassing those currently experienced. To limit warming to either 1.5 °C or 2 °C, immediate and substantial reductions in greenhouse gas emissions are crucial by 2030, aiming for net-zero CO_2 emissions by the early 2050s and around the early 2070s, respectively. The report emphasizes the urgency of rapid, transformative, and inclusive actions in the next decade to mitigate climate change, minimize losses and damages, and produce positive outcomes for both humans and ecosystems (AR6 Synthesis Report — IPCC, 2023). Research from the International Energy Agency (IEA) shows that the whole transport sector accounts for around one-fifth of global carbon dioxide (CO_2) emissions, and since road transport accounts for three-quarters of transport emissions and aviation for only 11.6%, road transport accounts for 15% of total CO_2 emissions (Ritchie, 2020). Specifically for Italy, emissions from fuel combustion in the transport sector has not been decreasing in the last ten years, it has a mean of 103.64 million tons of CO_2 equivalent from 2012 to 2021 (Statista, 2021). Meanwhile, the total national emissions have been progressively decreasing from over 500 Mt of CO_2 equivalent in the 2000s to about over 400 Mt in 2021. The transportation sector amounted of about 23% of total emissions in Italy in 2021 and the scenario has not yet made a dramatic change in the recent days (Isprambiente, 2021).

1.2 Geographic Context: The City of Padua

The purpose of this work is to create a model for predicting road traffic CO_2 emissions specifically for the city of Padua getting support from inductive loop detector data, if possible, to count the number of vehicles circulating inside the Municipality of Padua. Usually these sensors are placed in the major traffic routes and are commonly used in traffic managing systems to monitor vehicle presence and traffic flow (Electricity-Magnetism, 2016). Padua is located in the Po Valley, in the heart of the Veneto region in northern east of Italy. The Po Valley is one of the most air-polluted geographical areas in Europe. The morphology of the territory, meteorological conditions, high industrialization, and vehicular traffic make the Po Valley a region characterized by high levels of air pollutants. Among the main and significant pollutants are nitrogen oxides (NO_x), ozone (O_3), and atmospheric particulate matter (PM) (European Environment Agency, 2023). These substances make the air in the plain potentially harmful to the respiratory system and cause tens of thousands of deaths every year in Italy (European Environment Agency, 2022). This geographical area features a particular climate effect that can be summarized by the following concept. Usually ascending in altitude, the temperature decreases, leading to colder conditions in the mountains compared to the plains. However, there are cases where this pattern is reversed, resulting in cold temperatures in the plains and increasing temperatures with elevation. This phenomenon is known as a temperature inversion and can lead to poor air circulation, trapping pollutants from industries and traffic at lower altitudes (Arpa, 2022). Additionally, the impact of droughts is more probable in these conditions, becoming more frequent and lengthier due to climate change. Lack of rainfall leads to pollutants not being washed away; indeed, improved air quality is observed after rainy days (7°Censimento Generale Dell'agricoltura, 2022). Padua must become a net-zero greenhouse gas emission city by 2030 like all cities and towns in Europe Union countries, but it is still far from it and so possible solutions are listed. Achieving a city with zero emissions involves addressing various sectors and is an ambitious but necessary goal to combat air pollution, mitigate climate change and improve overall urban sustainability. The main solutions are: the adoption of electric vehicles by providing incentives and developing charging infrastructure; investing in high capacity and energy efficient public transportation systems; making a transition to renewable energy sources and implement energy efficient technologies; establishing waste-to-energy technologies to convert inorganic waste into energy and promoting effective recycling programs to minimize waste and promote circular economy (Environment Action Programme to 2030, 2024). Through this comprehensive investigation, it is intentional to contribute valuable knowledge that informs policy decisions, technological innovation and public awareness campaigns, because it is our collective responsibility to aspire towards a future where technology advancements coexist harmoniously with a clean and breathable atmosphere for generations to come.

1.3 History of Climate Modelling

Several methods to create vehicle emission models have been previously used and they were all sharing the focus on the environmental impact of burning fossil fuels, particularly in relation to carbon dioxide (CO_2) emissions from transportation. In this section the literature discusses the many methods that can be used to do so, and which were implied in this work.

The first article about global warming ever registered was published in 1938 by Guy Callendar, in this report he compiled measurements of temperatures from the 19th century and correlated these with old measurements of atmospheric CO_2 concentrations. He concluded that over the previous fifty years the global land temperatures had increased and proposed that this could be explained as an effect of the increase in carbon dioxide (Callendar, 1938). The first computerized regional weather forecast was done in 1950 and the first general circulation model (GCM) was done by Norman

Phillips in 1956. The GCM is a type of climate model which includes a mathematical model of the general circulation of a planetary atmosphere, these are mainly Navier-Stokes equations on a rotating sphere with thermodynamic terms for various energy sources that are the basis for computer programs that simulate Earth's atmosphere. The GCM was then realized by the Met Office in a more accurate and precise way in 1972 (Carbon Brief, 2018). Anyway, the most relevant year was 1990 when the first Intergovernmental Panel on Climate Change (IPCC) report was published, it highlighted climate change as a challenge with global consequences, emphasizing the need for international cooperation. It performed a critical part in the creation of the UNFCCC (United Nations Framework Convention on Climate Change), the key international treaty to reduce global warming and address the consequences of climate change (IPCC, 2019).

1.4 Vehicle Emission Model Literature Review

The first vehicle emission models were developed in the 1990s and were considering just a warmed-up state of a vehicle's engine and just a few emission components. The main disparity is that modern emission models are based on actual road tests on thousands of different vehicles and can evaluate the exact fuel consumption and all known exhaust compounds (Koupal et al., 2010). Estimating vehicle fuel consumption and emissions in real-world scenarios is a challenging task due to the complicated nature of the functions involved. The outcomes are influenced by a multitude of variables, including vehicle state parameters like speed and acceleration, ambient conditions such as temperature, and driver control inputs like acceleration-pedal position and gear shift speeds. The complexity comes from the sensitivity of vehicle energy usage and emissions to these diverse factors (Ahn et al., 1998). The measurement of vehicle exhaust emissions is categorized into laboratory and real-world methods. Laboratory measurements are performed in controlled environments for vehicle emission testing, while real-world measurements include tunnel tests, remote sensing tests, near-road measurements, and on-board tests (Smit & Kingston, 2019). Each method serves specific functions with unique advantages, catering to diverse research requirements. Emission models are commonly used to calculate emission factors from various measurement techniques, including tunnel studies, on-road measurements, and laboratory tests. In the early 1980s, initial validation efforts in the United States of America, primarily through tunnel studies and ambient monitoring, revealed significant disparities between air quality models and measurements. This led to a continuous progress to enhance model accuracy. Validation studies increased in number from the 1990s onward, with a predominant focus in Europe (54%), followed by North America (32%) and Australasia (12%). A database analysis identified six distinct validation methods applicable at various spatial scales (Smit et al., 2010). The first one is laboratory validation where tests directly measure vehicle emissions using techniques like model emission factor determination, however, only a limited number of vehicles (or engines) and driving cycles can be tested with this method due to its high cost. Vehicle on-board measurement, as an alternative to laboratory testing, allows validation at the journey level under real-world driving conditions. This method involves comparing emission factors with total emission levels measured by on-board devices over the corresponding distance for one or more vehicles. While it offers reasonable control over factors like cold start and vehicle loading, challenges include issues with detection limits, data quality, and the size and weight of on-board systems (Ma et al., 2012). Another method is tunnel validation which is employed by determining emission factors based on differences in pollutant concentrations at tunnel entrances and exits. This method considers tunnel features, traffic flow, and conditions, using either measured tunnel air flow or a dilution factor based on a tracer gas (Gëller et al., 2005). One more validation model is remote sensing, it involves directing an IR/UV beam across the road to measure pollutant-to-CO_2 ratios, enabling the computation of mean emission factors for comparison with model emission factors. Remote sensing provides a location-specific snapshot, making emission factors not directly equivalent to distance-based ones averaged over various driving conditions. Additionally, potential driver deceleration introduces predetermine underestimation. Therefore, remote sensing data is most valid for models predicting emissions at high resolutions (Guo et al., 2007). Validation using ambient concentration measurements is another option, it involves comparing measured ambient pollutant concentrations with combined emission and dispersion modeling results through inverse modeling, considering local traffic conditions. The approach captures a variety of driving conditions and a large vehicle sample, advantageous for model validation. However, challenges come from the combined use of emission and dispersion models, environmental simplifications, and indirect measurement, leading to potential errors in estimating non-traffic sources. The last alternative involves the ambient-mass balance method, that determines emission fluxes by measuring pollutant concentrations upwind and downwind of specific areas at various heights, typically using aircraft or masts. These measured data are then compared with area-wide emission predictions calculated by the model during the same period (Hlavinka & Bullin, 1988). These methods were the main studies employed up to 2010. Nowadays the growing environmental awareness has encouraged governments to seek accurate forecasts and effective preventive measures. A noteworthy contribution to this effort is the utilization of advanced artificial intelligence for modeling and predicting CO_2 emissions from vehicles. Deep learning models have been developed using a dataset sourced from Kaggle, an online community platform for data scientists. This dataset features diverse parameters, including vehicle class, engine size, transmission, fuel type, and fuel consumption (Al-Nefaie & Aldhyani, 2023). Anyways, numerous developing nations encounter air pollution challenges, yet the absence of local data often requires them to rely on adjusted U.S. or European emission models. This approach can lead to inaccuracies stemming from variations in driving conditions and fuel specifications. In response to this issue, the International Vehicle Emissions (IVE) Model was created through collaboration between the International Sustainable Systems Research Center (ISSRC) and the University of California at Riverside. Diverging from modified U.S. models, the IVE model distinguishes itself by its versatility, adaptability, and capacity to provide precise estimations of vehicle emissions across diverse regions. It considers factors such as engine technology, driving behavior, and local emission factors (Davis et al., 2005).

1.5 Introduction to Inductive Loop Detectors and Emission Factors

Regarding this work, the emission model had the intent to use traffic monitoring systems to be assessed, which use detectors to estimate traffic flow in the cities by counting the number of vehicles, depending how they are placed they can even monitor vehicles entering and exiting the city. Typically, these detectors involve radars or inductive loop counts placed underground. Inductive loop detectors have been invented in the early 1960s and have become the most utilized sensor in traffic management systems by detecting vehicle presence using electromagnetic induction. The main components of this instruments include: one or more turns of insulated loop wire wound inside a small box buried in the ground, a cable that connects the turn to the electronics and the counter section that is an electronic unit held in a nearby controller cabinet (Traffic Detector Handbook, 2006). The inductive loop section uses a Variable Frequency Oscillator (VFO) and a single-stage transistor amplifier to generate an oscillating signal influenced by the presence of vehicles. The electronic vehicle detector section includes a voltage comparator and relay to activate when a vehicle is detected. The counter section consists of entry/exit loop counters and a difference counter to track the number of vehicles entering, exiting, and remaining at the intersection (Oluwatobi et al., 2021). A visual scheme is shown in

Figure 1.

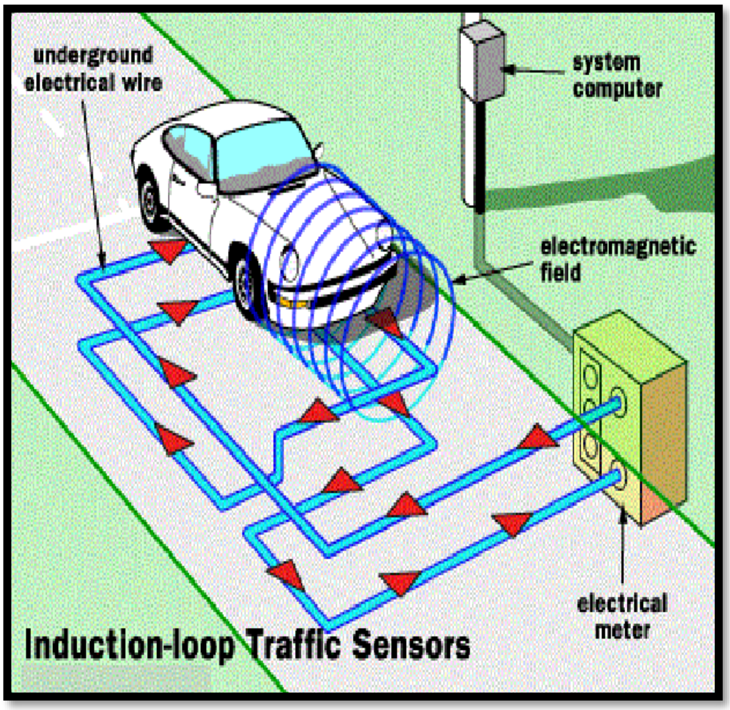


Figure 1: Induction-loop Traffic Detectors (High Density Traffic Management, 2014)

All these different methods have in common a specific process to estimate the emissions of greenhouse gasses (GHGs) and pollutants, relying heavily on the correlation between collecting data analysis and establishing a correct emission factor. Collecting data analysis involves gathering comprehensive information on various aspects related to emitting sources, including activity levels, technology specifications, and operational parameters (Silva et al., 2006). This data serves as the foundation for determining emission factors (EFs), which is a numerical value that represents the amount of a specific air pollutant emitted per unit of a particular activity or process. It quantifies the rate at which climate-altering gases are released into the atmosphere because of human activities. The U.S. Environmental Protection Agency defines EFs as values relating the quantity of a pollutant released to the atmosphere with the associated activity.

For GHGs, EFs are typically expressed as mass per unit of emissions-producing activity, such as kilograms of CO_2 emitted per ton of coal combusted. Generally, the following formula is used to calculate emissions:

$$E = A \times EF$$

Where:
E = Emissions
A = Activity Data
EF = Emission Factor

EFs can be quantified through stoichiometry for processes following chemical or mass balance reactions, empirical measurements or expert judgment. EFs can address single source categories or serve as integrated values across multiple sources, processes, or value chains, incorporating life-cycle analysis. Expert judgment plays a role in establishing representative average emissions rates for specific technologies. The width of activity covered by EFs varies, with some focusing on specific sources (for example CO from gasoline combustion) and others providing integrated values across complex processes (Greenhouse Gas Management Institute, 2022). Specifically for thermal engine vehicles there are many ways to evaluate an emission factor, but this paper focusses mostly on traffic monitoring measurements utilizing inductive loop detectors and making an overall esteem of vehicle emissions inside the borders of a specific city. Remote sensing measurements can also develop fuel-based EFs by measuring pollutant and carbon-containing species ratios in vehicle plumes relative to fuel consumption. While suitable for area-wide emissions estimates, this approach may lack precision for meso- or micro-scale emission inventories. Additional data, such as vehicle class information, is required for disaggregate EFs (Franco et al., 2013).

2. Materials and Methods

2.1 Methodology for Advanced Model

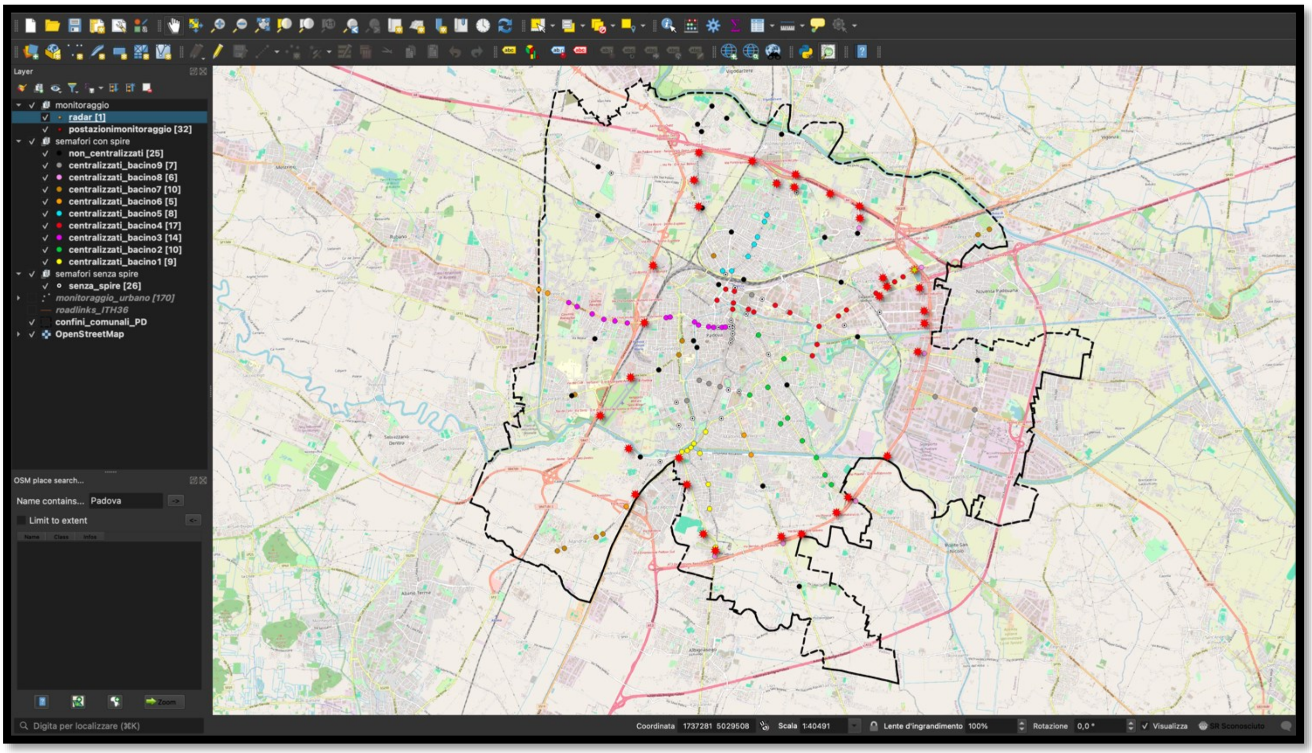
Amongst the different methods implied to estimate the amount of vehicle emissions, the paper written by "Daniel, 2016" providing a detailed approach to monitor greenhouse gas emissions in urban transport was of great help for the purpose of this work. It is a guide implying three different methods, depending on the available data: basic, advanced and developed approach. The goal was to be as accurate and reliable as possible using the material at disposal, the developed method had way too many variables that could not be recruited, but the advanced approach saw light by using inductive loop traffic sensors to count the number of urban vehicles entering in the Municipality of Padua. The official data was given by the executives of the Municipality itself, a special acknowledgement for availability and access to data goes to Enrico Simone Rampazzo and all to the urban planning sector. It included multiple excel files having data taken from 33 traffic monitoring stations and 137 traffic light systems, and a map in a pdf file showing the location of each element. The data was collected from 2012 to 2020 and it was taken periodically, every ten minutes accounting to hours, days, months and years. All the stations and traffic light systems were already classified with the following features:

- Identification number
- Number of system centralization (an element can be not centralized)
- Number of loop detectors (it can be zero since not every system is equipped with counts)

The main problem encountered is that all the given elements represented a point on the given pdf-map corresponding to an address handwritten in excel tables, but every dot did not have specific coordinates.

The QGIS software has been very useful, indeed, it was the chosen software with the objective of geo-localizing every element. The first layer was created to visually identify the created points in space. OpenStreetMap was used in the software to create a layer showing the world road map using public geographical data, once selected the city of Padua, the location of each point was easily identified by finding the associated street names. The next layer was imported from the official Veneto region website "Portale della Regione Veneto" and it represents the borders of the Municipality of Padua. Finally, a point layer was created by mashing together all traffic lights and monitoring stations into a single shapefile, shown in *Figure 2*. A shapefile is a digital vector storage format that contains geographic location and associated attribute information, in this case the vector's information included in the attribute table are listed as following:

- Xls number – the identification number found in the excel file
- Position – street name of each point
- Pdf number – the identification number found in the pdf image (some were different from the excel file)
- Turn number – whether if the monitoring station has turns installed and its number
- Centralization – whether if the monitoring station is centralized and its basin number



Name contains... Padova

☐ Limit to extent

Coordinata 1737281 5029508

Scala 1:40491

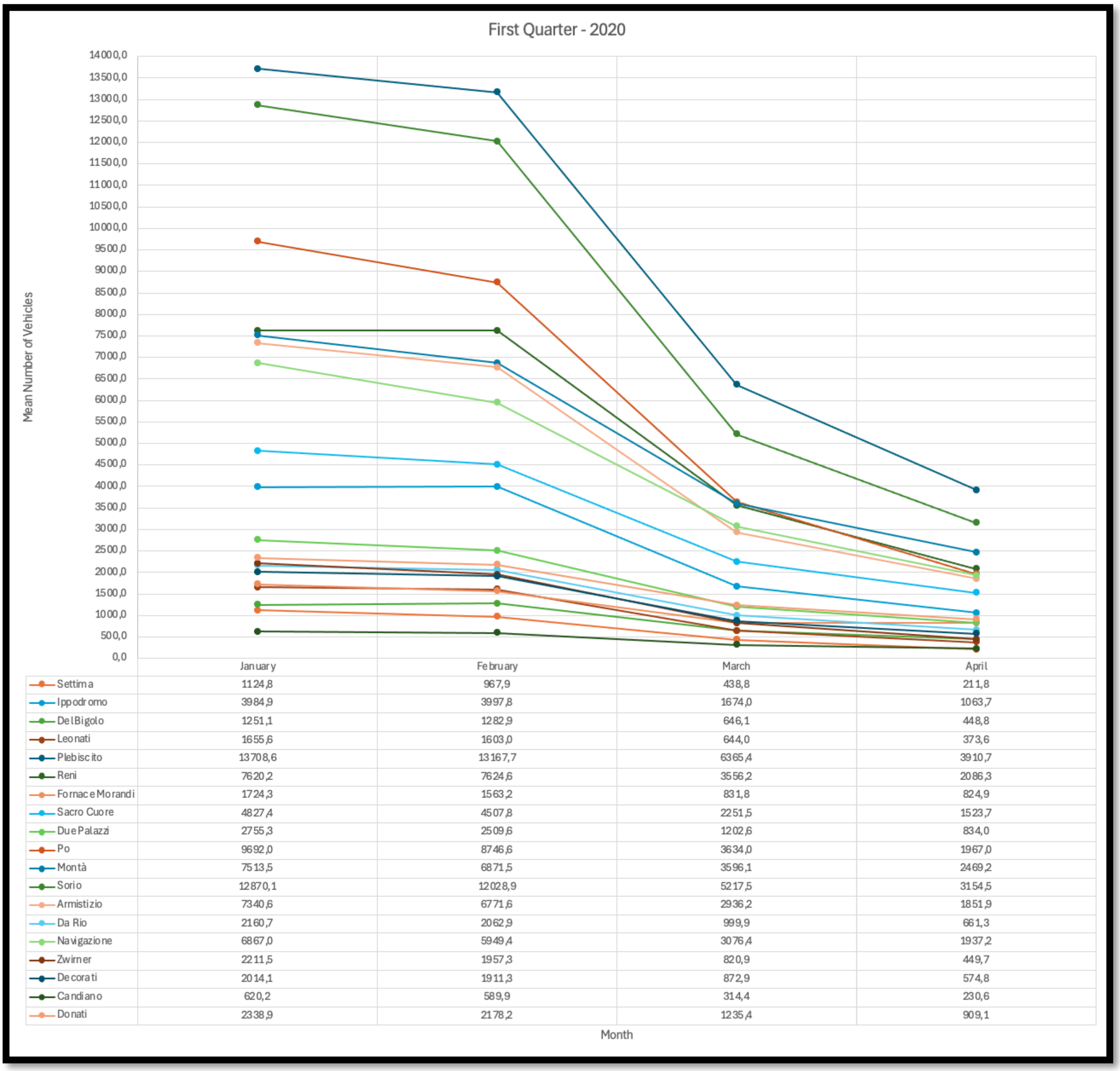
Lente d'ingrandimento 100%

Rotazione 0,0 °

✓ Visualizza

Figure 2: the created shapefile concerning traffic monitoring counts layer inside Padua’s boundary, on the OpenStreetMap layer. Implemented in the QGIS software.

All the given data was already saved in the past years by city officials, it was stored for their necessities only for selected periods weather if a traffic light turn was malfunctioning or just for exact statistical analysis. Data was selected with the criteria of having the lengthiest period and with the biggest number of dots on the map as possible. Most of the data was showing just a few days or weeks of specific monitoring places, the best choice was the first quarter of 2020 including 19 entering points in the map situated on the main outearn streets of Padua, so, this period was selected. Another useful tool was the Microsoft Excel software, utilized to estimate the monthly averages for every turn location from January to April of 2020 and to generate the corresponding graph shown below (*Figure 3*).



	January	February	March	April
Settima	1124,8	967,9	438,8	211,8
Ippodromo	3984,9	3997,8	1674,0	1063,7
DelBigolo	1251,1	1282,9	646,1	448,8
Leonati	1655,6	1603,0	644,0	373,6
Plebiscito	13708,6	13167,7	6365,4	3910,7
Reni	7620,2	7624,6	3556,2	2086,3
Fornace Morandi	1724,3	1563,2	831,8	824,9
Sacro Cuore	4827,4	4507,8	2251,5	1523,7
Due Palazzi	2755,3	2509,6	1202,6	834,0
Po	9692,0	8746,6	3634,0	1967,0
Montà	7513,5	6871,5	3596,1	2469,2
Sorio	12870,1	12028,9	5217,5	3154,5
Armistizio	7340,6	6771,6	2936,2	1851,9
Da Rio	2160,7	2062,9	999,9	661,3
Navigazione	6867,0	5949,4	3076,4	1937,2
Zwirner	2211,5	1957,3	820,9	449,7
Decorati	2014,1	1911,3	872,9	574,8
Candiano	620,2	589,9	314,4	230,6
Donati	2338,9	2178,2	1235,4	909,1

Figure 3: monthly average number of vehicles entering specific spots in Padua during the first quarter of 2020.

At the start of the year, Italian landscape showed the Coronavirus disease 2019 (Covid-19) historically taking over humanity with the official first global case recurring the 30th of January 2020. During March several Ministerial decrees were issued setting urgently some severe restrictions that forced people to stay inside their inhabitations thus showing less vehicle activity on the Paduan roads. From the analyzed data it is clear how vehicles circulating were decreasing progressively during March and ongoing up to the end of the pandemic, being even lesser in April. Anyways the most relevant data is from the first two months since Covid-19 was not present yet, January and February's data is much more like the modern condition.

The excel data was then transferred to the QGIS software where a vector was created including just the points in question. The monthly mean numbers were reported in the attribute table of each element, then the vector's symbology was changed using the size method and the equal count class division, street name labels for each element were assigned. This was done to visualize graphically the number of vehicles entering the city in the selected month shown in the figures below (in order by month: *Figure 4, Figure 5, Figure 6, Figure 7*).

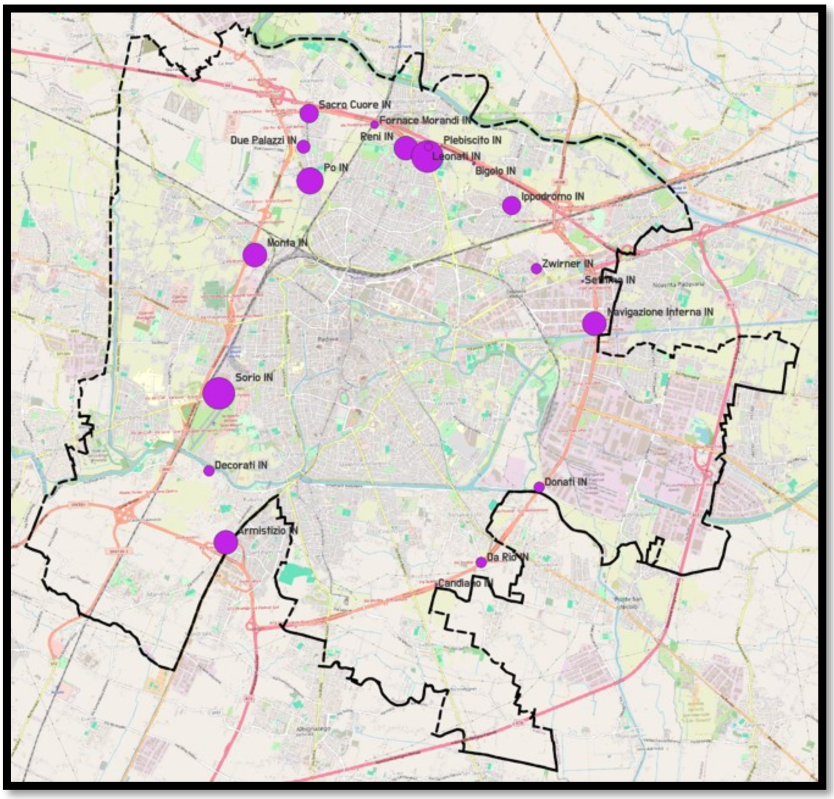
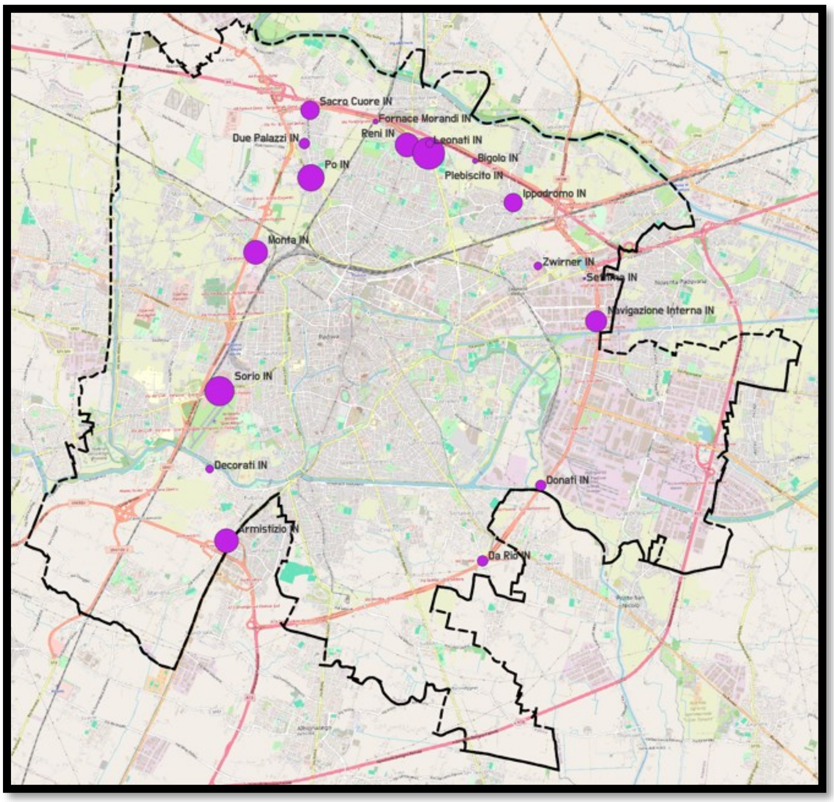


Figure 4: Average number of vehicles entering Padua in January 2020, from 19 monitoring places. Implemented in the QGIS software.

Figure 5: Average number of vehicles entering Padua in February 2020, from 19 monitoring places. Implemented in the QGIS software.



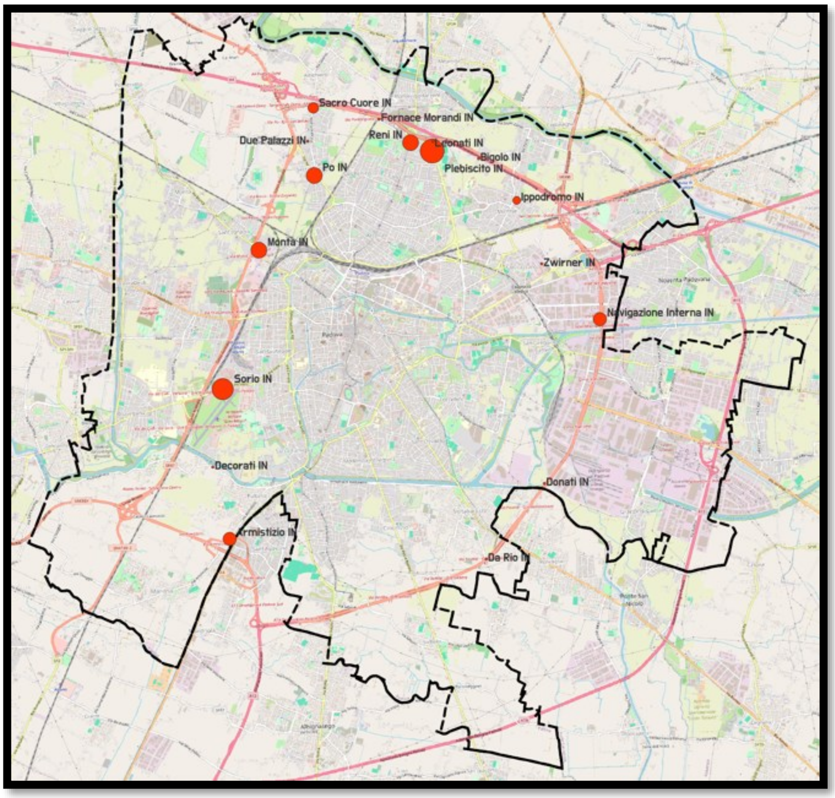


Figure 6: Average number of vehicles entering Padua in March 2020, from 19 monitoring places. Implemented in the QGIS software.

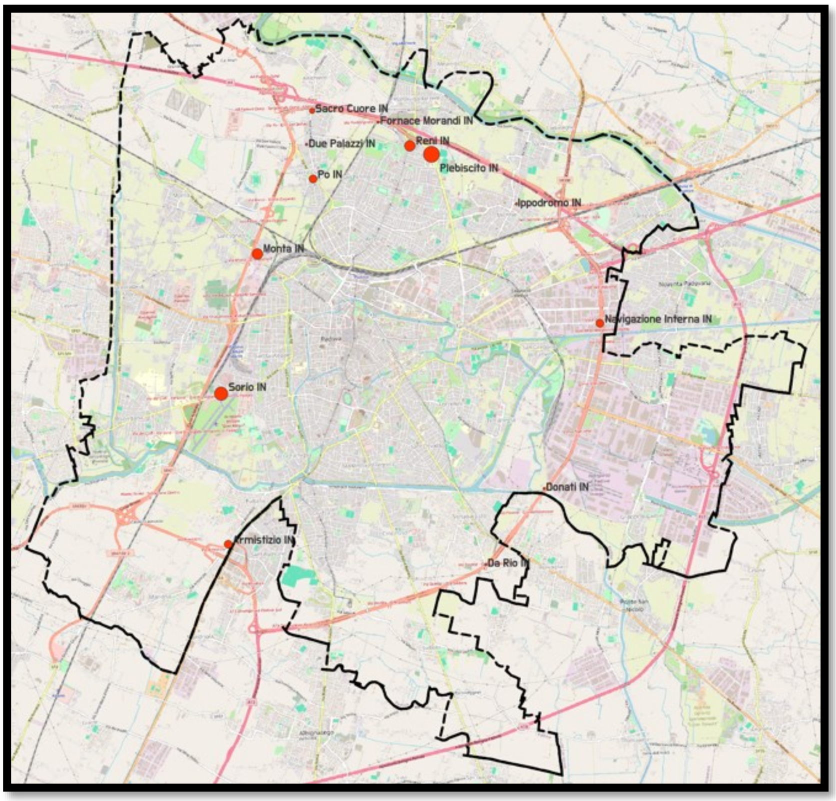


Figure 7: Average number of vehicles entering Padua in April 2020, from 19 monitoring places. Implemented in the QGIS software.

The decreasing traffic flow in March and April of 2020 can be clearly seen from the pictures thanks to QGIS. This part of the work has the purpose to show how many vehicles are entering daily and monthly the city of Padua, even though, more recent yearly data would have been a better representation of the entire framework. The pandemic has been catastrophic worldwide on various sectors, but reflections can be done about how Covid-19 affected transportation. An UFNCCC report statistically established that global lockdown saw a surface transport decrease by 50% and it induced to a large drop in emissions, accounting up to 27% from individual countries. This drop in CO_2 emissions had no detectable impact on climate change, since accumulated GHGs during the last years is a lot more compared to just the missing half from a few months (Le Quéré et al., 2020). The data shows the great opportunity in doing more in reducing emissions in the transport sector.

The missing piece to calculate emissions utilizing the advanced approach is the VKT (vehicle kilometer travelled) and the length and subdivision of roads, which are the clue components of the equation provided by the GHG emission step-by-step guide written by "Daniel, 2016". The formula is shown in *Figure 8.* Also, how city subdivision should be implemented is shown in *Figure 9.*

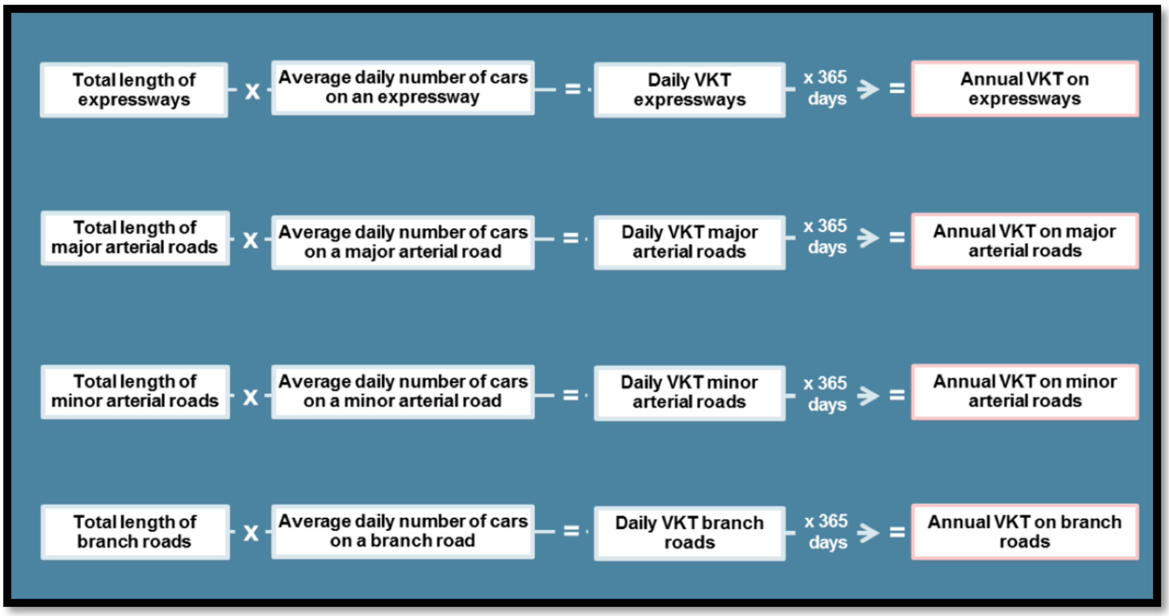


Figure 8: Advanced model. Proposed procedure to calculate on-road vehicle emissions using monitoring data. Retrieved in: (Daniel, 2016)

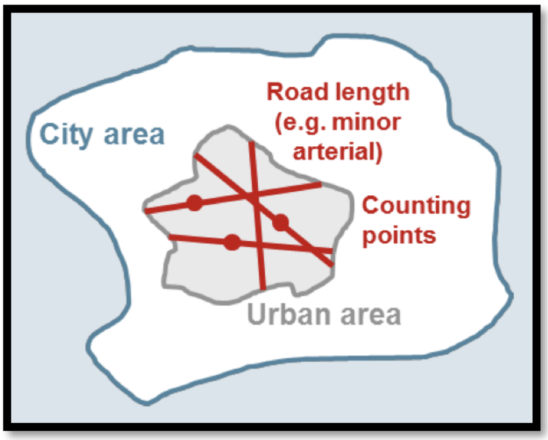


Figure 9: Advanced model. Visual criterial proposed to calculate emissions. Retrieved in: (Daniel, 2016)

As mentioned before, it was not possible to have the data of every single monitoring station during the same period, so the division proposed by the study was not optimal for this's study specifically. Analyzing every single motorway and arterial road was unmanageable since data was not present, so alternatives were considered by having just 19 spots on the map. The best possible solution was to divide Padua's area between these 19 positions by making an esteem of the mean VKT, but data was missing and could not be obtained, so the entire advanced model became unreliable.

For future implementation of the advanced model, to be as accurate as possible, it is necessary to have well taken data in all possible positions during the same period, and it is of better representation if derived from a whole year or more. The mean kilometer travelled by vehicles is a great issue, it can be monitored accurately by placing sensors on vehicles and implementing the model with a statistical approach, but the research would become too vast and dispersive, since traffic flows are not ordinary as a few tests' subjects. Statistics on the average kilometer travelled by cars in a year in Italy have been found in the next chapter where the basic model was implemented, these are just a sample regarding cars and are not even close to analyzing traffic flows in a precise way. The basic model is less precise, but it has been selected so it was possible to obtain results, since variables were missing to conclude the advanced model.

2.2 Methodology for Basic Model

Since the advanced approach encountered some issues, it was decided to proceed using the basic model. In this case necessary information was found on databases regarding the national country of Italy: transport activity involved was the national yearly mean of cars only, fleet composition was available on national documents, although, class and quantity of vehicles was the total number of registered vehicles for Padua only. The implementation of this method appears to be less precise than the previous but is the closest conclusion to create an assessment. The assumptions not scaled just for the city or present just for a single vehicle category cannot be realistic, since the major issue is that not every registered vehicle is in use. On the other hand, monitoring car-by-car is a complicated theory that surely violates privacy policies and so, using public databases is the best way to proceed by implying this model.
The equation concerning the calculation for this method is the following (*Figure 10*):

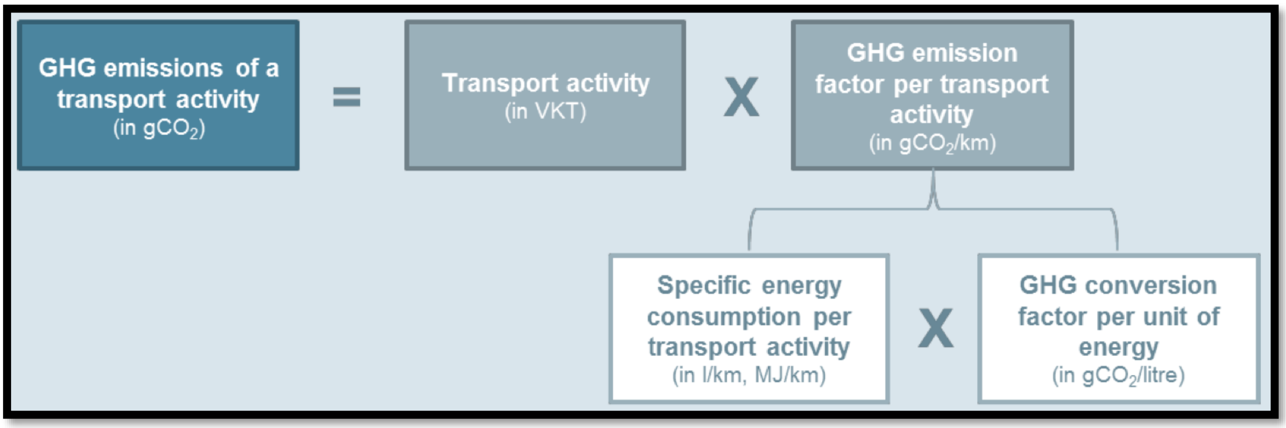


Figure 10: Basic model. Proposed procedure to calculate on-road vehicle emissions. Retrieved in: (Daniel, 2016)

GHG emissions are esteemed using national VKT means, European emission factors, national traffic flow subdivision and number of registered vehicles is considered within the municipality borders.

2.3 Statistical Analysis

Most of the statistical analysis was already done by national institutions, such as Istat and Anfia. The public register of vehicles available on Istat's website (National Statistics Institution) has a specific database for the district of Padua that counts the number of registered vehicles yearly, dividing them into class types, including cars, busses, heavy goods vehicles, trucks, trailers, motorcycles and three-wheelers (Istat - Pubblico registro automobilistico, 2023). The National Association of Automotive Industry (Anfia) elaborates new registrations and the respective homologations it acquires from the Ministry of Infrastructures and the Sustainable Mobility. In-use and new-registered vehicle subdivision into type of fuel came in handy to determine emission factors in the following chapter, shown in *Figure 11, Figure 12* and *Figure 13* (Anfia, 2024). The Odysse-Mure project provides updated databases and tools to implement the framework of the Energy Efficiency Directive in the European Union in the most efficient way possible, in our case it was used to estimate the mean car activity in Italy done year-by-year in VKT (Vehicle Kilometers Travelled) (odysse-mure, 2023).

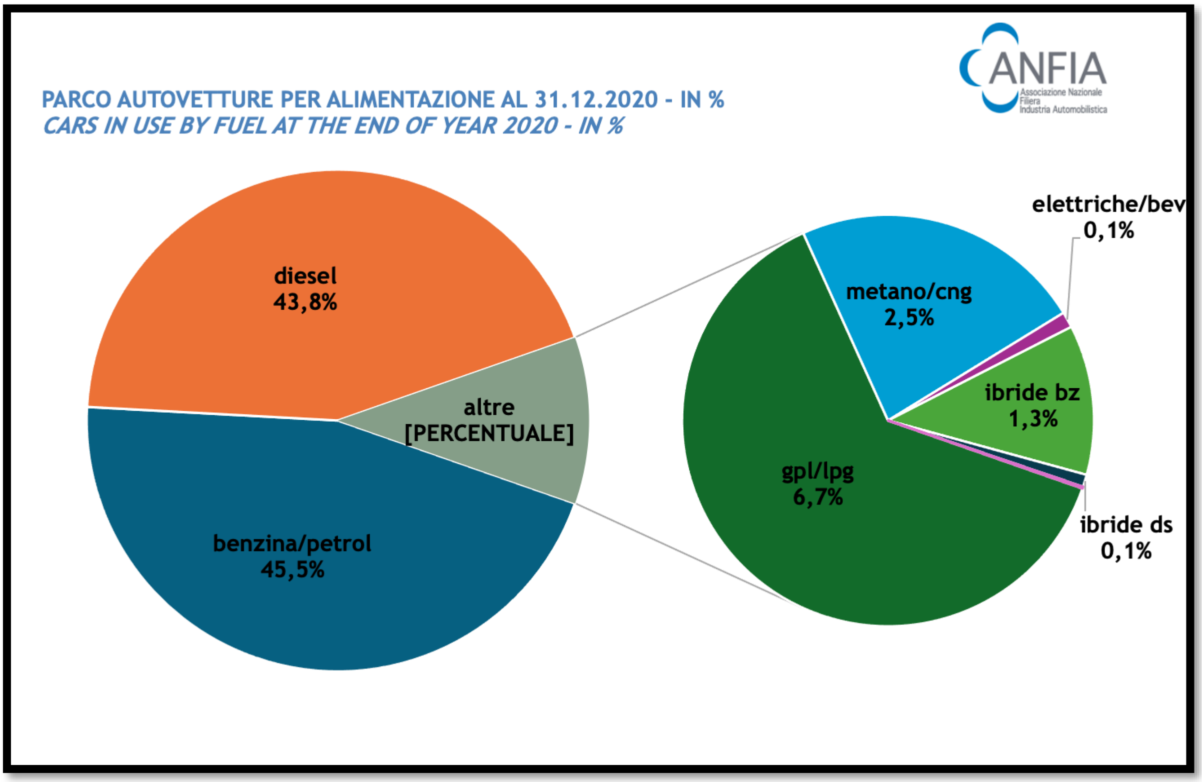
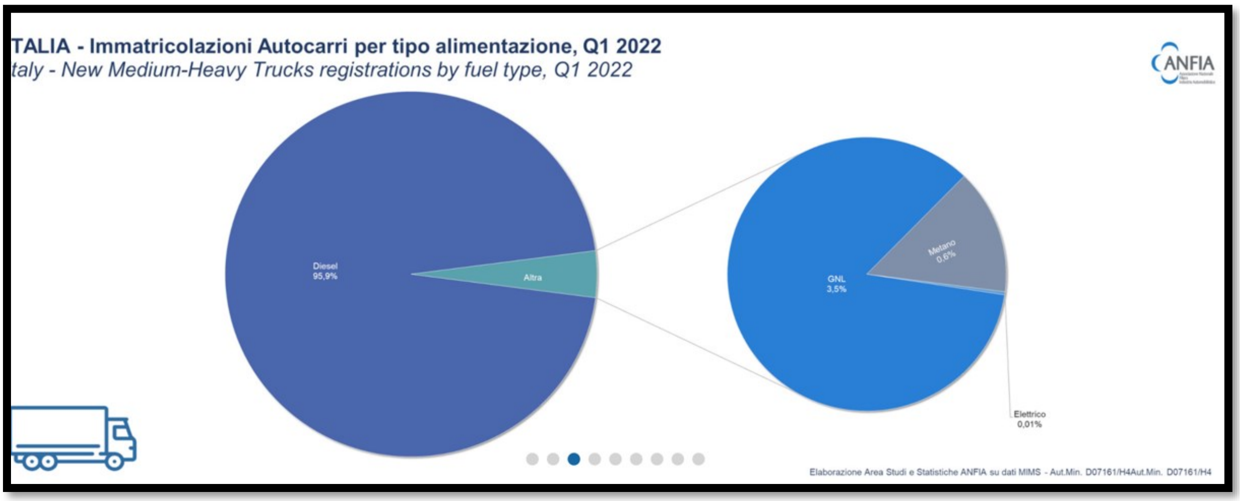


Figure 11: Cars in use divided by fuel in 2020, in percentage. Italy's national data. Retrieved in: (Anfia, 2024)

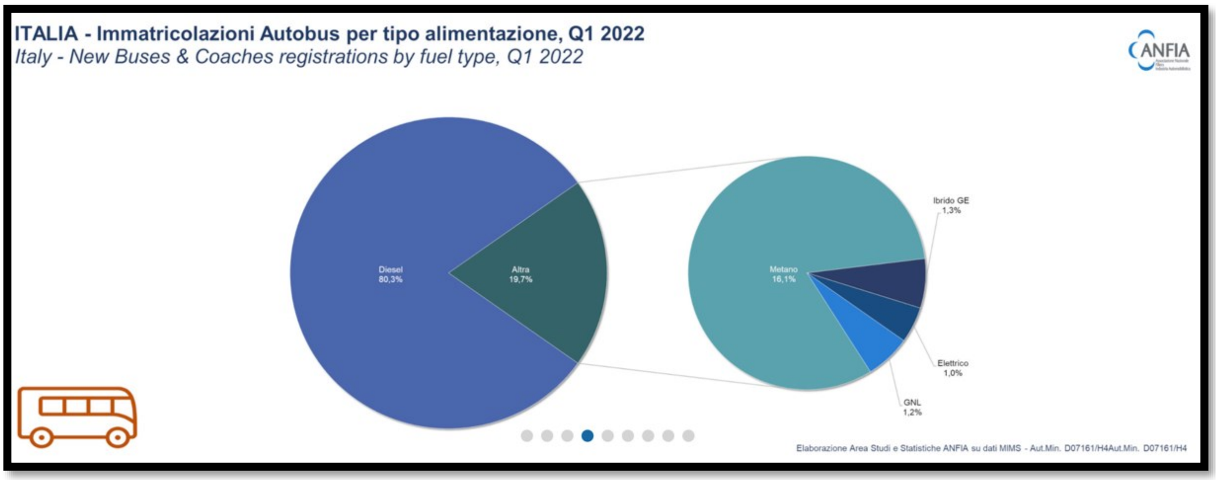


TALIA - Immatricolazioni Autocarri per tipo alimentazione, Q1 2022

taly - New Medium-Heavy Trucks registrations by fuel type, Q1 2022

Elaborazione Area Studi e Statistiche ANFIA su dati MIMS - Aut.Min. D07161/H4Aut.Min. D07161/H4

Figure 12: New medium-heavy trucks registrations divided by fuel in 2022, in percentage. Italy's national data. Retrieved in: (Anfia, 2024)



ITALIA - Immatricolazioni Autobus per tipo alimentazione, Q1 2022

Italy - New Buses & Coaches registrations by fuel type, Q1 2022

Elaborazione Area Studi e Statistiche ANFIA su dati MIMS - Aut.Min. D07161/H4Aut.Min. D07161/H4

Figure 13: New busses and coaches registrations divided by fuel in 2022, in percentage. Italy's national data. Retrieved in: (Anfia, 2024)

2.4 Emission Factors

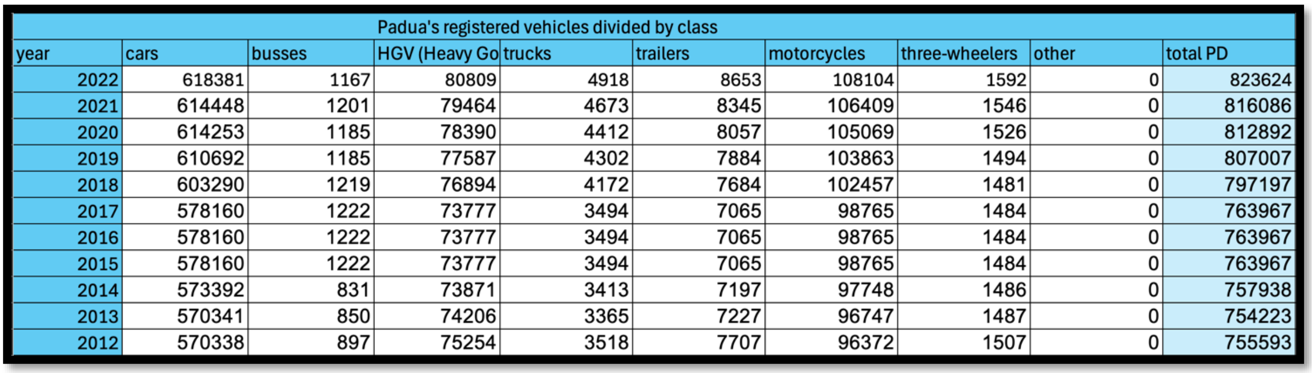
The European Environment Agency holds an emission factor database included in the EMEP/EEA inventory Guidebook 2023, which gives technical guidance to prepare national emission inventories. Since the database lists lots of specific information about EFs and, in this case, it was needed only the on-road transport sector one. EFs were filtered by Nomenclature for Reporting (NFR) in the category "1.A.3.b" of road transport, by fuel and pollutant. The analyzed classes were passenger cars, light duty vehicles, heavy duty vehicles, mopeds & motorcycles, automobile tire and brake wear, automobile road abrasion. The most relevant fuel types were present: diesel, petrol, gasoline, liquefied petroleum gas (LPG) and compressed natural gas (CNG). EFs for hybrid cars were present in the petrol data, they were separated and put in a specific class for HEV. Full electric vehicles (EV) have no direct emissions, so they were not considered. Since GHGs emitted by vehicles are a lot of different kinds, it was decided that only the most relevant ones were considered, such as: carbon monoxide (CO), carbon dioxide (CO_2), nitrous oxide (N_2O), nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOC) (EMEP/EEA Air Pollutant Emission Inventory, 2023). These GHGs were converted to a unique value using the global warming potential (GWP) formula, mass multiplied by GWP, to have a single result measured in CO_2 equivalent. The GWP makes different greenhouse gases comparable with regards to their effectiveness in causing radiative forcing. The main compound GWP values were adopted from the IPCC fifth assessment report, 2014 (AR5) (Global Warming Potential Values, 2021). Values are equal to 1 for CO_2 and 265 for N_2O, having a hundred-year horizon, however the rest are indirect GWPs, so estimates of their impacts can be highly uncertain. In this case, the most common ones are CO, NMVOC and NO_x, some studies show how they can be estimated. An accurate approximation of the entire indirect forcing of CO requires a three-dimensional chemical model, since it is difficult to calculate the amount of O_3 produced, and the result shows that is likely to be 1.0 to 3.0 (IPCC, 2023). NO_x is shorthand for the sum of nitric oxides (NO) and nitrogen dioxides (NO_2), these two gases have similar GWPs that are estimated to be between 7.0 to 10.0 for a hundred-year horizon and is thereby comparable to the one of methane (Lammel & Graßl, 1995). Some studies show that GWP_{100} for NMVOC compounds ranges from 2.36 to 5.83 (Fry et al., 2014). For this work, it was decided to use a mean number for global warming potentials for these pollutants, so all the values are reported in the following table.

Pollutant	**CO_2**	**CO**	**NMVOC**	**NO_x**	**N_2O**
GWP100	1.0	2.0	4.0	9.0	265.0

3. Results and Discussion

3.1 Calculations and Considerations

The procedure to calculate vehicle emissions for the municipality of Padua was implemented entirely on the Microsoft Excel software. The first thing done was the creation of a table that included the yearly number of registered vehicles sorted into the following class types: cars, busses, heavy goods vehicles, trucks, trailers, motorcycles and three-wheelers as shown in *Figure 14*. Accounting to a total for all the city of Padua.

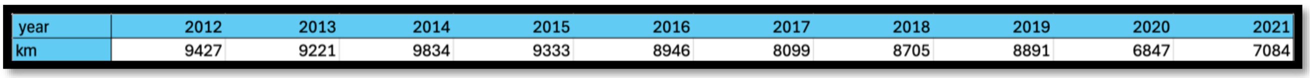


Padua's registered vehicles divided by class

year	cars	busses	HGV (Heavy Go	trucks	trailers	motorcycles	three-wheelers	other	total PD
2022	618381	1167	80809	4918	8653	108104	1592	0	823624
2021	614448	1201	79464	4673	8345	106409	1546	0	816086
2020	614253	1185	78390	4412	8057	105069	1526	0	812892
2019	610692	1185	77587	4302	7884	103863	1494	0	807007
2018	603290	1219	76894	4172	7684	102457	1481	0	797197
2017	578160	1222	73777	3494	7065	98765	1484	0	763967
2016	578160	1222	73777	3494	7065	98765	1484	0	763967
2015	578160	1222	73777	3494	7065	98765	1484	0	763967
2014	573392	831	73871	3413	7197	97748	1486	0	757938
2013	570341	850	74206	3365	7227	96747	1487	0	754223
2012	570338	897	75254	3518	7707	96372	1507	0	755593

Figure 14: Padua's yearly number of registered vehicles divided by class. Retrieved in: (Istat - Pubblico registro automobilistico, 2023)

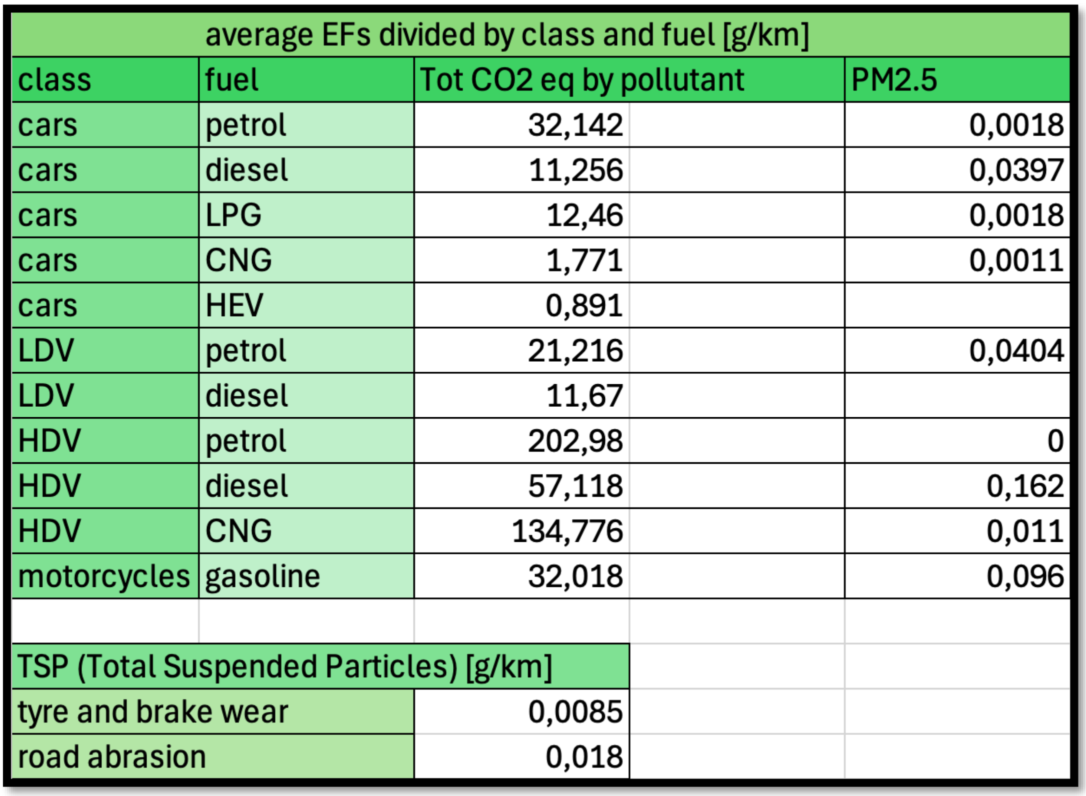
The other statistics reported in Excel were the yearly national VKT from 2012 to 2021, shown in *Figure 15,* since Covid-19 affected the world in 2020 and 2021, the latest reported kilometer travelled average that is more representative for recent years is the one from 2019 which is equal to 8891 km.



year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
km	9427	9221	9834	9333	8946	8099	8705	8891	6847	7084

Figure 15: Yearly national average vehicle kilometer travelled (VKT). Retrieved in: (odysse-mure, 2023)

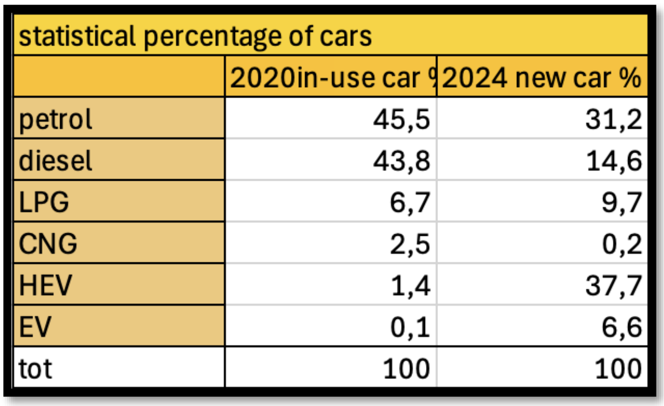
EFs retrieved in the database were already divided into classes, including passenger cars, light duty vehicles, heavy duty vehicles, mopeds & motorcycles, automobile tire and brake wear, automobile road abrasion. Every class had between ten and forty components depending on specific type of vehicle, size of the vehicle, size of the engine and emission standard (Euro 1 to 6). Since all these components of traffic flow were too complex to analyze individually and did not have a high relevance, it was decided to estimate an average of every class's emission factor. Additionally, means were calculated distinctly for every fuel type and for the most relevant GHGs. Fuel types are diesel, petrol, gasoline, liquefied petroleum gas (LPG) and compressed natural gas (CNG). Hybrid electric vehicles (HEVs) were already classified inside gasoline and diesel groups, since differentiating had a relevance for fleet composition, a distinct category for HEVs was created. Clime-altering gasses were carbon monoxide (CO), carbon dioxide (CO_2), nitrous oxide (N_2O), nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOC). The results were converted in CO_2 equivalents by employing the GWP converting formula and then summed to have a total EF output for every fuel type and every vehicle class. The EF for the total suspended particulate (TSP) was not converted to CO_2 equivalent, since they can only be classified as pollutants and are not clime-altering gasses affecting global warming. TSPs were calculated distinctly from $PM_{2.5}$, indeed, TSP is formed by bigger particles and must be treated in a different category. In the table below *(Figure 16)* the total CO_2 equivalent EFs means can be seen, separated from TSP and $PM_{2.5}$.



average EFs divided by class and fuel [g/km]			
class	fuel	Tot CO2 eq by pollutant	PM2.5
cars	petrol	32,142	0,0018
cars	diesel	11,256	0,0397
cars	LPG	12,46	0,0018
cars	CNG	1,771	0,0011
cars	HEV	0,891	
LDV	petrol	21,216	0,0404
LDV	diesel	11,67	
HDV	petrol	202,98	0
HDV	diesel	57,118	0,162
HDV	CNG	134,776	0,011
motorcycles	gasoline	32,018	0,096
TSP (Total Suspended Particles) [g/km]			
tyre and brake wear		0,0085	
road abrasion		0,018	

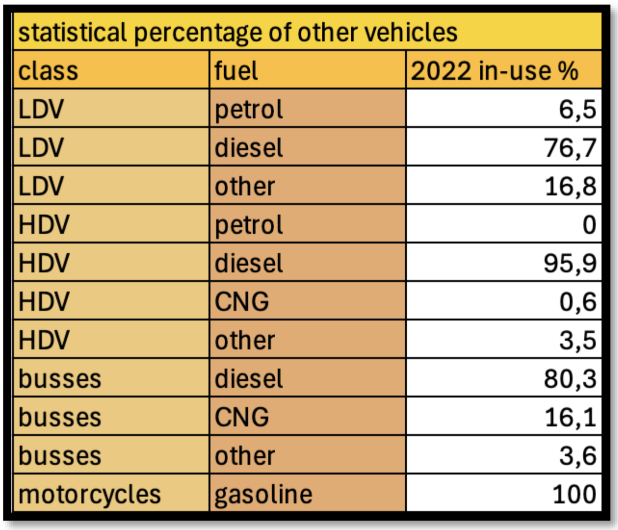
*Figure 16: average emission factors divided by class and fuel. In g/km. Retrieved in: (*EMEP/EEA Air Pollutant Emission Inventory*, n.d.) and calculated by using Excel.*

The next thing to do was transcribing the statistical percentages of traffic flow type by fuel from the Anfia databases to Excel, already divided into the desired vehicle class types, therefore the tables below were created. Respectively *Figure 17* and *Figure 18.*



statistical percentage of cars		
	2020in-use car	2024 new car %
petrol	45,5	31,2
diesel	43,8	14,6
LPG	6,7	9,7
CNG	2,5	0,2
HEV	1,4	37,7
EV	0,1	6,6
tot	100	100

Figure 17: Cars in use divided by fuel in 2020, in percentage. Italy's national data. Reported in Excel. Retrieved in: (Studies and Statistics, n.d.)



statistical percentage of other vehicles		
class	fuel	2022 in-use %
LDV	petrol	6,5
LDV	diesel	76,7
LDV	other	16,8
HDV	petrol	0
HDV	diesel	95,9
HDV	CNG	0,6
HDV	other	3,5
busses	diesel	80,3
busses	CNG	16,1
busses	other	3,6
motorcycles	gasoline	100

Figure 18: Registration statistics of other vehicles divided by fuel in 2022, in percentage. Italy's national data. Retrieved in: (Studies and Statistics, n.d.)

It is clearly noticeable that passenger car data comes from 2020 in use cars and for other categories the used year is 2022. Since Anfia held a national statistics database for new automobile registrations even for the start of 2024 *(Figure 19)*, additional considerations could have been made about the difference of the year.

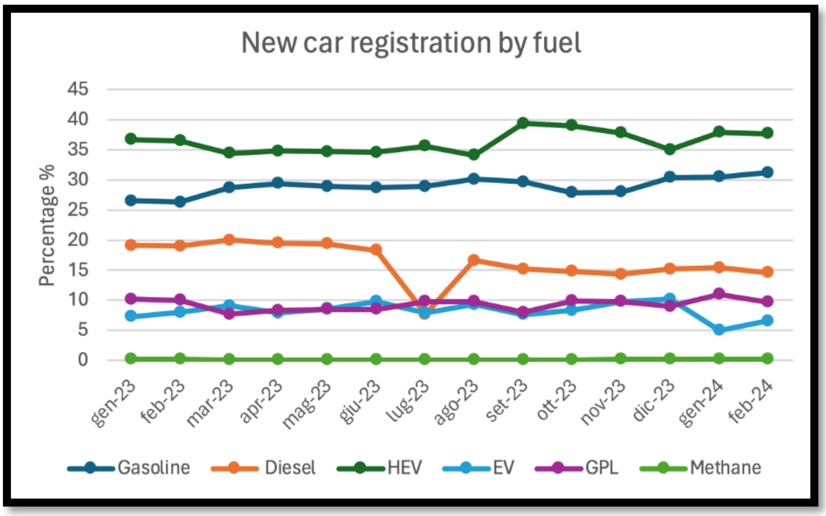
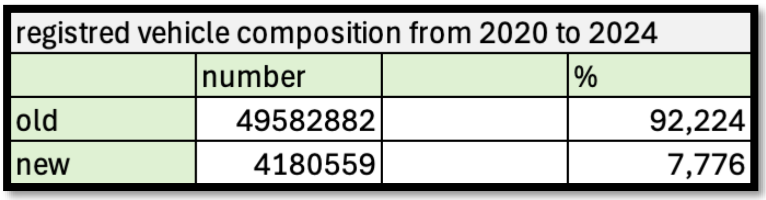


Figure 19: New car registration by fuel from 2023 to the start of 2024. Retrieved in: (Studies and Statistics, n.d.)

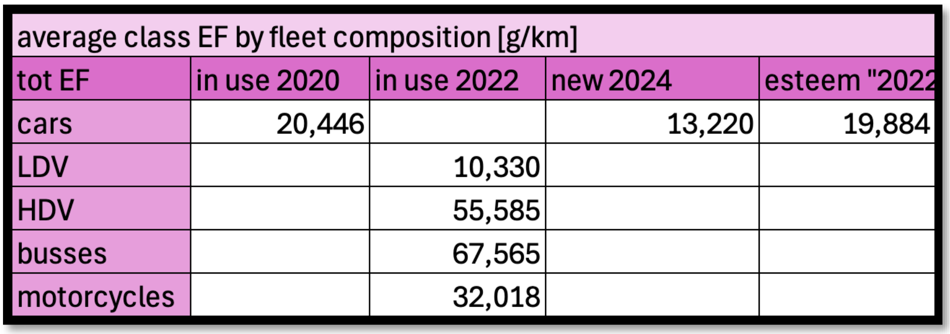
To have a coherent work, it was decided to use 2022 as the reference year to calculate emission factors for every population class, the only issue was that data for passenger cars was not present. An esteem for 2022 EFs for automobiles was implemented by applying the cumulated total national number of registered vehicles from 2020 to 2023 and the cumulated new registration one to obtain the fractions of old and new vehicles from those years. Computations are shown in *Figure 20.*



registred vehicle composition from 2020 to 2024			
	number		%
old	49582882		92,224
new	4180559		7,776

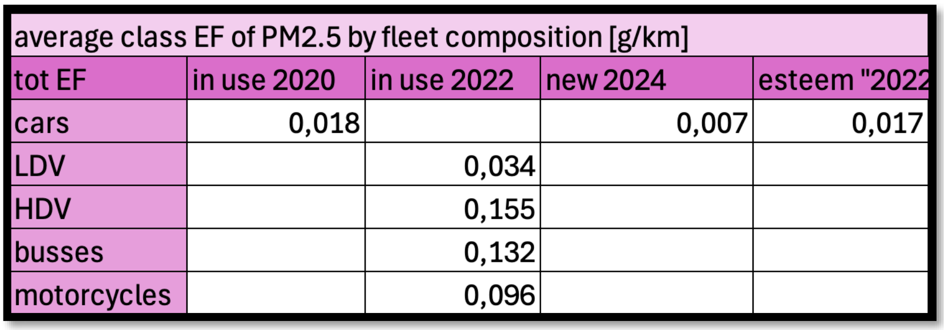
Figure 20: Esteem of the composition of registered vehicles from 2020 to 2024.

The mean EFs for every vehicle class was obtained by multiplying the percentages of fleet composition, sorted by fuel, by the correspondent EFs calculated previously. The following tables show the final EF results. The first one (*Figure 21)* is the sum of clime-altering gasses EFs converted in CO_2 equivalent regarding traffic fleet composition, and the second *(Figure 22)* concerns $PM_{2.5}$. EFs regarding TSP that are coming from tire and brake wear and road abrasion remain unchanged, because these are characteristics common to all types of vehicles.



average class EF by fleet composition [g/km]				
tot EF	in use 2020	in use 2022	new 2024	esteem "2022
cars	20,446		13,220	19,884
LDV		10,330		
HDV		55,585		
busses		67,565		
motorcycles		32,018		

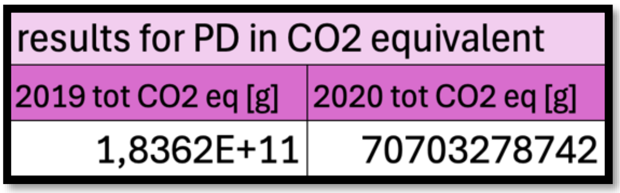
Figure 21: Average fleet composition emission factors of total GHGs divided by class. In g/km.



average class EF of PM2.5 by fleet composition [g/km]				
tot EF	in use 2020	in use 2022	new 2024	esteem "2022
cars	0,018		0,007	0,017
LDV		0,034		
HDV		0,155		
busses		0,132		
motorcycles		0,096		

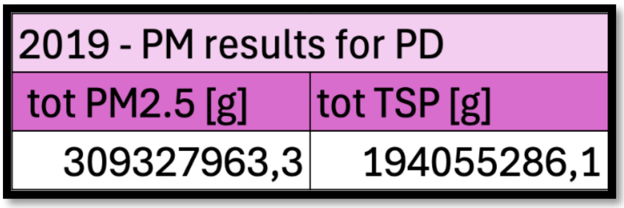
Figure 22: Average fleet composition emission factors of PM2.5 divided by class. In g/km.

In conclusion, emissions were calculated by making the sum of the average EFs (2022) multiplied by the number of vehicles of every class (2022), then multiplying the result by the VKT from 2019. To have a comparison, this process was repeated using VKT from 2020, which was a year affected by the pandemic, having the number of vehicles was halved, since, as affirmed in the previous chapter, transport decrease during this year was roughly 50%. Finally, results in grams of CO_2 equivalent and grams of particulate matter, computed with 2019 VKT, are shown respectively in *Figure 23* and *Figure 24*.



results for PD in CO2 equivalent	
2019 tot CO2 eq [g]	2020 tot CO2 eq [g]
1,8362E+11	70703278742

Figure 23: Padua's results in CO2 equivalent calculated respectively with VKT from 2019 and 2020. In grams.



2019 - PM results for PD	
tot PM2.5 [g]	tot TSP [g]
309327963,3	194055286,1

Figure 24: Padua's results for particulate matter calculated with VKT from 2019. Respectively PM2.5 and total suspended particulate (TSP). In grams.

The basic model's results for the Municipality of Padua, utilizing 2019's VKT, are equal to 184 kt of CO_2 equivalent yearly emissions of GHGs, 309 t of yearly $PM_{2.5}$ and 194 t of yearly TSP emissions.

3.2 Result Comparison and Discussion

ISPRA is the Superior Institute for Environmental Protection and Research in Italy, the annually inventory of national atmosphere emissions can be simply accessed on their website, according to the legislative decrees n. 51/2008 and n. 30/2013. Analyzing 2022, the transport sector represents 26.6% of total emissions in which road transport is 91.5% of it. The entire country emissions in the transportation sector in the years of 2019 and 2022 are very similar, accounting to about 100 000 kt for the whole sector and 91 500 kt emissions of GHGs only for road transportation. According to the findings, road transport emissions of Padua are 0.2% of Italian ones (Isprambiente, 2022). The chart below (

Figure 25) shows total national emissions of on-road transport through time divided by vehicle type from 1990 to 2022.

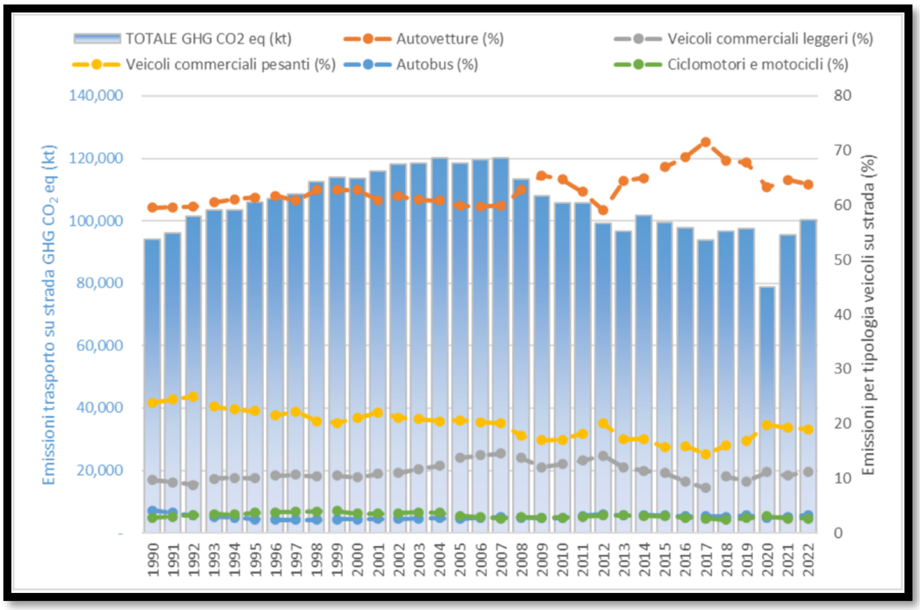


*Figure 25: GHG emissions from road transport divided by vehicle type in Italy from 1990 to 2022. Retrieved in: (*Le Emissioni Nazionali Di Gas Serra Settore Trasporti-2022 Dipartimento per La Valutazione, i Controlli e La Sostenibilità Ambientale*, n.d.)*

Other emission models were already developed in Europe, one of the most relevant ones is the Open GHG Map which is an inventory that geographically spatializes the national emissions by utilizing activity data from OpenStreetMap (OSM), the EU's Emissions Trading System (ETS) registry of point source emitters and airport traffic data. This method ensures that the national total matches the register, produces results in both gridded and administrative unit formats, and maintains detailed information on the sources of emissions. The inventory calculated emissions for all 116 572 municipal and local government units in Europe and it sums up to a total of 108 000 cities. When the model was compiled the most recent year for data availability from Eurostat (the European Statistical Office) was 2018 (Moran et al., 2022). Emission records for Padua are present, the total reported is 730 kt of CO_2 equivalent and according to Italy's percentage of transport sector emissions (26,6%) the converted value for transport only is 194 kt, which is very similar to the basic model's result for the municipality (184 kt). In the results comparison it is noticeable that Open GHG Map slightly overestimates the value, although variables come from different years and outputs can be a little diverse.

Another topic is the comparison between results from Covid-19 years and not. 2020's scenario saw the pandemic beginning to take hold and to spread all over the world, lockdowns were established for several months by governments, and it was not possible to circulate freely as before due to infecting risks. Regarding road transportation, this first year characterized by the disease saw a decrease by 50% in vehicle use so the number of homologations was simply halved just to make a rough esteem. Italy's average VKT was reduced from 8891 km in 2019 to 6847 km in 2020, it was not a drastic change since freight was still travelling through the country. In some cases, smart working was not possible, and people had still to transfer to go to the workplace, plus going to get first necessities and essential goods could not be denied. Results show that emissions of GHGs drop from 184kt to 70,7 kt which is slightly underestimated.

Atmospheric particulate matter (PM) are solid or liquid microscopic particles of matter suspended in the air, having impacts on climate and precipitation that adversely affect human and animal health, indeed, exposure to urban atmospheric PM can cause acute and chronic health implications for every organ in the body. Coarse particulate matter has a diameter bigger than 10 μm (micron), easily filtered by the upper respiratory system. On the other hand, fine particulate matter has a diameter under 10 μm (PM_{10}) and can easily penetrate in human bodies. Anyways, only $PM_{2.5}$, which has a diameter smaller than 2.5 μm, can penetrate in profundity reaching lungs and creating serious health problems (Ministro della Salute, 2015). Concerning PM_{10} and TSP emissions, it should be considered that exhaust gases are not the only source of particle emissions in road transport. Non-exhaust sources like brake, tire and road wear contribute almost as much to consumed gas pollution. This is especially the case in stop-and-go traffic in an urban environment. Anyways, the most dangerous particles are the fine fraction of particles that come from exhaust gasses. $PM_{2.5}$ concentration limits imposed by the European Union came into effect the 1st of January 2020 and are set at 20 $\mu g/m^3$ daily average in a year (European Commission, 2020). Supposing that pollution from other sectors is consistent and even, transport sector emissions should be around one quarter of the total, so the threshold sets at 5 μg/m^3. To observe if the computed $PM_{2.5}$ is within the limits, a volume of breathable air can be derived by making some assumptions, by knowing the area and supposing the needed height. Most of the buildings in Padua Municipality have two to three floors, some high skyscrapers are present, but even some parks, lots of streets and other structures. The column of air height can be represented by a significative number that is around 5 to 10 meters. The area of the city is of public knowledge, and it is equal to 92,85 km^2. Obtained concentrations are 1.78 μg/m^3 if height is equal to 5 m and 0.89 μg/m^3 if height is equal to 10 m. The numbers are widely under the threshold value, esteems of concentration dispersion in the air are of difficult assumption since other variables should be considered, such as wind speed and weather conditions. The local environmental monitoring agency, ARPAV, analyzes live data offered by three distinct air quality monitoring stations in Padua's city center. Average daily concentrations of $PM_{2.5}$ are usually around 10 μg/m^3, having maximum peaks reach 25 μg/m^3 (ARPAV, 2024). The values obtained previously are then matched to total $PM_{2.5}$ concentration by roughly multiplying them by four just for comparison purposes, resulting in 7.12 μg/m^3 if height is equal to 5 m and 3.56 μg/m^3 if height is equal to 10 m. To make the basic model's results match with real detected data, vertical height must be around 3.5 m to meet the 10 μg/m^3 concentration or 1.4 m to reach the maximum equal to 25 μg/m^3. Studies about vertical distribution patterns of $PM_{2.5}$ in low troposphere affirm that the low height of the planetary boundary layer (PBL) facilitates the accumulation of pollutants near the ground, even though it is not mandatory (Song et al., 2021). In conclusion, fine particulate emissions are averagely respecting the concentration limit imposed and, to authenticate the model, it can be evident that ARPAV's statistics shown are comparable to particulate matter results obtained.

4. Conclusions

4.1 Introduction to European Goals Towards a Zero-Emission City

European commission stated that Europe has a vision to achieve long term goals and to become the world's first climate-neutral continent by 2050. Most Europeans are concerned by climate change as the last two decades have been registered as the warmest years on record and because extreme weather events have been increasing globally. The strategy implies embracing a net-zero greenhouse gas (GHG) economy regarding every key sector, including energy, transport, industry and agriculture. To achieve a climate-neutral economy EU has listed seven detailed points to do so. The first step is to improve energy efficiency in industrial processes and even in service ordinary buildings, 75% of these constructions were built before energy performance standard existed, so the great task is to renovate old structures. Another important objective for the EU is the electrical energy supply transition towards renewable energy, this can lead to a development of other decarbonization possibilities in mobility and industries such as electricity or e-fuels (hydrogen and Power-to-X). Other points are creating a competitive industry by utilizing the influence of circular economy, including raw material recovery and recycling; developing bioeconomy to transform more efficiently agriculture and farming's biomass into clean energy or fuel and increasing CO_2 absorption by restoring degraded forests; implementing the carbon capture and storage as the mechanism to reduce emissions that are difficult to eliminate in the atmosphere.

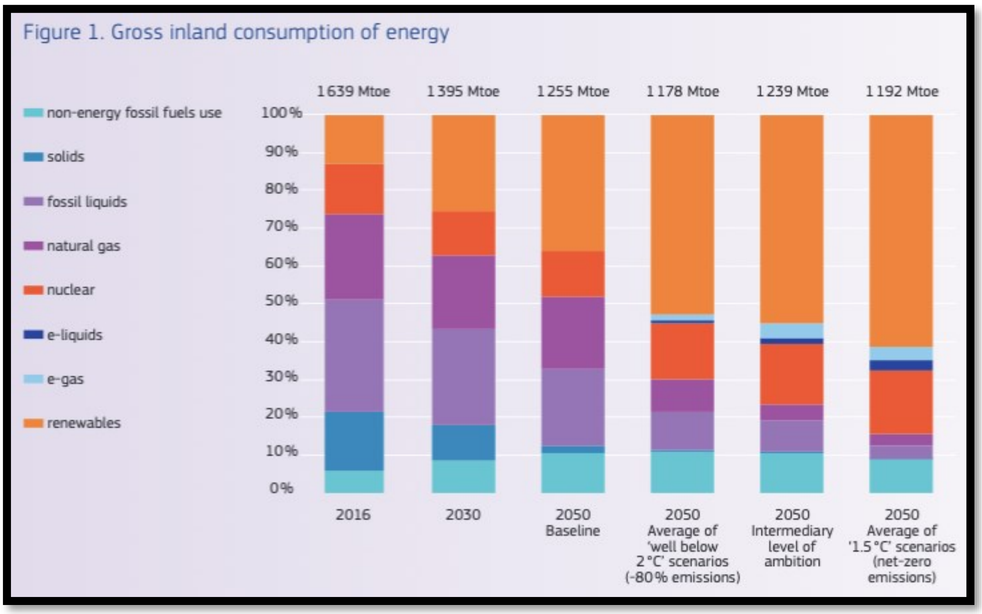


Figure 26: Europe's energy supply data and future scenarios. Retrieved in: (European Commission, 2019)

Although, the pragmatic task is to reach net-zero emissions in the transport sector by 2050, which accounts for a quarter of the EU's GHG productions. This regards vehicles in the first place, especially personal passenger automobiles, and sees a transition to greener fuels necessary. Automotive industry is already investing in low or zero emission technologies for automobiles, powered by electricity or e-fuels. Hydrogen and biogas can substitute clime-altering fuels in heavy-duty vehicles and busses, but also in the naval and aviation sector. Other than innovating vehicles itself, an important aspect to cover is the support to road mobility and the formation of new interconnections. A vital part of this transition relies in the infrastructure, which will require accelerated set-up development implementing smart and fast charging for EV and refueling stations that are more numerous and efficient for the on-road mobility (European Commission, 2019)

The European Union mandates aim to reduce greenhouse gas emissions in the transport sector by 42% and, also, a reduction of air pollutants such as nitrous oxides and particulate matter by up to 65% by 2035. As urban centers worldwide face the intensifying impacts of climate change, the vision of a zero-emission city will transition in 2050 from an aspirational ideal to an urgent necessity. Despite various mobility strategies, there is no definitive solution for adapting transport systems to meet these 2035 targets, since there are an infinite number of answers to traffic pollution and global warming (Tsiropoulos et al., 2020). Undoubtedly, the two main methods are: making changes in mobility behavior and shifting towards different types of transport used. By using just the first way, a scenario is formed that sees behavioral change as the main goal, this achieves significant emission reduction by shifting up to 45% of car traffic to local public transport and cycling, this solution has a minor environmental impact compared to motorized individual transport. This requires sustained behavioral changes not accomplished by most people in recent years and a framework to encourage all of this. Scenario number two, where just the second assumption is considered, comprehends a substitution of about 60% of internal combustion engine vehicles (ICEVs) that must be replaced by battery electric vehicles (BEVs) or plug-in hybrid electric vehicles (PHEVs). This approach significantly increases the demand for critical resources like cobalt (Co), neodymium (Nd), dysprosium (Dy), and lithium (Li) by up to 63-185 times compared to 2019 levels. BEVs, being more effective in reducing CO_2 and pollutants in passenger transport, should be prioritized over PHEVs, as they achieve optimal efficiency when used primarily as electric vehicles. Successful implementation requires extensive development of charging infrastructure and renewable energy generation, requiring action from both public and private investors. Otherwise, various moderate approaches that combine elements of the two cases in question can be possible, keeping the total change weighted percentage the same. (Berg Mårtensson et al., 2024).

4.2 Alternatives by Changing Mobility Behavior: Shared Rides and Public Transport

Mentality must change within people to radically reduce GHG emissions, especially in private vehicle usage. Climate awareness should be more emphasized by governments, since misinformation about global warming is predominant between most people. In Italy, state car incentives are existent, but to the majority they are not enough to make a transition towards an EV or a HEV, since it is not convenient. Other than that, individuals are not inclined to change and are still preferring their manual transmission car over less-emitting new technology. Besides changing vehicle types, the key concept is to encourage citizens to decrease the number of total vehicles in use, if it is possible, by implying shared mobility rides or using public transport. There is a verity of shared mobility options that can become part of everyday use or can be just of occasional use, the most common forms are listed below. Car-sharing is a short-term use of a shared vehicle. Micromobility is the employment of vehicles smaller than cars, such as bicycles and electric scooters. Ridesharing enables people with the same destination to share a journey. Ride sourcing and micro transit both involve ride splitting, for the first one is necessary an online reservation and is more comparable to collective taxies, meanwhile, the second one is more like public transport, since it employs drivers. Implementing shared mobility can alleviate issues caused by pollution and traffic congestion by reducing the total vehicle circulation, easing traffic crowding, and decreasing the emission of polluting gases and GHGs in urban areas. Integrating shared mobility with electric vehicles (EVs) may further boost the adoption of both technologies and reduce energy consumption (Pamidimukkala et al., 2023).

Investing in shared modes can encourage a shift from privately owned vehicles, but these means typically carry fewer passengers per trip compared to public transport, making them less efficient. In fact, the World Research Institute affirms that public transport is one of the most effective and affordable solutions for addressing today's climate and development challenges. Buses and trains can reduce greenhouse gas (GHG) emissions by up to two-thirds per passenger per kilometer compared to private vehicles. The UN's latest climate action report highlights that increasing public transit usage is essential for combating the climate change. Additionally, improving access to reliable public transport offers significant benefits for society, including lower traffic fatality rates, healthier urban populations, and greater access to jobs, education, and services. However, despite gradual infrastructure growth in recent decades, the public transport sector is not on track to meet climate and development goals, indeed, to avoid the most severe impacts of climate change, global public transport capacity must double by 2030. This demands rapid expansion of infrastructure which has not yet fully recovered from Covid-19 declines in many areas (Welle et al., 2023). Another aspect is energy's origin and economy, since its costs account for roughly 30% to 50% of the total public transport budget and transitioning to sustainable energy sources or collaborating with energy providers and local investors can generate significant savings. However, the sector requires an all-around approach to reduce overall CO_2 emissions from passenger transport and achieve net-zero emissions. Promoting a modal shift towards environmentally friendly transportation is crucial for reducing emissions. Every person who opts for public transport, cycling, or walking instead of using a car decreases energy consumption and carbon emissions. Cities and governments can encourage this shift by implementing measures such as improving infrastructure for public transport and active mobility and making private car use less appealing through traffic calming measures. The final step is enhancing the energy efficiency of transport modes and vehicles. A straightforward example is upgrading bus fleets to electric zero-emission buses and ensuring they are charged with renewable energy sources (Cormier, 2022).

4.3 Alternatives by Changing Vehicle Type: EVs and E-Fuels

Nowadays and for the future to come, the most effective and reliable way to drastically reduce emissions from road transport is a transitioning to different types of transportation, the best solutions up to date are e-fuels and electric vehicles (EVs). Studies show how a shift to just EVs could reduce CO_2 emissions due to traffic by 72%, NO_x emissions by 79%, VOCs by 99%, sulfur oxides by 51% and PM by 56%. Apart from this aspect, EVs have lots of advantages compared to traditional internal combustion engine vehicles (ICEV), ease, reliability, affordability, convenience and efficiency. In fact, in most nations electric energy is way cheaper than fossil fuels, with an average price per mile around 4 times less than ICEVs which varies from country to country. Typical worldwide EV sale rates are very low, due to the high initial price and low resale value. For example, in Ghana, estimates show that the total cost per mile of EVs, including the purchase of the vehicle, is higher than ICEVs until the seventh year after the purchase (Ayetor et al., 2023). Anyways, if all ICEVs will be replaced by EVs the electricity demand will considerably increase. USA Facts, a not-for-profit and nonpartisan civic initiative making government data easy to access and understand, reported that in the United States of America, it may take from 20% up to 50% more electricity to power travel if all cars and trucks were EVs, based on 2019 statistics. Since a converted number equal to 4,800 billion kWh was used to fuel gasoline vehicles, it would take roughly 800 to 1,900 billion kWh of electricity to power all vehicles, as the US used about 4,130 billion kWh of electricity. These results were calculated according to the EPA (U.S. Environmental Protection Agency) which states that every liter of gasoline is equivalent to 8.9 kilowatt-hours (kWh) of electricity and according to the Office of Energy Efficiency and Renewable Energy which concluded that EVs are roughly two and a half to six times more efficient using energy from the power grid than conventional cars are using gasoline (USAfacts, 2023). Regarding Europe, studies have been made in Germany to monitor it's 2030 Climate Action Plan by deriving mobility scenarios for traffic systems. Assuming an energy consumption of 16–20 kW/100 km for BEVs and 10 kW/100 km for plug-in hybrid electric vehicles (PHEVs), and a national average annual driving distance of 13,602 km, the entire German car fleet of approximately 45.7 million vehicles would require an additional 19–74 TWh of electric energy by 2030. This is based on the first scenario composed by 35–54% BEVs and 11–30% PHEVs and scenario number two where 14% would be BEVs and 10% PHEVs. If internal combustion engine vehicles (ICEVs) are to be gradually replaced by battery electric vehicles (BEVs) in the coming decades, the additional electric energy needed to power these vehicles, preferably sourced from renewables, must be considered. This concern necessitates an over regional perspective (Byrne et al., 2021). Enel Green Power, one of the largest worldwide companies on renewables, affirms that the transition to sustainable energy production cannot be achieved by abandoning fossil fuels all at once. This process must be gradual and carefully managed to ensure grid stability, resilience, and efficiency. The key to this transition is electrification: progressively replacing fossil fuel-based technologies with those that use electricity from renewable sources across all sectors. This shift will also reduce air pollution in cities and significantly enhance energy efficiency with grid digitalization. With technology at our disposal, using just renewables creates instability and discontinuity in electrical grids, so, a mixed solution is severely required. Relying on machines with internal inertia or combustion is still necessary. Since coal is the most polluting and emitting source, alternatives can be implied. Natural gas can be a transitional solution, indeed, it offers several advantages over coal, as quantified by the International Energy Agency (IEA). The most notable benefits are improved efficiency and that it produces up to 50% less carbon dioxide, for the same amount of electricity generated (Enel Green Power, 2022). Another valuable alternative towards decarbonization is the adoption of nuclear energy production. Despite concerted international efforts over the past twenty years to boost electricity generation from wind, solar, and other renewable sources, fossil fuels remain a dominant part of the energy mix. In fact, data shows that fossil fuels produced more electricity in 2017 than ever before. Nuclear power plants produce no greenhouse gas emissions during operation and, over their life cycle, emit roughly the same amount of carbon dioxide equivalent per unit of electricity as wind and one-third as much as solar. Thanks to its reliability and scalability, nuclear power can directly replace fossil fuel plants, eliminating the need for fossil fuel combustion in electricity generation. Today, the use of nuclear energy prevents emissions equivalent to removing one-third of all cars from the world's roads and this solution could be amplified (World Nuclear Association, 2023). Energetically speaking, one of the states that is doing well under this aspect is France. France in 2022 was ranked second in total electricity production in Europe, having its first source of electrical energy generation in nuclear, set at 62%, followed by renewable energies at around 25%, and having just 13% of electricity production from burning fossil fuels (France - IEA, 2022). Another aspect of the increasing production of Electric Vehicles is the increasing demand of raw material to produce battery components. In fact, it is crucial to plan for proper management when batteries will reach their end-of-life. Studies about a forecast on how the EV batteries will be treated yearly up to 2050 have defined four different scenarios, considering a combination of future EV sales and the service lifetime of EV batteries. The results indicate that the amount of end-of-life EV batteries could increase up to 72 times by 2040. Measures to ensure their optimal use, either as secondary energy storage equipment or for optimal material recovery, need to be implemented. Reusing these batteries in a second life could provide between 700 kWh and 35 MWh of storage capacity by 2050. As more EV batteries enter the market, the availability of secondary materials will increase significantly. By 2050, secondary materials from EV batteries could potentially supply up to 80% of cobalt, copper, and nickel, and 60% of lithium (Sanclemente Crespo et al., 2022).

In the debate on phasing out traditional engines by 2030 the e-fuels come into play as an alternative to EVs. These are synthetic fuels produced from water and atmospheric CO_2 by a process known as electro-synthesis. Historically, the push for this type of fuel was born for the lack of raw material: it was so for Nazi Germany that had a deficiency in oil, but had large reserves of coal, produced synthetic fuels in the 1940s to cover 92% of aeronautical needs and 50% of land-use vehicles during World War II (Department of Energy, 2008). For producing the electro fuels, an electrolysis process it is involved to obtain hydrogen from water. The successive reaction of electro-synthesis with carbon, obtained from atmospheric CO_2, allows to obtain hydrocarbons with chains of various lengths: from simpler molecules, such as methane gas, to liquid mixtures of compounds such as hexane or butanol, can be used as fuel often without any special modifications to existing engines. Anyways, the high energy and economic cost of high temperature processes is among the main obstacles to the spread of biofuels (Balali & Stegen, 2021). It is equally important that the energy used is renewable to achieve the zero net emissions target. The most serious problem of e-fuel is another: any fuel, due to the high temperatures and pressures reached in combustion engines, leads to the production of other pollutants such as NO_x and particulate matter. E-fuels could therefore also be a public health problem, if used massively for vehicular traffic in urban centers or entire regions with poor air circulation, such as the Po Valley (Robbins et al., 2014). Another option also produced by electrolysis could be hydrogen. Hydrogen is a molecule that can be used as a fuel and compared to traditional fossil fuels, but it emits only water as a waste product instead of GHGs. The problem is that on Earth the simple molecule H_2 is not found. Hydrogen is almost always bound to other elements, such as oxygen or carbon. To have it in its simple form it must be separated from the rest of the compounds in which it is found, and to do so a massive quantity of energy is required and therefore a lot of money (U.S. Energy Information Administration (EIA), 2023). Unfortunately, electrification cannot give a complete answer to the demands of our society and the chances that it can do so in the following decades remain uncertain, especially in fields such as aviation. The risk that fossil fuels remain in use for a long time is real and strongly threatens the objectives of decarbonization. A mix of alternatives could be the right way to go, and the e-fuels, especially hydrogen, could play a significant role towards the path to zero emissions due to 2050.

4.4 Conclusive Advice

Since road emissions are a significant contributor to the total emissions of GHGs and major air pollutants, accurate estimation is essential for evaluating air pollution mitigation strategies. Emission models serve this purpose by providing emission factors based on the vehicle fleet composition, road type, and traffic activity. Installing stationary detectors is a cost-efficient method for collecting traffic activity data that can be adopted to every city in the world. Also, it would be useful to apply sensor data for dynamic, location-specific estimation of vehicle fleet composition in conjunction with the traffic estimator. Regarding Padua, future work implementing the advanced model can be done. The employment of the model requires more detailed data over a long-term period, a year or more, this could be possible by collecting it personally or finding more accurate sources. Another important key piece of information is the VKT esteem. National statistics are not enough to apply such an accurate method, a deeper look to the city subdivision and its average distance travelled from the entrance point could be considered. Anyways, the basic model has been satisfying even with its low accurate variables, since results were generally close to real life data.

This work's objective is to quantify the emissions that vehicles release in the atmosphere by calculating it in first person and making sure the model is valid by comparison approaches. Addressing to Europe's 2050 goals, the best practical solution for the road transport sector is a mixed transition to Electric Vehicles and non-pollutant e-fuels, both relying on a clean electrical network by using renewable, nuclear and sustainable energy. UN's Sustainable Development Goals are supposed to be delivered by 2030, the world has just passed halftime for its promises, but it is nowhere near halfway. Changes are needed immediately, and the expectation is that this work is somehow beneficial to policymaker's decisions who are still exploring the most effective way to reduce GHG emissions. Finally, in my opinion, other than encouraging to use more public transport means, the most effective way to severely reduce emissions is to enhance incentives for EVs to achieve cost parity with ICEVs due to their high initial price and, additionally, the price of electricity is a crucial factor in the cost per mile for EVs, because any significant increase in electricity prices would reduce the EV's advantage. Therefore, policymakers need to explore cheaper and more reliable renewable energy sources to make electricity more affordable than it is.

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