Article

Transportation and Air Quality. Perspectives and Projections in a Mediterranean Country. The Case of Greece.

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Abstract: This study provides a thorough review and analysis of the evolution of the Greek vehicle fleet over the last ~30 years, which is next used for the generation of high granularity fleet projections and for the estimation of relevant environmental benefits by 2030. The integrated methodology developed takes also into account vehicle clustering and the Brown's Double Simple Exponential Smoothing technique that together with the adoption of COPERT based emission factors allow for the estimation of the anticipated emissions in 2030. Expected 2030 emissions levels suggest a reduction across all pollutants in comparison to 2018, ranging from 3.7% for PM_{10} to 54.5% for NMVOC (and 46% for CO, 14% for SO_2, 28% for NO_X and 21% for CO_2). We find that Greece is on track with national goals concerning the reduction of air pollution from the transportation sector, stressing the positive contribution of EVs and new, "greener" vehicles, and setting new challenges for the further improvement of the sector beyond the 2030 outlook.

Keywords: Air pollution, transportation policy, vehicle fleet projections, electric vehicles, Exponential Smoothing, Greece

1. Introduction

The transportation sector is responsible for a significant share of air pollutant emissions including those contributing to global warming and others affecting human health, with systematic exposure to even low level pollution concentration being found to lead to chronic disease and early death [1]. Although technology advancements and overall progress in the field of modern vehicles have contributed considerably towards efficiency improvement and thus emission reduction, the transportation sector in Europe still carries a significant share of the overall GHGs emissions, in the order of 20% [2]. Despite the fact that the sector produces lower quantity of certain pollutants when compared to other sectors, impact is higher since pollution is largely concentrated in high population density urban centres [3]. Nonetheless this is the result of a vehicle use factor limited in the order of 5%, since vehicles remain idle (parked) for approximately 95% of the time [4,5].

Owing to the COVID-19 pandemic, travel behaviour and patterns have changed dramatically, with use of public transport presenting an important decrease globally [6]. In Greece for example, there is a reduction of buses and subway use in the order of 30% between 2020 and 2021 and for the months of September and October [7]. Even though overall mobility has been restricted, gradual recovery underway reflects on the higher use of private vehicles leading to heavy peak hours traffic and respective pollutions. In the meantime, driven primarily by developing countries, the global vehicle fleet grows steadily with projections suggesting that by 2038, vehicles around the world will have outnumbered 2.2 billions, compared with 1.31 billions in 2020 [8].

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In the meantime, a trend is recorded in southern Europe (Italy, Spain and Greece), according to which two-wheel vehicles gain market share. This might be explained by their lower procurement, maintenance and operation cost as well as their flexibility in heavy traffic driving. This comes down to an average ratio of ~100 motorcycles per 1000 city citizens for the above countries, which is higher that the corresponding figure for the rest of Europe. Besides, and according to [9] two-wheel vehicles could stand as one of the main solutions of the development of alternative transportation models and for tackling the problem of air pollution in urban centers. This may be supported with the establishment of appropriate incentives, as well as through information campaigns, already attempted in major cities like Barcelona, London and Vienna, where positive outcomes have already been noted, [9].

Moreover, heavy traffic results to increased fuel consumption and air pollution from internal combustion vehicles, with an immediate impact on other aspects of everyday life such as with the reduction of productive time for vehicle drivers [10]. Such impacts are further aggravated by the fact that road networks in metropolitan cities, like Athens in Greece, are congested to a large extent. Therefore, effective congestion management requires extensive use of public transport and pollution emissions can be reduced with the "immediate" introduction of zero-emission vehicles for private and public use. Nevertheless, in terms of policies and their implementation, transition is complex, with a series of emerging societal implications.

Indeed, private vehicle ownership and use as a way of living has been highly valued societally [11] in contrast to aspects of sustainable development and living quality [12] in urban ecosystems. Recent studies however [13], indicate that concerns are growing with regards to issues such as the development of green urban settings and environmental justice, against the direction of expanding road networks and private vehicle use.

Alongside the above, the transport sector is undergoing a significant transformation with technological trends such as electrification, autonomous vehicles and micro-mobility vehicles. Therefore, the need for an in-depth study of the sector, its growth and quality trends particularly with a focus on private vehicles is essential to inform effective planning. On top of that, the association between atmospheric pollution and the transportation sector is of increased research interest over the last decades, with the relevant body of literature constantly evolving and providing a wealth of data, methodologies and models both at national and international level.

One such notable study was carried out for Greece, capturing the period between 1992 and 2000 [14] and providing a detailed analysis of CO_2, CO, NO_X and NMVOC evolution, on the basis of the COPERT methodology (Computer Program to calculate Emissions from Road Transport). The specific methodology, being the reference method in this field, was developed in the context of the CORINAIR program, under which consistent and transparent monitoring of emissions is conducted for the European regions since the 1980s [15]. In more detail, the study examined the relation between vehicle fleet growth, substitution of older vehicles with new -at the time- catalytic converter vehicles and the relevant changes in the generation of atmospheric pollutants. Results obtained from the study indicated considerable increase in emission levels between 1992 and 2000, specifically 68% in CO_2, 52% in CO, 28% in NO_X and 39% in NMVOC, which designated the largest (negative) effect of fleet expansion against the positive effect of introducing catalytic converter vehicles.

In a following study [16], it was shown that in 2000 the local transportation sector of the two major cities of Greece, i.e. Athens and Thessaloniki, was responsible for 70% and 50% of annual NO_X and NMVOC respectively. Next, in 2004, a national-scale program was launched by the Greek Government [17], to record in detail national emissions by sector and develop a dedicated database for the transportation sector, allowing for further categorization per different type of vehicle. Simultaneously, with the support of the European Monitoring and Evaluation Programme (EMEP), a spatial analysis of human and nature induced pollution has been conducted [18], designating the significant contribution of the transportation sector. Specifically for the prefecture of Attica and for Athens, a further study [19] used a grid of $1x1km^2$, to show the role of the local transportation sector and its contribution to hazardous CO, NMVOC and NO_X emissions.

In the same context, the development of a computational system for the recording of human-induced air emissions in Greece is described in [20], where top down and bottom up approaches were applied, that together with GIS and SQL tools led to high frequency emission zone data for CO, NO_2, NO, SO_2, NH_3 and NMVOCs for 2003.

Subsequently, research conducted for Greece in 1990-2009 showed a gradual decline in transport induced air pollution [21]. At the same time, the study quantified the positive contribution of the local passenger vehicle fleet upgrade, illustrating the negative effects brought by older heavy-duty vehicles. The study underlined the criticality of vehicle engine powertrain specificities and called for the development of programs for the upgrade of existing vehicle fleets. In a relevant study from the same authors [22], the same period, the COPERT IV methodology was adopted, together with a top-down approach, with results obtained showing a reduction in the quantities of CO, NO_X and PM_{10}. Next, using a similar methodology, i.e. the EMEP/CORINAIR and COPERT IV, the impact of introducing EURO5 and EURO6 vehicles was evaluated and associated with the relevant fuel consumption. Further use of the same methodology for the highly populated area of Attica (Athens) looked at a bundle of scenarios while involving more technical parameters such as the average vehicle speed, type of fuel, fleet evolution, size of engine, etc [23,24]. In this context, one of the main conclusions reached was that the prefecture of Attica is responsible for a high share of national emissions for CO, NO_X, $PM_{2.5}$, VOCs and NMVOCs and also comprises the second most important regional source of PM_{10} emissions.

At international level, the transportation sector is found to have a significant contribution to air pollution, and is often found to be the main source of NO_X and PM_X emissions [25]. Indicatively, in studies concerning Beijing [26], the COPERT III methodology was used, with results demonstrating transportation's role in urban emissions. Through the adoption of a bottom-up approach similar conclusions were drawn for Shanghai, where the transportation sector is considered to be the main driver of pollution, with further results yielding that 20% of emissions derive from vehicles' cold starts [27]. In India at the same time [28], heavy-duty vehicles, buses and the numerous two-wheel vehicles comprising the local fleet lead to an outstanding 94.5% of the overall CO_2 emissions at the national scale. Moreover, even in islands where stationary air pollution sources might be prevalent [29] it is particularly older vehicles that are the main source of CO, NO_X, SO_2, PM_{10}, CH_4, NMVOC and also CO_2 [30].

The present study contributes to the body of literature on transport emissions by providing new insights for the Greek transportation sector, focusing on the previous and forthcoming decade. Specifically, this study.

- Analyzes and provides a taxonomy for passenger vehicle fleet data for Greece during 1990-2018.
- Produces forecasting results for the Greek passenger vehicle fleet in 2030 opening up a granular approach to vehicle mix insights.
- Generates annual emission factors for major air pollutants and CO_2 up to 2030 deriving from each taxonomized passenger vehicle subcategory, enabling scenario building for policy making.
- Estimates annual air pollution and CO_2 emissions up to 2030 for each taxonomized passenger vehicle subcategory.

Following this brief introduction, this manuscript continues with section 2 that focuses on materials and methods used in this study. Subsequently section 3 presents the results through a wealth of figures and tables. Section 4 discusses the results and their broader implications and finally section 5 provides the concluding remarks.

2. Materials and Methods

2.1. Mapping and Recording of Active Fleet

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The current study deals with the mapping of the total vehicle fleet in Greece from 1990 to 2030. As mentioned before, many studies intertemporally assess the Greek vehicle fleet, calculating and predicting its evolution, documenting the derived pollution, while also attempting to predict relevant future developments. In all respects, the main challenge is in reliable data collection, regarding the vehicle fleet and its characteristics. Concerning a country's fleet size, it is necessary to quantify all existing vehicles in circulation, all brand-new vehicles that are under sale through dealerships, all vehicles (brand-new or second hand) imported by individual traders or purchasers and finally all withdrawn vehicles (for various reasons such as aging, damage, stealing etc.). Therefore, the most important characteristics concerning a fleet are each vehicle's: type and size, segment, age, fuel type, engine technology according to European standards (Euro 1 to 6) classification, engine displacement and the annual mileage each vehicle travels.

For the case of Greece, data collection related to the vehicle fleet was accomplished by gathering information from the official competent bodies and via Government reports, for the period between 1990 and 2019. More specifically, the official data sources used in this study, correspond to the Ministry of Infrastructure and Transport [31], the Hellenic Statistical Authority [32], the European Commission's Mobility and Transport Publications [33], the European Automobile Manufacturers Association [34–37], the Hellenic Association of Motor Vehicle Importers-Representatives [38], Emisia Company (a spin-off company of the Aristotle University of Thessaloniki that uses COPERT, the EU standard vehicle emissions calculator in Greece [39]) and the CO_2 Data Bank of the European Environment Agency [40].

Following the processing of the collected data, the total fleet of vehicles for the year 2019 is briefly presented, with specific data for the case of Greece in relation to the average EU vehicle fleet:

- The total EU passenger car fleet exceeds 242.7 million and has an average age of 11.5 years old, while the growing trend of the fleet continues with a rise of 1.8% compared to 2018. Alternative drive cars (Hybrid, LPG, Natural Gas, all types of electric cars) are just 4.6% of the total EU car fleet. The oldest vehicle fleets are in Lithuania (16.8 years old), Estonia (16.7 years old), Romania (16.5 years old) while Greece stands at the 4th place (16 years old) with a total vehicle fleet of more than 6.4 million vehicles.
- The average vehicle ownership in the EU (motorization rates) corresponds to 569 cars per 1000 inhabitants, with Latvia having the lowest density (342 per 1000 inhabitants), Luxembourg having the highest (694 per 1000 inhabitants) and Greece presenting a ratio of 489 cars per 1000 inhabitants, practically 100 less than in 2018.
- 52.9% of all passenger cars in the EU use gasoline while 42.3% use diesel. Another 0.8% are hybrid electric, 0.2% are exclusively electric, 0.2% are plug-in hybrids and finally, the remaining 3.6 % use natural gas, LPG, etc. Greece with more than 5.2 million passenger cars, differs significantly from any other country, having the highest share (91.1%) in gasoline usage among all EU countries and the lowest share of diesel usage (8.1%), while the share of electric vehicles (all types) is at the level of 0.5%.
- There are more than 6.2 million medium and heavy-duty trucks in the EU, with an average age of 13 years. Notably, the oldest fleet operates in Greece, which demonstrates an average age of more than 21.2 years. Only 0.04% of all trucks in the EU have zero emissions, 97.8% run on diesel and 1.3% on gasoline.
- The light commercial vehicles sector exceeds 28 million trucks with an average age of 11.6 years, with 90% using diesel and only 0.3% being electric. Again, the oldest fleet operates in Greece, with an average age of 19.5 years.
- Finally, the bus sector operating across the EU numbers 692,207 vehicles, with an average age of 11.7 years. A large percentage, in the order of 94.5% rely on diesel fuel, while it is only 0.6% that are electric, with the oldest EU bus fleet operating in Greece, with an average age of 19.9 years.

Consequently, it is a fact that Greece carries particular features regarding the total fleet of vehicles (more than 8.4 million vehicles) and also presents noticeable differences compared to any other EU country. Concerning large vehicles, Greece has the oldest fleet.

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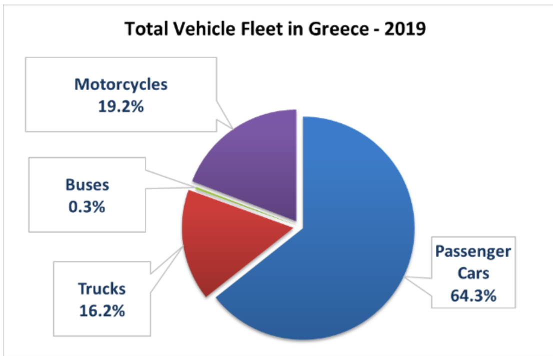
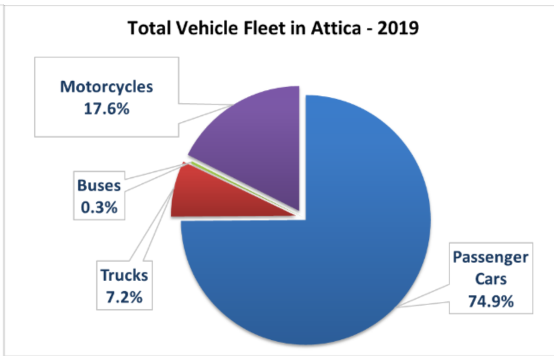
Moreover, as already mentioned, the country's passenger car fleet is the 4th oldest, and uses mostly gasoline. To that end, Attica is the most populous prefecture of Greece, including also the city of Athens, i.e. Greece's capital. Figure 1 represents the main categories of the vehicle fleet mix regarding both Greece and Attica. As one may see, motorcycles account for about 19% of the fleet (17.6% for Attica), while it is more than 64% (almost 75% for Attica) that corresponds to passenger vehicles, which also comprise the main focus of this study.



(a)



(b)

Figure 1. Total vehicle fleet mix for Greece (a) and Attica (b) for 2019.

Figure 2 demonstrates that Attica's vehicle fleet has reached almost 48% over the respective total, with almost 4 million vehicles. Taking into consideration the aggregate of vehicles (approx. 0.8 million) in Thessaloniki, which stands as the second largest city of Greece, it is obvious that these two urban centers define the general composition of the vehicle fleet, representing more than half of the country.

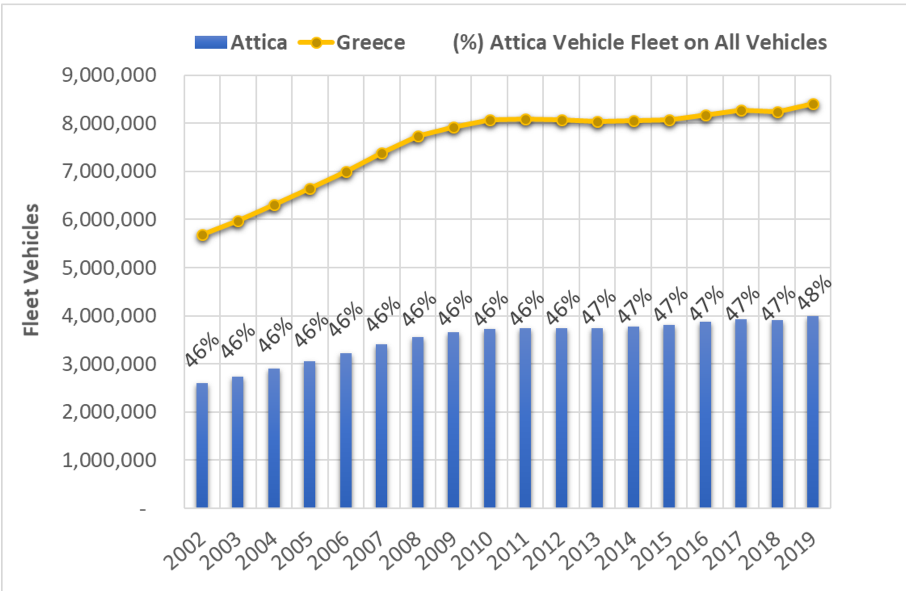


Figure 2. Total fleet of circulating vehicles in Greece and in Attica, for time-period 2002 to 2019.

Finally, as it derives from Figure 3, it appears that in recent years, the regional share of passenger vehicles in Greece remains almost constant. In particular, Attica's passenger vehicle fleet has clearly the largest share. More specifically, the category of passenger vehicles constitutes 73.9% of the total number in Attica, 53.5% of the total number of passenger vehicles in the country and 34.4% of the total number of all country's vehicles. Therefore, and since passenger vehicles hold the largest share, it is the given category the specific study focuses on. At the same time, it becomes clear that any changes in the use of passenger vehicles that take place in Attica, essentially affect the majority of the fleet throughout the country.

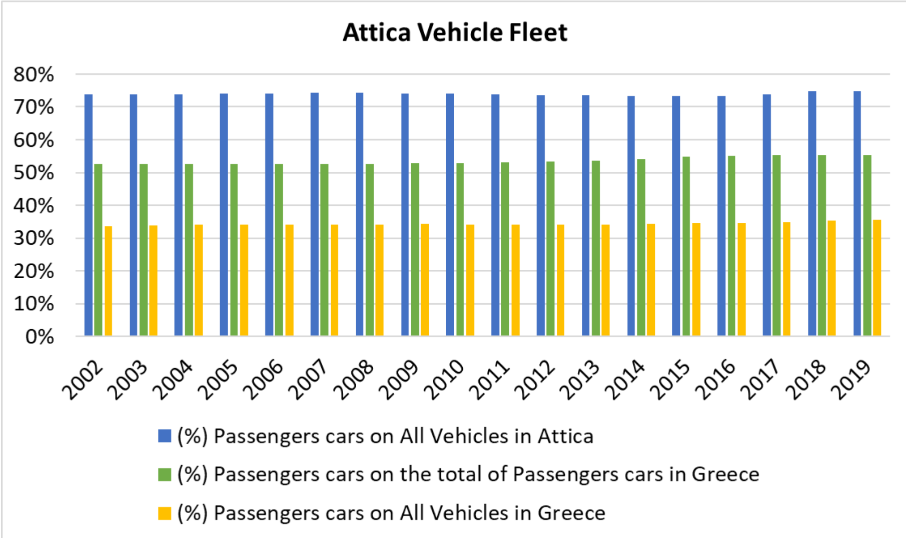


Figure 3. Percentage ratio of passenger vehicles in Attica, to the total number of vehicles in Attica, Greece and passenger vehicles in Greece.

2.2. Models for the Estimation of Transportation Sector Pollutants

The main categories of models for the estimation of air emissions relating to the transportation sector include static (Top-Down) models and dynamic (Bottom-Up) models [41]. Both categories are used for the estimation of air emissions and for the management of atmospheric pollution in the transportation sector, under different scenarios and spatial scales.

Static models are next divided in two sub-categories corresponding to average speed models, like VEPM [42] and aggregated emission factor models like NAEI and MOBILE [43]. They are considered to be appropriate for the estimation of pollutants at broader scale, e.g. at national or city level, and they normally use emission factors per different fuel and pollutant together with average distance driven. They lack however, in terms of spatial analysis and are considered to be more effective for short period estimations.

Dynamic models are also divided in two sub-categories corresponding to traffic situation models, like HBEFA, ARTEMIS, COPERT and instantaneous models, like PHEM and MOVES [44,45]. They depend on the volume of data available and they account for more parameters like type of vehicle, vehicle speed, traffic conditions, hot /cold engine start, engine efficiency degradation in the course of time, etc. Moreover, in addition to their ability to provide long-term evaluations, they can also perform efficiently in short-distance and small-scale area problems.

In this context, the model that stands out is the COPERT model, which comprises a well-advanced, modern and widely used model amongst reference models used across the EU, with its early development dating back to the 80's [46,47], currently being in its 5th iteration [39]. Concerning pollution estimation, three different methods are used, associating with emission factors or fuel consumption or the percentage of the overall emissions, depending on the examined pollutants and the data available [48], and taking into account numerous parameters.

2.3. Vehicle Fleet Forecasting Scenarios

Rapid technological developments, including to the field of vehicles, make forecasting inherently challenging. Research agenda and political discourse on the most promising low emission vehicle engines are challenging [49]. At the same time, most technology development scenarios forecast that until 2030 hybrid vehicles will present the higher demand, followed by fully electric vehicles, conventional fuel vehicles and fuel cell vehicles

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[50]. What matters most however, is that the growth of electric vehicles is followed by an increasingly "cleaner" electricity grid [51]. The Greek National Energy and Climate Plan foresees that by 2030, one out of three new vehicles will be electric in a fleet of approximately 5.5m vehicles [52]. The forecasting approach adopted is based on the following basic steps [53]:

- Data collection and analysis: Requires data collection from cross-checked records and data cleaning for gaps and errors.
- Evaluation of demand parameters: Includes the identification and evaluation of internal and external parameters that might have a material impact to demand. Consideration will be given to technological development, political directives, affordability and others.
- Time horizon: Focus on near-term, mid-term and long-term demand forecasting.
- Forecasting evaluation: Forecasting scenarios will be evaluated as they are developed.

In addition, and in terms of scenarios' formulation, it is always important that the scenarios created may both be broad enough and be able to capture long-term trends in an effort to provide accurate forecasts. [54]. The Greek Government to that end simulates the transport sector with software such as LEAP [55] and methods such as COPERT, focusing primarily on the vehicle fleet mix. As a result, the initial markets conditions and the time of new vehicle sales define to a significant extent the modelling results [56]. A relevant step by step approach that has been proposed by [39,57], is shown in Figure 4.

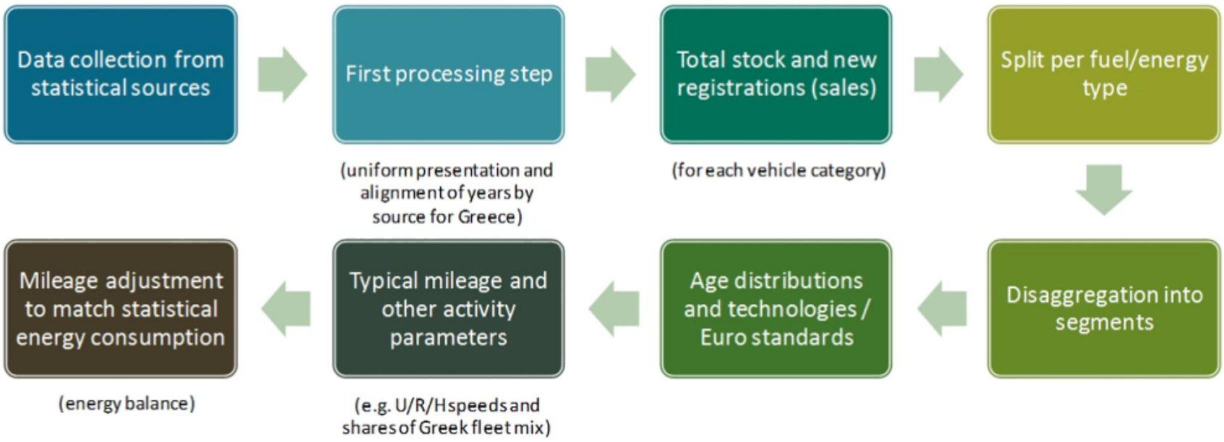

Figure 4. Vehicle fleet scenario development method [57].

Next, forecasting methods broadly fall into two categories [58,59]:

(a) Qualitative forecasting methods such as Delphi, Market Research, Consensus Methodς, Visionary Forecast Prediction and Historical Analogy.

(b) Quantitative forecasting methods based on historical data with time series forecasting or causal models such as Multiple Regression Analysis, Econometric Models, Input-output Model, Economic Input-output Model and Leading Indicator Analysis.

Forecasting the vehicle fleet size to 2030 in the current study is based on the application of the Brown's Double Simple Exponential Smoothing method [60]. Data includes timeseries of vehicle type, fuel type and EURO standards between 1990-2018. Time series smoothing is employed twice and takes into account the relevant trends, while Brown's method has been previously used successfully in vehicle fleet forecasting and air pollution studies [61–63]. Application is initially based on quantitative historical data concerning the size and type of vehicle fleet and subsequently the forecasting of each of the fleet subcategories.

Therefore, Brown's Double Simple Exponential Smoothing method has been applied for each one of the 28 different vehicle subcategories characterized by fuel type and standardization (Petrol (Prev Euro, Euro 1÷6), Diesel (Prev Euro, Euro 1÷6), Dual Fuel (Prev Euro, Euro 1÷6), Alternative Fuel (Euro 4÷6), PHEV/Plug in Hybrid Electric Vehicles (Euro 5÷6) and BEV/Battery Electric Vehicles (Euro 5÷6). Prev Euro category refers to older vehicles preceding the introduction of Euro categorisation. Subsequently, every few years the new vehicles added in the fleet comply with the Euro 1, 2, ..6 standard in force, hence delivering significant emission control improvements.

For every vehicle category time series, the Simple Exponential Smoothing method (equation 1) is applied as:

$$V_t = \alpha \cdot Y_t + (1-\alpha) \cdot V_{t-1}, \tag{1}$$

where:

V_t = smoothened time series values V_t. For $V_0=Y_0$ smoothened state of the time series estimates.

α = data smoothing factor for values $0 \leq \alpha \leq 1$; Smoothing weight for the level of the time series, is estimated with MS Excel solver.

t = time quantity as an annum, for t=1 assume $Y_1=V_1$ and subsequently t = 2, 3, …, n.

Y_t = the observed value at time.

Subsequently, the smoothened time series values V'_t are estimated with equation (2):

$$V'_t = \alpha \cdot V_t + (1-\alpha) \cdot V'_{t-1}, \tag{2}$$

where:

V'_t = the smoothed values of the time series resulting from the application of the second smoothing.

The forecast beyond $F_{i,t+m}$, for every i category (i= petrol, diesel, dual fuel, alternative, PHEV, BEV), at m future time (m = 1, 2 , 3…, n) is given by equation (3):

$$F_{i,t+m} = \alpha_t + m \cdot b_t, \tag{3}$$

where:

$F_{i,t+m}$ = vehicle fleet i forecast for year t and every future time period m.

α_t = the estimated level at time t, $\alpha_t = 2 \cdot V_t - V'_t$.

b_t = the estimated trend at time t, $b_t = \frac{\alpha}{1-\alpha} \cdot (V_t - V'_t)$.

3. Results

3.1. Forecasting of the Vehicle Fleet

In Figure 5, the authors present actual data concerning the fleet size of petrol-powered passenger vehicles up to 2018, and forecasted data, for each vehicle category, with a prediction horizon that extends up to 2030. A gradual reduction in the number of older vehicles is anticipated, alongside a small increase in vehicles of the most recent Euro category. Remarkably, Greece is the only EU country with such large share (91,1%) of petrol-powered vehicles. In absolute numbers, the petrol fleet size peaked during 2010, approaching a total of 5 million cars. Thereafter, that increasing trend has stalled with the number of vehicles going down due to the economic crisis, in late 2009, while many consumers considered buying vehicles that utilize a different fuel type than petrol. The sales of new petrol-powered vehicles are expected to face a large reduction by and after 2025, with significant parts of the fleet being replaced by vehicles that are based on more environmentally friendly technologies. The structure of Greece's fleet is largely affected by the economic crisis. The recession was deep and lasted way longer than that observed in other EU States. Greek households were confronted with significant reduction of their disposable income [64], hence replacing a vehicle became the lowest priority. The total number of passenger vehicles is illustrated with the red dotted line (Figure 5). The upcoming years, the fleet size is expected to increase, matching the trends of EU-28. The latter average number of passenger vehicles per capita faced a significant increase during the most recent years, a momentum that is not expected to conclude before 2035 [65].

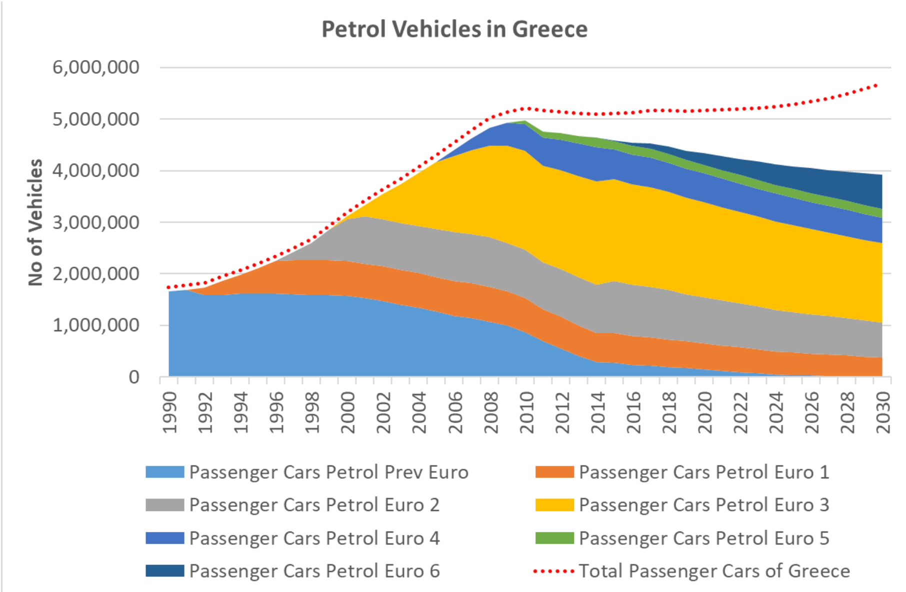

Figure 5. Time-evolution of the fleet size of petrol-powered vehicles and total passenger vehicles in Greece, 1990-2030.

In Figure 6, the fleet size of diesel-powered vehicles is presented. The fleet size is significantly smaller in comparison to the corresponding petrol-powered fleet. However, it comprises vehicles of newer technology, i.e. Euro 5 and Euro 6. The cause of dominance of these 2 categories stems from restrictions for private use of diesel-powered vehicles in Athens and Thessaloniki, the 2 largest cities of Greece. The ban was lifted by the end of 2011, for Euro 5 vehicles and newer.

By 2011, the technology progressed significantly (with Euro5 vehicles), resulting in low diesel engine capacities, while, at the same time featuring similar performance characteristics with petrol-powered engines. In fact, according to the official technical characteristics, by the time, diesel-powered vehicles are more frugal and more environmentally friendly than petrol equivalent vehicles. A claim that proved false (diesel gate scandal), by official reports. In particular, there were many occasions identified, where conducted measurements recorded much higher emissions of pollutants than those reported by the automotive industry [66].

In either case, with respect to previous technologies, the vehicles performed better in almost every aspect. At the same time, diesel-powered vehicles were promoted by the industry and the EU, and gained significant market share [67]. That is the case, after 2009, and that is the reason behind the significant fleet size growth becoming eminent after 2016. In absolute numbers, diesel vehicles peaked by 2019. Thereafter, the fleet size has been continuously decreasing. Given the international trend, which is against the use of diesel-powered vehicles, and that exhaust gasses are subject to increasingly stringent rules, many manufacturers have already stopped importing diesel vehicles in Greece. In the near future, the diesel vehicle fleet market will face a tremendous reduction, with newest vehicles numbers expected to maintain relatively steady. Also, since that type of vehicles are mainly preferred by users that prioritize fuel economy, it is most likely that they will choose hybrid, electric or dual-fuel vehicles.

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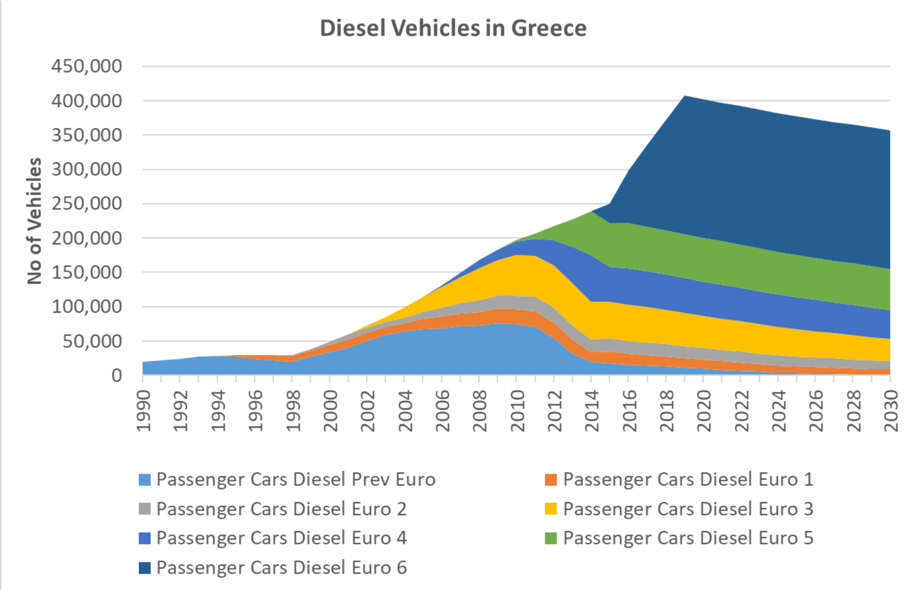

Figure 6. Time-evolution of the fleet size of diesel-powered vehicles in Greece, 1990-2030.

In Figure 7, authors present the time-evolution of the fleet size of dual fuel vehicles, which mainly comprises previous and recent generation vehicles that exploit LPG and natural gas as energy resource. Besides, LPG or natural gas, for the most part, these vehicles utilize also petrol. In Greece, this category was not very popular, until 2010. The main reason for that was the limited natural gas and LPG distribution network, which was accompanied by legal restrictions.

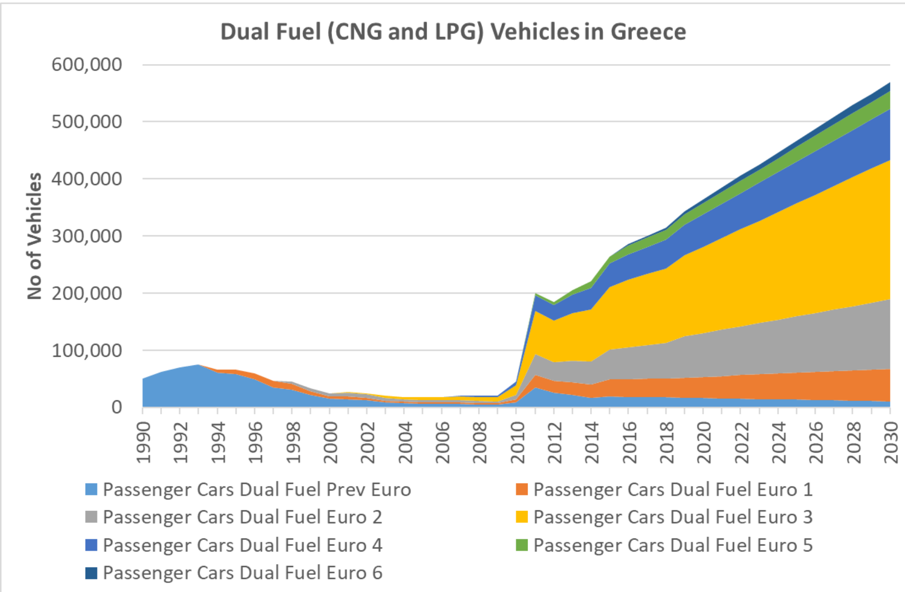

Figure 7. Time-evolution of the fleet size of dual fuel vehicles in Greece, 1990-2030.

Nowadays, there is strong interest in dual fuel vehicles, with newest generations considered a more environmentally friendly option compared to conventional petrol or diesel-powered vehicles. Dual fuel vehicles are chosen by high mileage drivers as fuel cost has been notably cheaper. A large share of owners of older or new generation petrol-powered vehicles chose to convert their vehicle, in order to take advantage of the cheap LPG and reduced maintenance. There is also a large share of imported dual fuel vehicles by neighboring countries, explaining the upward trend, even for older vehicles. Despite the increasing vehicle numbers, the fleet size remains quite small.

In Figure 8, the time evolution of alternative vehicles, PHEV (Plug in Electric Vehicles) and BEV (Battery Electric Vehicles) is presented. The alternative category consists of hybrid vehicles which for the most part utilize petrol and for the least part biofuels. Before 2015, the number of Euro 4 and Euro 5 (since 2000 and 2010 respectively) hybrid vehicles has been small and only started growing since 2015. Indicatively, in 2014, the total number of vehicles was only 6000. Therefore, the figure data start after 2015.

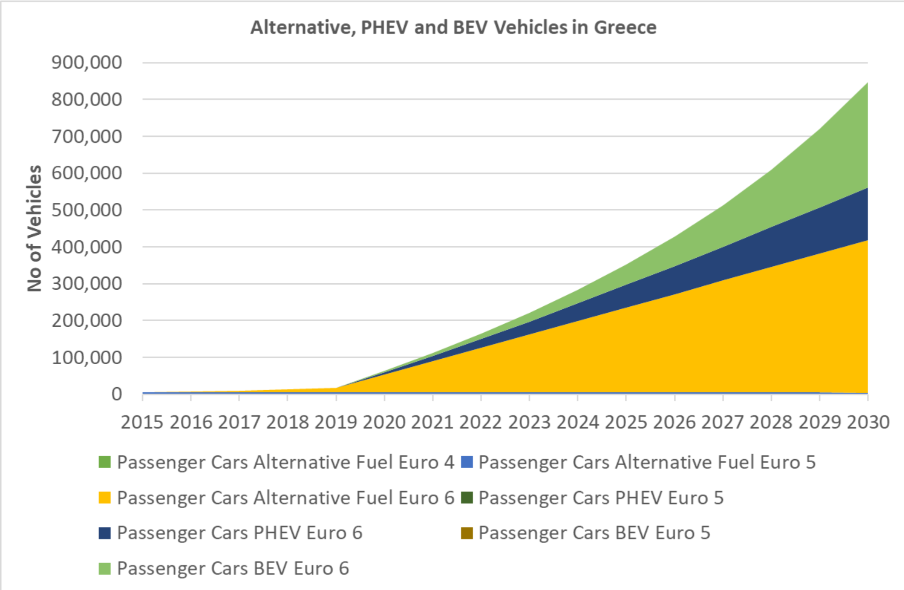

Figure 8. Time-evolution of the fleet size of alternative and electric passenger vehicles in Greece, until 2030.

This vehicle category is expected to face the largest growth, due to the rapid battery cost reduction allowing for larger battery packs and driving range. Currently, in Europe, there are attractive incentives for electric vehicles. The fleet size is expected to be as large as 850 thousand vehicles by 2030, with 49% belonging to the category of hybrid vehicles, 17% being PHEV, and almost 34% being BEV. With respect to the Greece's 2030 total fleet size, 14.9% will be hybrid, BEV and PHEV, with the latter two accounting for 7.5%.

Ultimately, the forecasted Greek passenger vehicle fleet size by 2030 shall approach 5.7 million units (Figure 9). The individual categories are grouped by fuel type, instead of technology of their power engine, allowing a more straightforward view. By 2030, the total vehicle fleet is expected to consist of petrol-powered vehicles by 68.8%, diesel-powered vehicles by 6.3%, dual fuel vehicles by 10%, hybrid vehicles by 7.3%, PHEV by 2.5% and BEV by 5.0%.

3.2. Prediction of Air Pollution Emissions

Following the passenger vehicle fleet forecasting, the air pollutant emissions are estimated. The detailed fleet data include pollution parameters based on engine displacement, vehicle type, on the fuel and year, from 1990 to 2018 and per specific pollutant. Further pollution data were obtained from the EMEP/CORINAIR methodology and the utilization of COPERT model as well as from the application of the Tier 3 methodological approach [68]. This data represents the official emissions of air pollutants from the transport sector in Greece. Hence, the base year regarding air pollutants prediction will be 2018.

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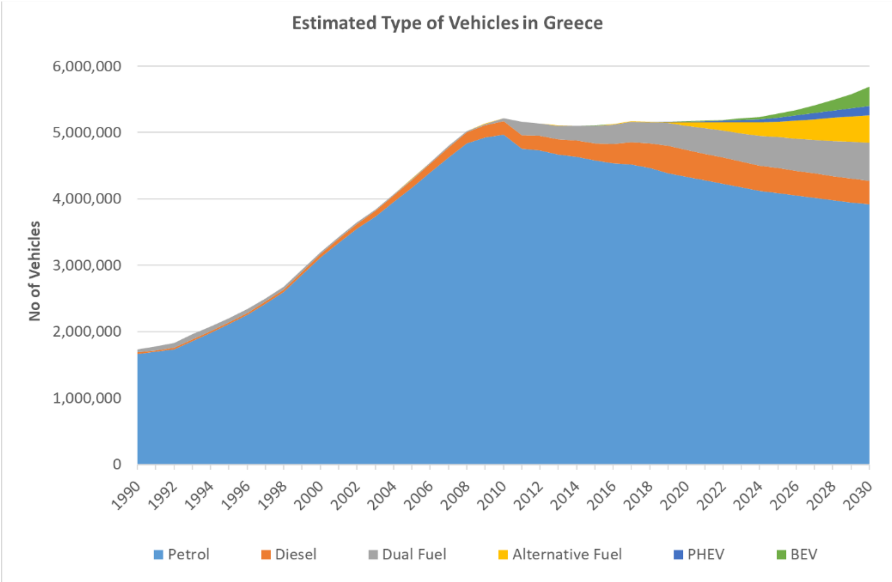

Figure 9. Number of passenger vehicles by fuel type in Greece, 1990-2030.

Subsequently, vehicles were grouped according to engine displacement and vehicle segment so that they are similar to the previous 28 vehicle categories by fuel type and by emission standards, such as Euro 1, 2, …6. The average air pollutant factors for every category were calculated in gr/km, according to the Tier 2 approach (COPERT) and were assumed to be fixed for future predictions. Nevertheless, new CO_2 emission targets were set for 2025 and 2030 [69,70], aiming to a 15% reduction for the period between 2021 and 2025 and by 37.5% for the period up to 2030. All calculations regarding new vehicles with Euro 6 emission standard will take into account the above-mentioned CO_2 reductions.

It should be stressed, that for the period between 1990 and 2018 the dataset includes information about the distance travelled by each vehicle subcategory. Therefore, the average distance travelled is calculated per category for each forecasted year, taking into account older categories' rate of change, the increased usage of new vehicles and the reduction trend of the distance travelled as vehicle fleet gets older. Below, Figure 10 presents the average annual distance travelled in Greece by passenger vehicles, which was produced by the average annual distance travelled by 28 different vehicle categories.

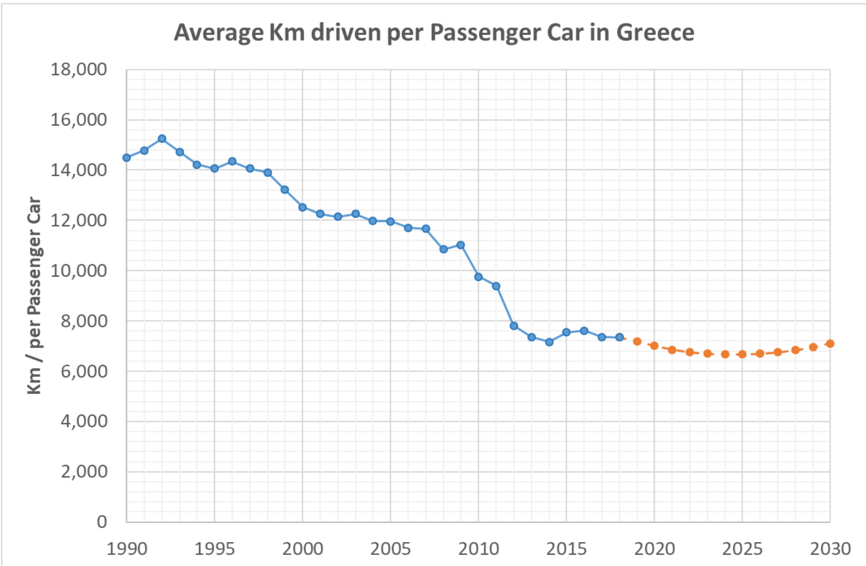

Figure 10. Average annual distance travelled (Km) in Greece by passenger vehicles, from 1990 to 2030.

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The mean value was calculated by dividing the sum of each category's mileage by the total vehicle number. More precisely, according to data of 2018 the average annual travelled distance of a passenger vehicle in Greece was 7348km, while in 2030 the same value is expected to be 7104km. Furthermore, vehicle use has decreased since 1990, mainly due to the public transportation's evolution, the financial crisis that led to sharp decrease in vehicle usage and the increase in fuel prices and because people start using light vehicles for small distances. It should be noted that more than 50% of passenger vehicles run primarily in Attica region, whilst since 2000, when the Athens subway, came into service passenger vehicle use has decreased. Concurrently, although the average mileage seems to decrease as vehicle fleet is ageing, after 2025, when older vehicles' replacement takes place and more vehicles are added to the total fleet, an increase in vehicle use is noted. That prediction reflects on reality since drivers tend to use new vehicles more, with electric vehicles presenting notably higher use factors.

Furthermore, pollution estimations were produced by the sum of each vehicle fleet category, by fuel and technology (28 categories), multiplied by the pollutant coefficient gr/km, as well as by the annual average distance travelled. In every figure depicted below, the darker color refers to data for the period between 1990 and 2018 and in lighter color is the forecasted emissions until 2030.

Figure 11 depicts the total CO emissions from passenger vehicles in Greece for the period 1990 to 2030. One may notice that from 1990 to 2018 there is a reduction of 92%, while from 1990 to 2030 CO emissions are expected to be reduced by 96%. At the same time, according to the estimations for the period between 2018 and 2030 a 46% reduction is expected. Moreover, in 2030 responsible for the 23.7kton of CO emitted are petrol vehicles by 73.9%, diesel vehicles by 2%, dual fuel vehicles by 8.9%, alternative fuel vehicles by 9.6% and PHEV by 5.6%, while BEVs have zero emissions.

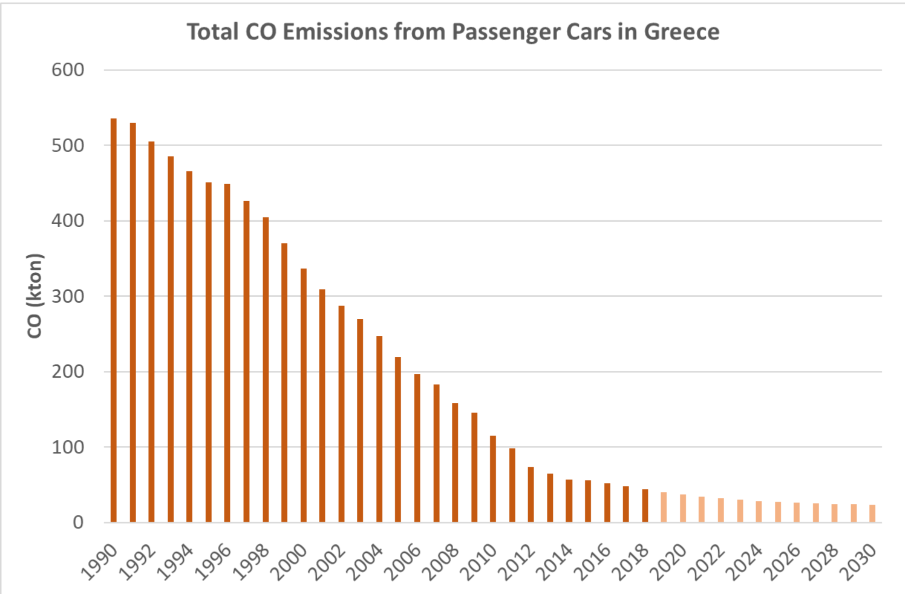

Figure 11. Total CO emissions from passenger cars in Greece for the period 1990-2030.

Figure 12 depicts the total SO_2 emissions from passenger vehicles in Greece for the period 1990-2030. It is noteworthy that the presented steps, picture the successful introduction of gradually lower sulphur diesel based on EU Directives. Action plan that had been implemented by Greek government, concerning strategies (primary anti-pollution measures at the refinery) to prevent pollution and, as a result reduced fuel sulphur levels in the fuel. For the period between 1990 and 2018, there is a decline in emissions of 99%, while until 2030 the corresponding emissions are expected to decrease by 99.2%. Meanwhile, from 2018 to 2030 a total mitigation of 14% is predicted. Finally, in 2030, from 30tons of SO_2 emitted into the atmosphere, 62.7% represents petrol vehicles, 17.2% diesel

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vehicles, 7.5% dual fuel vehicles, 12.6% alternative fuel vehicles and less than 1% PHEV, while BEVs have zero emissions.

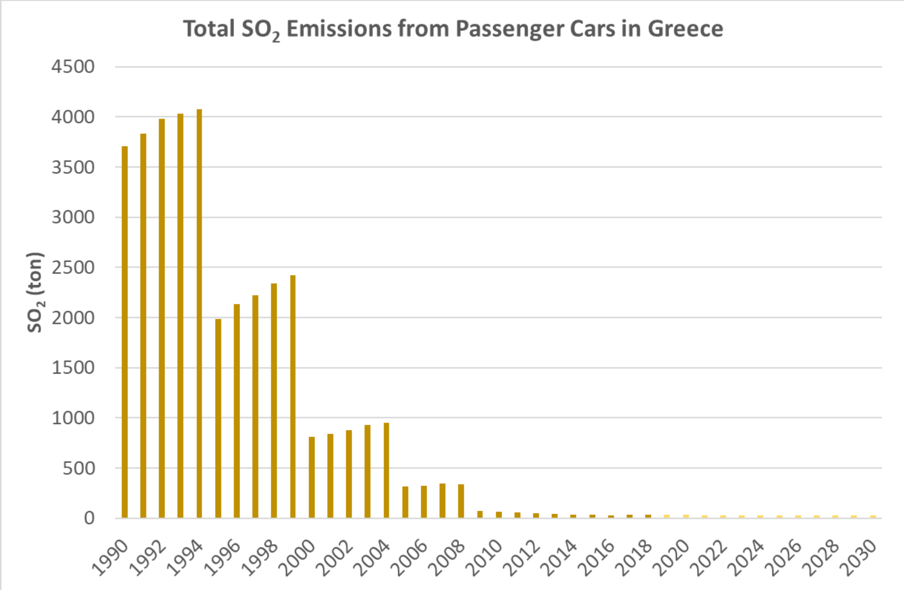

Figure 12. Total SO_2 emissions from passenger cars in Greece for the period 1990-2030.

By the same token, in Figure 13 the total NO_x emissions from passenger cars in Greece for the period 1990-2030 are presented. For the period between 1990 and 2018, there is an emission decline of more than 84%, while until 2030 the corresponding emissions are expected to decrease by almost 89%. Between 2018 and 2030 a total mitigation of 28% is expected.

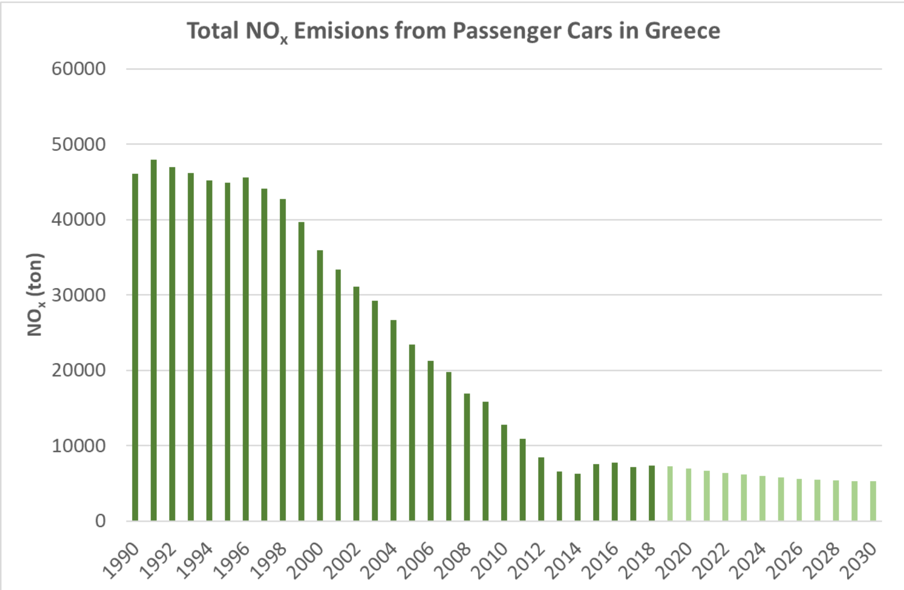

Figure 13. Total NO_x emissions from passenger cars in Greece for the period 1990-2030.

The contribution of diesel vehicles to NO_x emissions after 2014 is notable and is largely due to their growing market share. In 2030, 5.3kton of NO_x will be emitted, out of which 24.6% will be attributed to petrol vehicles, 67.1% to diesel vehicles, 3.1% to dual fuel vehicles, 3.9% to alternative fuel vehicles and 1.3% to PHEVs while BEVs have zero emissions.

Figure 14 depicts the total PM_{10} emissions from passenger cars in Greece for the period 1990-2030 including the non-exhaust PM_{10} (tyre - break wear, road abrasion). For the period between 1990 and 2018, there is an emission decline of more than 12%, while until

2030 the respective emissions are expected to be less than 15%. Concurrently, for the predicted period, a total PM_{10} mitigation of 3.7% is expected. Similar to Figure 13, a rise of PM_{10} is presented after 2014 due to increased market share of diesel vehicles. While a gradual PM_{10} reduction is observed, after 2025 the total PM_{10} emissions will increase as a consequence of the ever-increasing vehicle fleet. The above-mentioned observation is thoroughly explained in the discussion section. In 2030, out of the 1.03kton of PM_{10} emitted, 49.4% will have come from petrol vehicles, 20.4% from diesel vehicles, 5.0% from dual fuel vehicles, 15.7% from alternative fuel vehicles, 3.9% from PHEVs and 5,6% from BEVs.

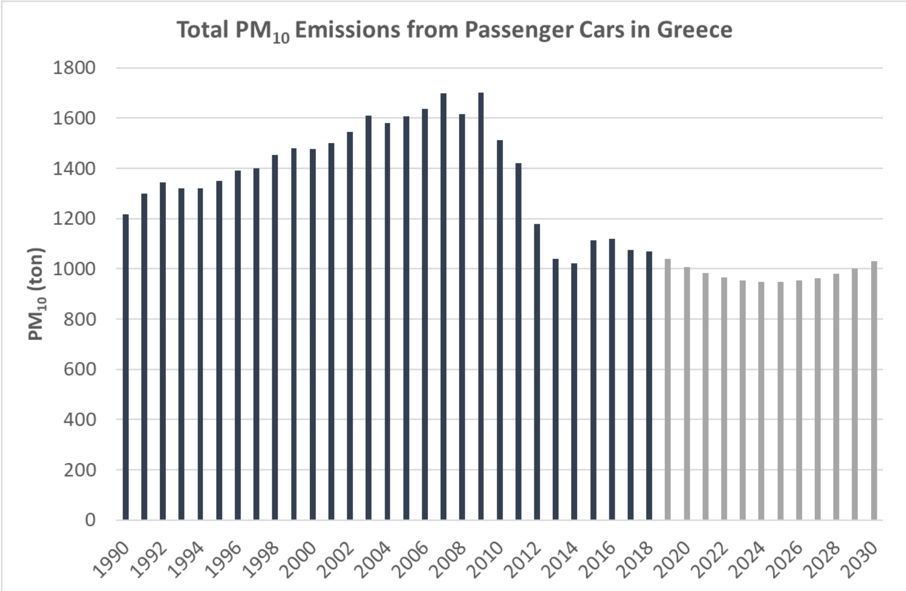

Figure 14. Total PM_{10} emissions from passenger cars in Greece for the period 1990-2030 including the non-exhaust PM_{10} (tyre - break wear, road abrasion).

Figure 15 presents the total NMVOC (Non-methane volatile organic compounds) emissions from passenger vehicles in Greece for the period 1990-2030. For the period between 1990 and 2018, there is an emission decline of more than 84%, while until 2030 the respective emissions are predicted to fall by 93%. Also, between 2018 and 2030 a total mitigation of 54.5% is expected. For as long as cleaner vehicles are increasingly introduced in the vehicle fleet, NMVOC emissions will continue to decrease. In 2030, out of the 4.75 kton of NMVOC emissions, 82% are expected to be from petrol vehicles, 0.6% from diesel vehicles, 4.0% from dual fuel vehicles, 13.4% from alternative fuel vehicles and less than 1% from PHEV, while BEVs shall carry zero emissions.

Figure 16 presents the total CO_2 emissions from passenger vehicles in Greece for the period 1990-2030. One may see the different pattern in relation with pollutants, since CO_2 emissions are strongly related to car fleet size. As the vehicles' number up to 2009 increased, so did the emissions. It is noteworthy, that after 2014, when vehicles' number started to climb, CO_2 emissions did not increase as sharply as expected, since new and more efficient-fuel diesel vehicles entered the market under the EU's strict regulations.

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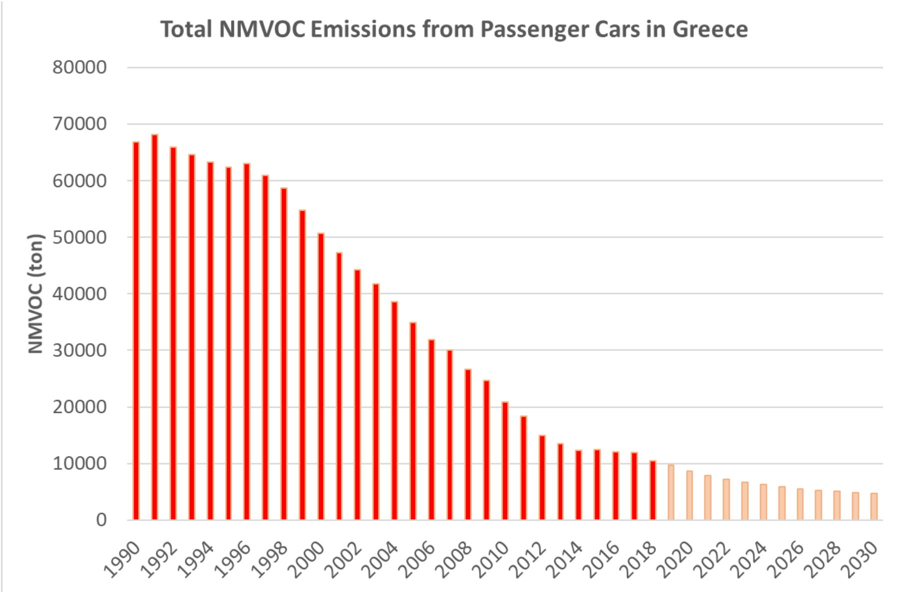

Figure 15. Total NMVOC (Non-methane volatile organic compounds) emissions from passenger cars in Greece for the period 1990-2030.

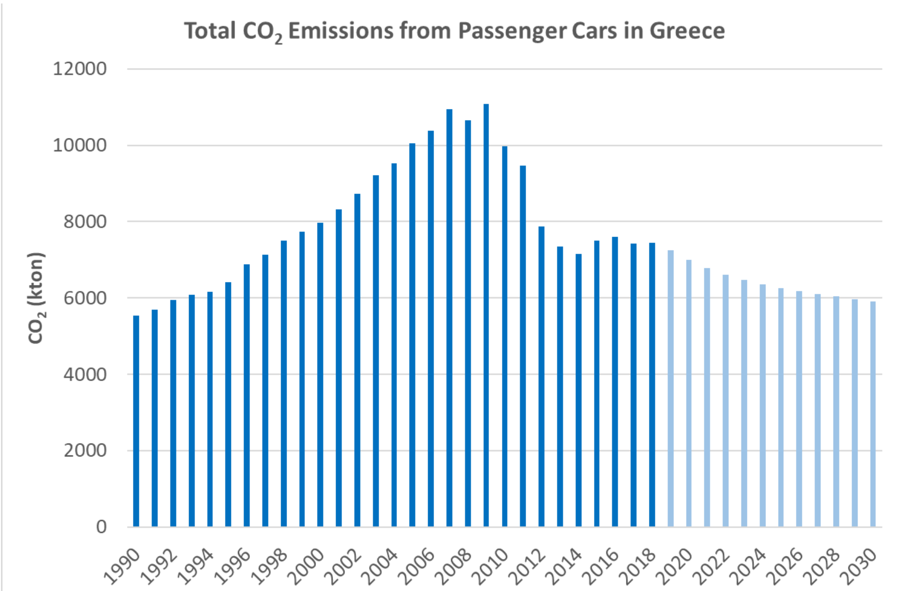

Figure 16. Total CO_2 emissions from passenger cars in Greece for the period 1990-2030.

For the period between 1990 and 2018, there is an emission climb of more than 34%, while until 2030 the respective emissions are predicted to be higher than 6%. Nevertheless, from 2018 to 2030 a total mitigation of 20.6% is expected, albeit vehicle fleet will only continue to increase. The above-mentioned observation is thoroughly explained in the discussion section. In 2030 almost 5.9kton of CO_2 will be emitted out of which 61.3% will be attributed to petrol vehicles, 20.4% to diesel vehicles, 5.6% to dual fuel vehicles, 10.6% to alternative fuel vehicles and 2.2% to PHEVs, while BEVs will have zero emissions.

Finally, in Figure 17 the average values of emitted air pollutants and CO_2 by vehicle, for the period 1990-2030 are presented. For each pollutant the value of kg per vehicle is calculated by dividing the sum of total emissions by the total vehicle number. Hence, it may be argued that in the course of time, mitigation of air pollution is closely linked to the replacement of all ICE vehicles with BEVs.

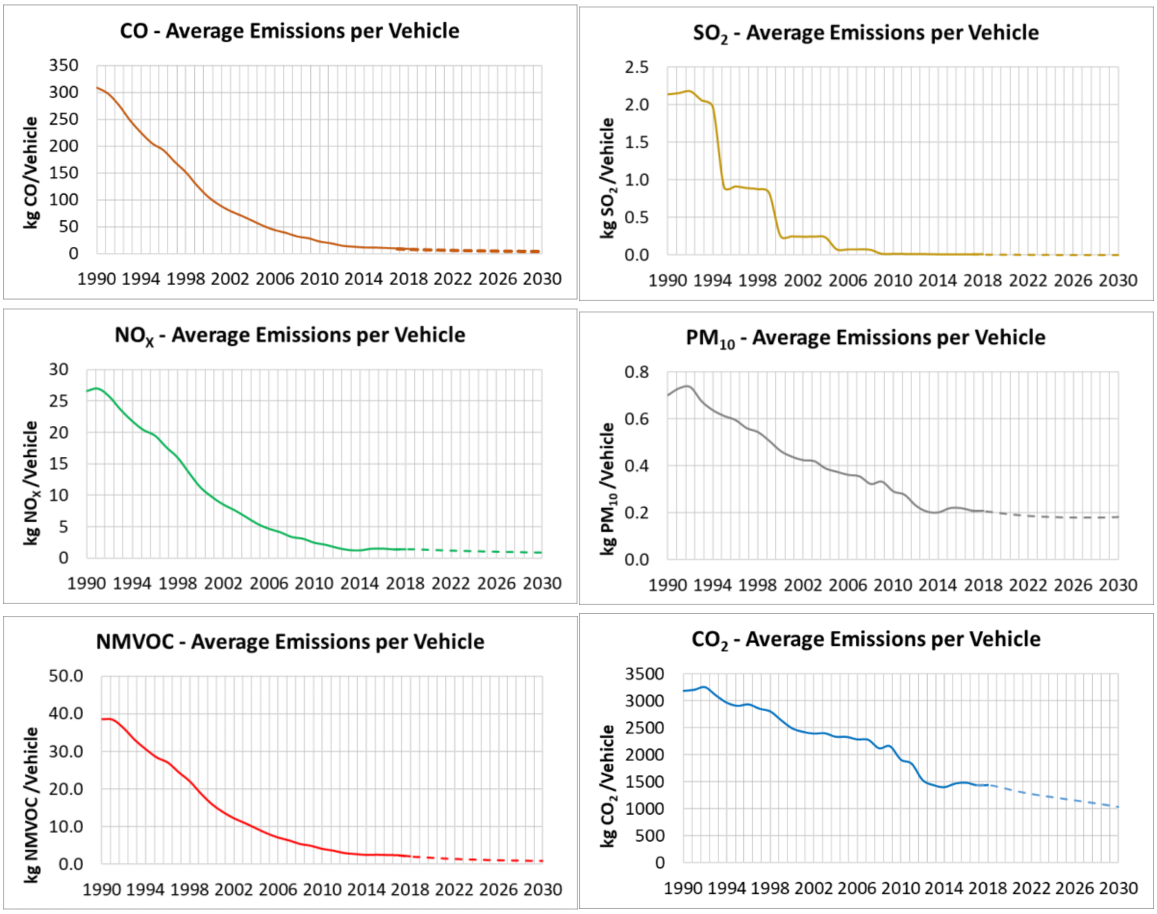

Figure 17. Average values of emitted air pollutants and CO_2 by vehicle, for the tested period between 1990 and 2030, in Greece.

To sum up, Table 1 provides the reduction percentages for each pollutant in the period under consideration. For the period between 2018-2030, the largest improvement will occur in NMVOC with a reduction of 58.7% and the smallest improvement in SO_2 with a reduction of 21.6%. At this point it should be noted that further improvement will come with the elimination of ICE vehicles. Within the forecasted period, PM_{10} is the pollutant with the least reduction, potential partly due to non-exhaust emissions. In addition to this, with regard to CO_2, it is clear that although the fleet emits less, there are opportunities for improvement and this will only happen when more ICE vehicles are replaced by PHEVs and BEVs.

Table 1. Average total emissions reductions per vehicle.

Pollutant	1990-2018	1990-2030	2018-2030
CO	-97.2%	-98.7%	-51.1%
SO_2	-99.7%	-99.8%	-21.6%
NO_X	-94.7%	-96.5%	-34.7%
PM_{10}	-70.5%	-74.2%	-12.6%
NMVOC	-94.7%	-97.8%	-58.7%
CO_2	-54.8%	-67.4%	-27.9%

4. Discussion

The main objective of this study is to project the evolution of the local vehicle fleet in the medium-term, by different vehicle category, fuel type and vehicle technology and to produce detailed estimations and metrics on the anticipated air pollutants and CO_2 emissions at sector and vehicle level. The results show that the forecasted 2030 passenger vehicle fleet of 68.8% petrol, 6.3% diesel, 10% dual fuel, 7.3% hybrid, 2.5% PHEV and 5.0% BEV will contribute annually with 23.73 kton of CO, 29.86 ton of SO_2, 5.3 kton of NO_X, 1.03 kton of PM_{10}, 4.75kton of NMVOC and 5904 kton of CO_2.

Main culprit for most of these emissions will be petrol vehicles (specifically for: 74%: CO, 63%: SO_2, 49%: PM_{10}, 82%: NMVOC and 61%: CO_2). However, diesel vehicles will be responsible for 67% of NO_X emissions despite the relatively small fleet. Clearly, "stick and carrot" policies are required to reduce the number of petrol and diesel vehicles in the fleet.

Even if all fossil fuel vehicles were to be replaced with BEVs powered by a low carbon electricity grid, transport sector would still contribute particulate matter PM_{10} emissions. In 2018, 88% of PM_{10} was non-exhaust PM with the majority being emitted by vehicle tires and breaks as well as tarmac friction. Electric vehicles can reduce significantly break PMs emissions since they use electromagnetic breaks but being significant heavier tend to wear tires faster. The latter can potentially be reduced with improved tire compounds which will likely become available once electric vehicles start gaining a significant market share. Reducing emissions further requires increased use of public transit systems instead of private vehicles as well as cycling and walking.

Transport sector CO_2 emissions tend to correlate with the fleet size and peaked in Greece in 2009. Subsequently gradually replacement of old petrol vehicles with new diesel vehicles led to a slight reduction. This reduction was only slight, because of the prevalence of sport utility vehicles (SUVs), a 2019 trend observed across Europe where they represent 38% of sales. SUVs are typically heavier, have more powerful engines and worse aerodynamics leading to higher CO_2 emissions per vehicle by approximately 10% compared to other passenger vehicles. Most new vehicles are heavier than their predecessors as a result of vehicle size, safety features and significantly more complex cabling and sensor systems. EU vehicle CO_2 emission targets for 2025 and 2030 at 80gr/km and 60gr/km respectively will deliver impactful change [71].

Looking into the vehicle fleet forecasting and its impact on expected emissions electrification has the most important role in emissions reduction. Given the expected gradual fleet electrification, this leads to the expectation that transport emissions will be reduced substantially. Electricity grid decarbonisation will then become the focal point of transport emissions reduction [72–75]. The Greek electricity system is rapidly transformed with ongoing plans for retirement of lignite coal power plants in 2028 and aggressive growth for renewable energy and natural gas plants within the 2020s. Improvements are also being made in power supply security, accessibility and sustainability [76]. Greece has committed [52] to ambitious targets for greenhouse gas emissions reduction and achieving net zero by 2050. As a mid-term target for 2030 greenhouse gas emissions in Greece will be reduced by 40% compared to base year 1990, and renewable energy's role in electricity generation will reach 60%.

Distance travelled per vehicle is expected to be reduced in the next years. This is partly driven by the aging fleet which has been shown to result in a gradual reduction in use per vehicle. Given current affordability concerns it is not likely for vehicle replacement time to be reduced to a level that would impact on fleet age. Concurrently, there has been a consistent trend over the years for increased public transit systems which have been improving steadily. Moreover, it is noteworthy that micro-mobility vehicles, such as e-scooters and others offer more options in replacing short car trips. Long-term it is likely that autonomous vehicles will gradually make private vehicles redundant, reducing motorisation rate, as they will be too expensive and inconvenient to keep. Finally, population growth has significantly decelerated over the past years and even appears to be reducing in several wealthy countries therefore, not leading to growing vehicle demand beyond 2030.

Further positive developments within and beyond the 2020s are planned for emissions control and reduction in Greece as they have been part of recent political discourse and outlined by the PM's public announcements [77]. Specifically, the sales of petrol and diesel vehicles will be banned in 2030 and by 2025 all new taxis in Greece's two largest cities, Athens and Thessalonica, will have to be zero emissions vehicles alongside 1/3 of all hire vehicles across the country. Beyond transport, for areas where natural gas is available, new built properties will not be equipped with oil boilers. Policy making in Greece is strongly aligned with EU Directives to achieve net zero emissions by 2050 [78].

During the last two years, the COVID-19 pandemic has had a significant impact in reducing urban transport use across most countries and Greece. The urban traffic reduction has led to significant, up to 80% urban air quality improvement in 2020 co

mpared to 2019 in a range of large European cities [79]. Therefore, when electromobility takes on most of the urban private transport with parallel reduction of mileage driven by older private vehicles and increased use of public transport will lead to material air quality improvements. Beyond air pollution such changes will also impact significantly on the reduction of urban noise pollution which is largely driven by internal combustion engines.

5. Conclusions

In conclusion, this study has performed an in-depth analysis of the Greek private vehicle fleet, its forecasted mix and the impact that will have on air pollutants. Established data has been used and expanded for vehicle subcategories and Brown's Double Simple Exponential Smoothing method has been used for vehicle fleet forecasting to 2030. Expected emissions have been estimated with the COPERT tier 2 and tier 3 approaches for each one of the 28 vehicle subcategories and for every specific pollutant.

Reduction in transport emissions might be the most promising area for urban air quality improvement. While the trajectory of such reductions relies strongly on technological improvements and user adoption, country and city level specificities remain a significant determinant, not only of what might be possible but mostly of the pace of change. Greece and specifically the capital city of Athens with high population density and chronic lack of public transit infrastructure are ripe for improvements. These are essential and will improve the livelihoods of large segments of the population. The taxonomized, by vehicle subcategory, results are of high value to policy makers dealing with fleet characterization, anticipated fleet trends and associated emissions in producing nuanced policy.

Similar to other research this study is not free of limitations. Firstly, the smothering methodology has not been applied for electric vehicles, since their fleet in Greece before 2018 had barely reached 800 vehicles. Instead, data from the Energy ministry has been used. Secondly, forecasting has not been adjusted for policy interventions eg ban of petrol and diesel vehicle sales beyond 2030. Thirdly the average emission factors per vehicle even though they are specialised on the specificities of vehicle subcategories they will not be useful in extreme types of vehicle use ie vehicles driven exclusively on highways or those driven only for short distance journeys. Future research should focus on adjusting data for the specificities of the WLTP cycle and its relevance to real world use, not least in relation to ratios of vehicle use in cities, frequency of stops and temperature. Specifically for Greece, the capital city of Athens is of high importance and warrants a specialised study since it hosts a very high share of the vehicle fleet and suffers from the air quality degradations that comes with it.

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