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Alexandra Fortes Lopes

Impacts of COVID-19 pandemic on-road externalities

Impactos da pandemia COVID-19 nas externalidades rodoviárias

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Mecânica, realizada sob orientação científica de Doutora Eloísa Catarina Monteiro de Figueiredo Amaral e Macedo, Investigadora Doutorada (Nível 1), do Departamento de Engenharia Mecânica da Universidade de Aveiro, e de Doutora Margarida Isabel Cabrita Marques Coelho, Professora Auxiliar c/ Agregação do Departamento de Engenharia Mecânica da Universidade de Aveiro.

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Keywords Impact on mobility, coronavirus, pollutants emissions, environmental and social costs, COPERT

Abstract

The year 2020 was marked by the experience of a pandemic context, due to COVID-19. The rapid spread of this disease led to restrictive travel measures being implemented by all countries, causing traffic levels to decrease. In addition, the very perception of the risk of contagion led individual people to change their behaviours, impacting mobility patterns. These changes in the way people move had impacts on the environment, namely in terms of pollutant emissions and greenhouse gases. Besides air pollution, there are changes in externalities related to road safety and noise. Thus, it is essential to estimate how the pandemic affected these externalities and how to act in similar future situations. Thus, the dissertation aims to present an assessment of the mobility challenges and environmental impacts associated with the current pandemic situation, considering different European regions. A data-driven comparative analysis is carried out, based on several online mobility reporting platforms. Some mobility scenarios are defined, depending on the evolution of the pandemic situation in the regions. Traffic-related externalities and costs associated with accidents, air pollution, climate change and noise are estimated. The results suggest that indeed the level of restrictions imposed by the authorities in each city impact differently on people's mobility levels. The estimated CO_2 and NO_x emissions tend to decrease at times of more severe restrictions, as is the case in March 2020. With regard to estimated external costs, it can be seen that they follow the mobility and emission trends. For example, at the end of March 2020, total external costs decrease by 80 percent in Lisbon, 67 percent in Bucharest and 24 percent in Stockholm, compared to the beginning of the month. These changes demonstrate the pandemic's impact on road externalities and the need to study them.

Palavras-chave Impacto na mobilidade, coronavírus, emissões de poluentes, custos ambientais e sociais, COPERT

Resumo

O ano de 2020 foi marcado pela vivência de um contexto pandémico, devido à COVID-19. A propagação rápida desta doença levou a que medidas restritivas à deslocação fossem implementadas por todos os países, fazendo com que os níveis de tráfego diminuíssem. Além disso, a própria perceção do risco de contágio levou a que as pessoas, individualmente, alterassem os seus comportamentos, impactando os padrões de mobilidade. Estas alterações na forma como as pessoas se deslocam teve impacto no ambiente, nomeadamente a nível de emissões de poluentes e gases efeito estufa. Além da poluição do ar, verificam-se alterações nas externalidades relacionadas com a segurança rodoviária e com o ruído. Desta forma, é essencial estimar a forma como a pandemia afetou estas externalidades e como se poderá agir em situações futuras semelhantes. Assim, a dissertação tem como objetivo apresentar uma avaliação dos desafios da mobilidade e dos impactos ambientais associados à atual situação pandémica, considerando diferentes regiões europeias. É realizada uma análise comparativa orientada por dados, com base em várias plataformas online de relatórios de mobilidade. Alguns cenários de mobilidade são definidos, consoante a evolução da situação pandémica das regiões. As externalidades relacionadas com o tráfego e os custos associados a acidentes, poluição do ar, alterações climáticas e ruído são estimadas. Os resultados sugerem que, de facto, o nível de restrições impostas pelas autoridades de cada cidade impactam de forma diferente os níveis de mobilidade das pessoas. As emissões de CO_2 e NO_x estimadas tendem a decrescer em momentos de restrições mais severas, como é o caso de Março 2020. Relativamente aos custos externos estimados, verifica-se que acompanham as tendências de mobilidade e de emissões. Por exemplo, no final de Março 2020 os custos externos totais diminuem cerca de 80% em Lisboa, 67% em Bucareste e 24% em Estocolmo, em comparação com o início do mês. Estas alterações demostram o imacto da pandemia nas externalidades rodoviárias e a necessidade do seu estudo.

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Chapter 1

Introduction

1.1 Transport sector

The transport sector has been Europe's biggest source of carbon dioxide (CO_2) emissions, being responsible for over a quarter of all greenhouse gas (GHG) emissions. These have been increasing between 1990 and 2019 [EEA 2022c]. Within the transport sector, the road transport presents the largest share of CO_2 emissions, which represents up to approximately 72% of the CO_2 emissions. This is shown in Figure 1.1 [EC - Directorate-General for Mobility and Transport 2021]. The European Union (EU) has taken a leading role in trying to impose concrete targets and measures so that member countries can jointly contribute to slowing down this situation. The main objective to be achieved is to reduce the levels of GHG emissions by 40%, compared to 1990 levels, by 2030 [EC 2021a]. This is becoming a challenge since reducing emissions while transport demand grows at the same time involves efficient strategies [Krause *et al.* 2020].

In the EU-27, CO_2 emissions from passenger vehicles increased by almost 6% between 2000 and 2019, mainly due to an increase of over 15% growth in passenger transport volumes [EEA 2022c]. In fact, light passenger vehicles and light-duty vehicles present a high share within any European national vehicle fleet, dominating the roads, as shown in Figure 1.2 [EC - Directorate-General for Mobility and Transport 2021].

In particular, the data reported by Eurostat, Figure 1.3, shows the evolution in the number of registered passenger vehicles between 2013 and 2020, revealing an increase of approximately 13% in that period. Regarding the battery-only electric vehicle fleet, also presented in the chart, it was found that the year 2020 saw the highest number of cars, reaching 1 million for the first time. As shown in the figure, this growth was more pronounced between the years 2018 and 2019, with about 83% growth, and between the years 2019 and 2020, with about 64% growth. However, the share of these vehicles within the total fleet of passenger vehicles is currently 0.4% [Eurostat 2022]. Despite this increase in the number of electric vehicles, the share of passenger cars with alternative energy engines remains low within the EU member states. Based on these data, the present work will be mainly focused on passenger and light-duty vehicles.

Concerning the age of the passenger vehicles, their proportion is presented in Figure 1.4. It can be seen, for example, that Poland has the highest proportion of cars older than 20 years, while Luxembourg has the most recent vehicles, which are 2 years old or less. These discrepancies have an impact on the country's total emissions as vehicles of different ages, and consequently different Euro emissions standards, produce different

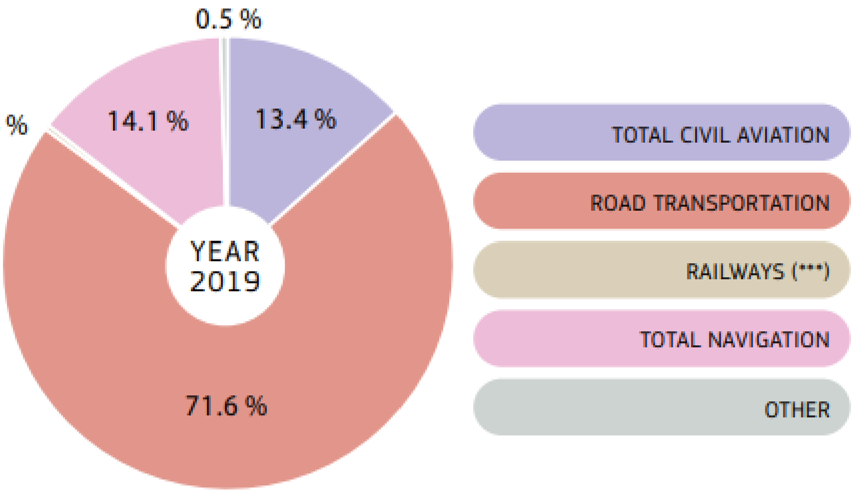


Figure 1.1: CO_2 emissions from transport - EU-27 by model (***) Excluding indirect emissions from electricity consumption. [EC - Directorate-General for Mobility and Transport 2021]

amounts of harmful components. For instance, it is estimated that the implementation of Euro 6 vehicle emission standard reduced some pollutant's emissions in more than 90% [ICCT 2016].

Besides the road externalities associated with GHG emissions, there are also externalities associated with air pollution, accidents, traffic congestion, and environmental noise.

For instance, transport and human mobility generate in residential and urban areas serious air pollution issues. Pollutants can be primary, if they are emitted directly from their source into the atmosphere, or secondary, if they are the result of chemical reactions that take place in the atmosphere itself. Moreover, the harmful effects of pollutants on human health and the environment depend on their concentration in the atmosphere and the time of exposure. Regarding the effects on human health, and according to the European Environment Agency (EEA), exposure to air pollution can be related to respiratory system diseases such as strokes, asthma, cancer and many more. In addition, the World Health Organization (WHO) links exposure to polluted air with type 2 diabetes, obesity and even diseases characterised by dementia [EEA 2022a]. The most drastic consequence of air pollution for human health is, beyond doubt, premature mortality. It is estimated by [EEA 2021] that about 307,000 premature deaths were caused by PM 2.5 (particulate matter with an aerodynamic diameter less than 2.5 m), in 2019, in EU member states. It is important to note that air pollution affects citizens in different ways since it may vary depending on pre-existing diseases and ages. Also, various studies show the relation between high exposure to air pollutants and socio-economic status [Ferguson *et al.* 2020] [Zhang *et al.* 2022].

The transport sector is the main source of emissions of pollutants such as nitrogen oxides (NO_x), particulate matter (PM), unburned hydrocarbons (HC), carbon monoxide (CO) and CO_2. For this reason, the EU regulates these emissions through the Euro Norms. The emission standards apply to categories of light-duty vehicles, heavy-duty

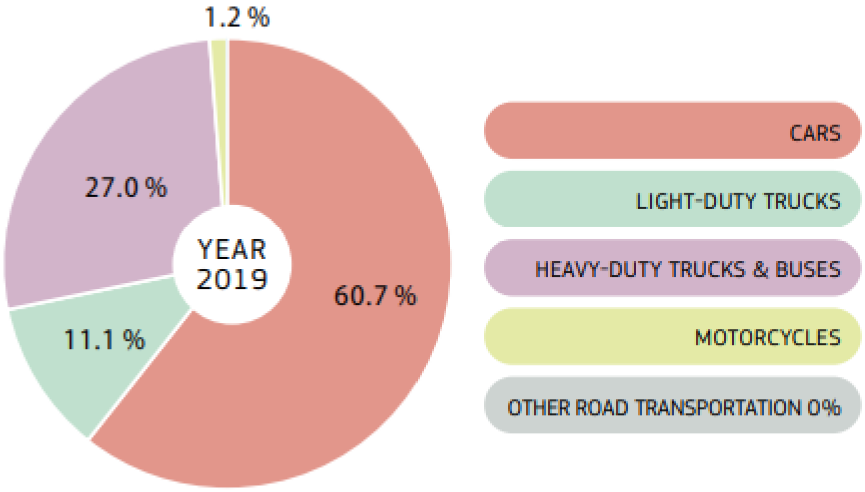


Figure 1.2: CO_2 emissions from road transport - EU-27 by transport mean [EC - Directorate-General for Mobility and Transport 2021]

vehicles, or other non-road mobile machinery. This control of emissions has contributed to the sense that it has generated very significant drops in emissions, achieving improvements in air quality and the amount of emissions of GHG [APA 2021]. Right after the Euro emission standards were implemented, CO emissions decreased by around 70%, between 2000 and 2013 [EEA 2015].

Furthermore, road traffic congestion, it is considered one of the major problems of urban transport. It is present in most large cities due to the dispersal of populations to more surrounding residential areas but still need access to infrastructure within the cities. In terms of direct impacts, traffic congestion can lead to an increase in travel time, stress in the driver – that can have numerous consequences - and vehicle operating and maintenance charges [Litman 2022]. All these factors are associated, implicitly, with other costs, i.e., congestion itself leads to additional external costs. As described in [Vosough *et al.* 2022], one of the tools for tackling traffic congestion is road pricing since it not only intervenes in the reduction of traffic but also in the reduction of pollutant emissions from vehicles.

In a further approach, this phenomenon is directly related to another road external factor, noise. According to WHO, the second most damaging environmental stress factor in Europe, after air pollution, is road traffic noise [EEA 2017]. Although road traffic noise is the most prevalent, rail and air traffic, as well as industrial activity, contribute greatly to the increase in these levels [EC 2021b]. Focusing on road traffic noise exclusively, the EEA's Environmental Noise in Europe 2020 report indicates that at minimum 20% of the European population is subjected to elevated noise levels during the day-evening-night period [EEA 2019b]. In Figure 1.5 it is possible to observe the population exposure to environmental noise, from different sources, inside and outside urban areas within areas covered by strategic noise maps, for the 33 EEA member countries (EEA-33), excluding Turkey. As mentioned previously, the proportion of environmental noise caused by road traffic is significantly higher compared to the other noise sources. In addition, the reported values are lower than the estimated since the Environmental Noise Directive

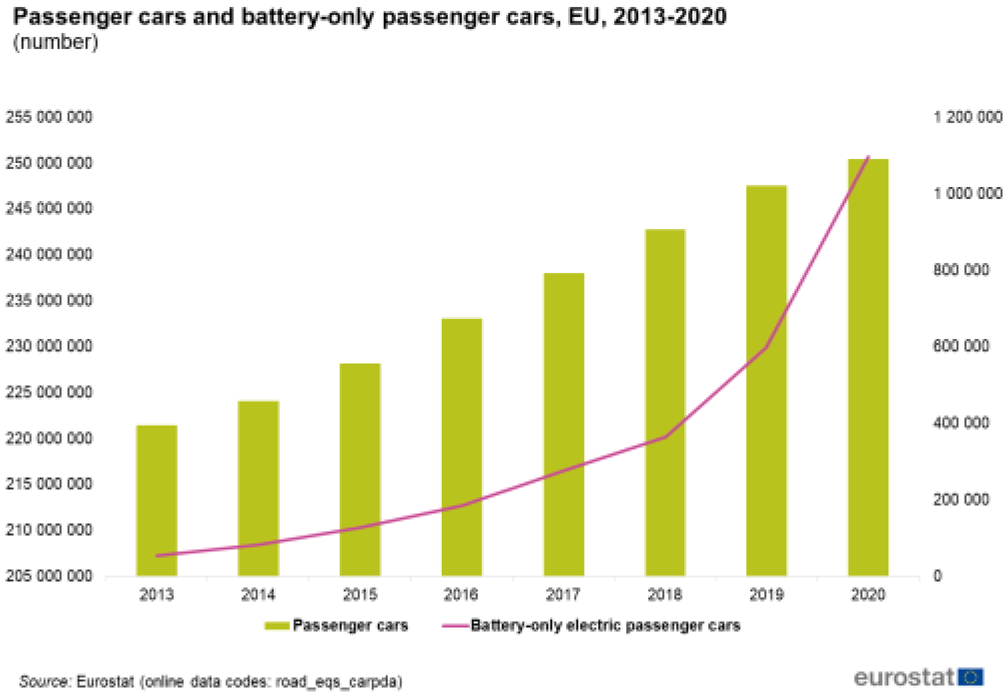


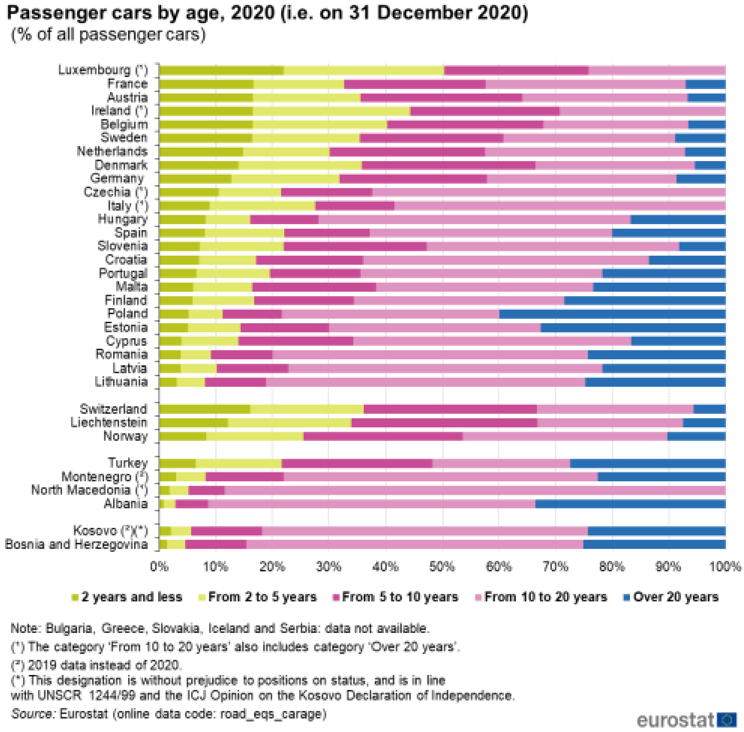
Figure 1.3: Passenger cars and battery-only passenger cars, EU 2013-2020 [Eurostat 2022]

(END) 2002/49/EC does not cover all roads and urban areas across Europe [EEA 2019b].

Moreover, the impact of noise emissions is considered to represent around 7% of global externalities in the EU [Cavallaro and Nocera 2022]. These consequences for people's health and well-being have led the WHO to draw up new guidelines on environmental noise. These recommendations have established a level of exposure beyond which the negative effects increase significantly. The measures that can be implemented to follow these recommendations involve reducing noise at the source level or the propagation path. This can be done through the reduction of traffic volumes on roads, technological improvements in the vehicles themselves, infrastructure improvements, urban planning, speed control, restrictions on the noisiest vehicles and noise barriers [EEA 2009]. In addition to the influence of noise on the well-being of the human population, it also has an impact on biodiversity, affecting terrestrial and aquatic species and, consequently, unbalancing ecosystems [EEA 2019b].

As mentioned previously, traffic congestion can generate stress peaks in drivers and consequently increase the probability of collision [Cabrera-Arnau and Bishop 2021]. Since most crashes occur in urban areas (although fatal crashes are more frequent in rural areas [Cabrera-Arnau and Bishop 2021]) and the trend of population settlement in urban areas is increasing, it is expected that the number of these crashes in urban areas will increase in the coming years. For this reason, it is necessary that policy measures are implemented in order to reverse this situation.

However, one of the EU concerns is related to ensuring road safety. In regions with high traffic volumes, the number of fatal accidents may be lower than in areas with less traffic. This can be explained by the fact that a lower average speed practiced


Passenger cars by age, 2020 (i.e. on 31 December 2020)
(% of all passenger cars)

Note: Bulgaria, Greece, Slovakia, Iceland and Serbia: data not available.
(¹) The category 'From 10 to 20 years' also includes category 'Over 20 years'.
(²) 2019 data instead of 2020.
(*) This designation is without prejudice to positions on status, and is in line with UNSCR 1244/99 and the ICJ Opinion on the Kosovo Declaration of Independence.
Source: Eurostat (online data code: road_eqs_carage)

Figure 1.4: Passenger cars by age, 2020 [Eurostat 2022]

by drivers due to congestion can decrease the level of severity of a crash. In other words, even if accidents do still occur, it is unlikely that these result in fatalities [EEA 2018]. In the European Union, about 23,000 lives were lost, in road accidents, and more than 1.2 million people were injured, in the year 2019. The average fatality rate per million inhabitants in that year was 61 [EC 2021c]. In terms of costs, road accidents are estimated to be equivalent to 3% of the gross domestic product (GDP) of most countries. The costs of a road accident can be seen as having both an economic and a social component [Russo and Comi 2017]. In the case of the economic component, it is related to the general costs of the crash, namely the material costs of the vehicle or infrastructure affected, as well as the administrative costs arising from the activation of emergency services or legal proceedings. Social costs are associated with human life, for example, lack of productivity, moral and psychological damage, and medical assistance costs [EC 2019].

1.2 Impact of the pandemic

The outbreak of the current pandemic crisis began in Wuhan, a province in China, in late 2019. However, due to the mobility of people around the world, the virus quickly spread to more countries, with the first confirmed case of infection in Europe recorded in early 2020 [Spiteri *et al.* 2020]. On the 11th of March of 2020, WHO declares that COVID-19 is considered a pandemic. The measures governments have been implementing pose impacts at various scales, affecting both mobility patterns and social behaviour, with subsequent impacts in terms of the environment. Overall, these measures (such as

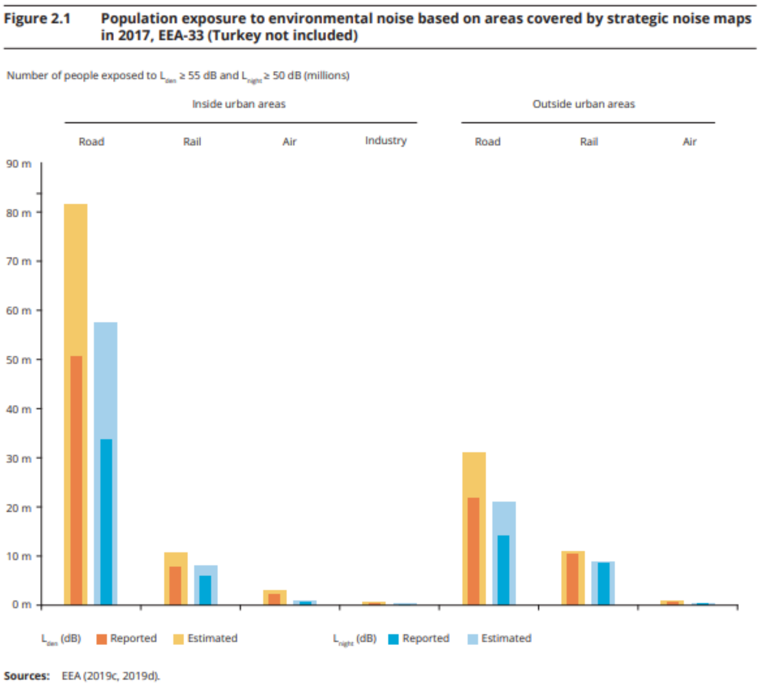


Figure 1.5: Population exposure to environmental noise based on areas covered by strategic noise maps [EEA 2019b]

lockdown and physical distancing) have induced a large part of the population to work from home, travel less, to possibly avoid public transport, reducing the traffic volume, leading consequently to a predictable reduction in noise and pollutant emissions, especially in CO_2 most evident in (big) cities [Schulte-Fischedick *et al.* 2021]. Regarding NO_x emissions, [Bartoňová *et al.* 2022] states that in the absence of a pandemic context, concentrations would have been higher. Overall, a significant reduction in their levels was observed in Europe. Further, [Guevara *et al.* 2022] concluded that the largest decreases associated with containment measures are for CO_2 (about -8%) and for NO_x (about 11%). In fact, their results showed that April 2020 was the month with the most severe restrictions. For most pollutants, the road transport sector contributed most to the reductions observed in the EU-27 and UK.

Between February and May 2020 there has indeed been a reduction in noise from road traffic, as reported by [Bartoňová *et al.* 2022]. In Ireland a study concluded that at many stations analysed there was a reduction in noise levels during the lockdown period, the most likely cause being a reduction in traffic levels [Basu *et al.* 2021].

In Figure 1.6 [EEA 2022b], it is represented the evolution of GHG emissions from 1990 until 2020, and then projections until 2040. It is possible to observe a significant decrease in these emissions by the year 2020, precisely because of the pandemic that was declared. One would expect these reductions to be directly proportional to the decrease in mobility patterns, but this may not be the case. For example, as shown in [von Schneidemesser *et al.* 2021], NO_x emissions do not follow a proportional reduction trend as vehicle activity and in general, these were accompanied by an increase in ozone at a similar magnitude [Grange *et al.* 2021]. In addition, a decrease in traffic volume in certain areas may be associated with an increase in speed, which will have an impact on noise and pollutant emissions. Nevertheless, lower traffic volumes should yield fewer road safety issues. For example, according to [ERTICO - ITS Europe 2022], road accident figures in 2020 are significantly conditioned by changes in mobility patterns in each country, depending on the pandemic situation. It is stated that the number of road deaths in 2020 has been reduced by about 17% compared to 2019. However, between 2020 and 2021 there was an increase of 5% across the EU.

This means the assessment of these externalities related to this pandemic is essential to better understand the impacts as well as how to act if this type of scenario becomes frequent since data suggest different effects among cities. Due to privacy issues and fears, monitoring population mobility can be a difficult task. However, new technologies have enabled a series of tools that can provide a basis for analysing mobility patterns and taking some actions if needed. For instance, the use of mobility apps such as Citymapper, or GoogleMaps can generate data that may indicate the level of adoption of physical distancing. Therefore, a wider study that provides an assessment of the impacts of road externalities in a pandemic situation on a comparative basis between cities of different densities and typologies would be useful, as is the main goal of the present dissertation.

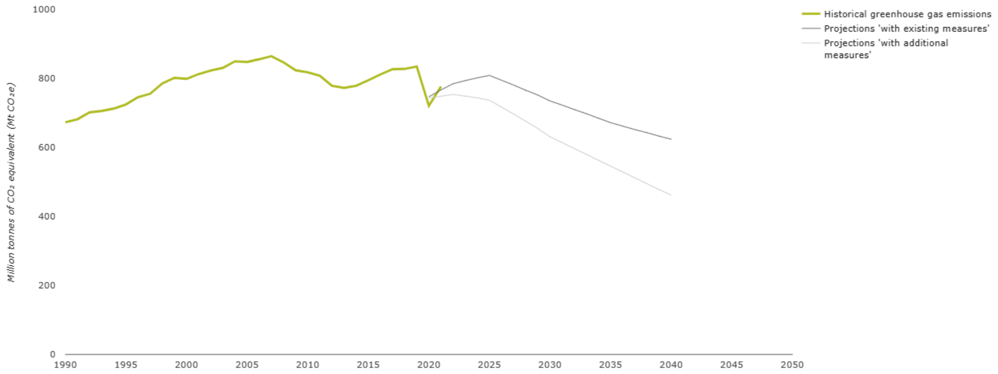


Figure 1.6: Greenhouse gas emissions from Transport in Europe [EEA 2022b]

1.3 Objectives

The work will consist in developing a study of road transport externalities associated with different pandemic periods in a selection of European cities with heterogeneous characteristics. Thus, the specific objectives are the following:

- Collection of road traffic, mobility and people's concentration in certain places data in several cities, for different periods (pre- and post-pandemic);
- Development of a database aggregating all information on mobility, including good practices;
- Application of different scenarios considering the general evolution of the pandemic situation;
- Estimation of pollutant emissions and external costs;

- Spatio-temporal analysis of road externalities and identification of patterns.

In addition, the proposed research work focused on urban areas, and many data-driven mobility reports will be explored. This study is expected to provide insights that can be used at a regional scale to support the design of more environmentally friendly mobility strategies, also improving mobility conditions. For this purpose, different scenarios based on mobility data will be designed and explored. As traffic levels seem to be returning to pre-pandemic levels, or at least becoming a new normality pattern, it is essential to understand the impacts this disruption related to the pandemic had inferred to mobility within a city. This study will seek to provide some insight into this and hopefully contribute to the knowledge and support the devising of more environmentally-friendly mobility strategies in similar situations.

1.4 Structure

This dissertation is divided into 5 chapters. In the first, Introduction, a general context is given of the situation of the transport sector globally, with emphasis on Europe, the most important externalities and the pandemic context that occurred. Next, in the literature review chapter, several studies that link mobility, its impacts and its relationship with the COVID-19 pandemic are presented. In Chapter 3, the methodology on which the work was based is presented, namely the case studies, data mining and management, and also the calculation of emissions. Chapter 4 discusses the results obtained in the study and, finally, Chapter 5 presents the concluding remarks of the developed study and future research topics.

Chapter 2

Literature review

Given the current public health crisis due to the COVID-19 outbreak, EU countries and their governments began to implement drastic measures in order to slow down the transmission of the virus in their communities. At an early stage, while the vaccine was still being developed, non-pharmacological interventions were established [An *et al.* 2021]. These included restrictions on the movement of people, the gathering of people not from the same household, social distancing orders, curfews, quarantines and partial or total lockdowns. In addition, in-person school activities were suspended, and public services closed.

Besides the direct health problems that may surge due to the COVID-19 disease, psychological effects are also being felt. The pandemic brought a feeling of uncertainty and unsafety causing people to change the way they move in their daily life, directly impacting the use of transport. This happened because since the beginning of this pandemic it has been stated that mobility patterns of people influence how the virus propagates, as with many other infectious diseases [Aaditya and Rahul 2021]. The two main aspects that can influence the change in mode choice are the consciousness of the disease and the perception of the severity of the lockdown imposed. Studies suggest that public transport contributes to the fast spread of the virus between cities and countries, due to the unavoidable contact between users [An *et al.* 2021]. Therefore, several immediate measures were put into practice, such as the mandatory use of masks, the maintenance of physical distance, and regular disinfection, which are the main proposed measures to stop the virus spread.

Thus, the insight of safety in public transport, regarding physical distancing and disinfection, determines people's desire to choose this mode of transport. This means that depending on the safety level perceived by users, various modifications can be anticipated on the different transport modes. To avoid affecting the demand, the public transport systems must agree with the psychological expectations of people. For instance, if people value physical distance and disinfection, one would expect an increase in the use of personal cars since they offer a sense of safety [Aaditya and Rahul 2021]. The same opinion is shared by [Vallejo-Borda *et al.* 2022] and [Jiao *et al.* 2022] who mention that active transport and motorised private transport were preferred over public transport due to the inherent close contact between passengers. Overall, the rise in the number of new cases and deaths by COVID-19 has led to a higher probability of switching from public transport to other modes [Vallejo-Borda *et al.* 2022]. However, this probability is lower for active modes of transport than private ones. In Australia, for example, at a time of easing restrictions, a rapid recovery in car travel has been noted, probably due to users' perceived risk of public transport [Vallejo-Borda *et al.* 2022]. Another study, conducted by [Bian *et al.* 2021], reports that in Seattle and New York, there has been a drop in vehicle traffic systems due to the measures implemented. It also agrees that the level of vehicle traffic recovered more quickly than other modes of transport in phases of the relief of restrictions. This may mean that some users of other modes of transport have switched to the private car.

During the pandemic, other types of habits were also created by societies to decrease contact with other people. For example, online shopping, teleworking and online meetings were adopted at the expense of conventional ways and may constitute a new normal [Luan *et al.* 2021]. This would explain the fact that mobility patterns are no longer the same as before. In fact, many companies and services have chosen to move their operations to online mode to provide business continuity [Pal and Kolay 2023]. Consequently, the number of trips for this purpose has decreased, contributing to a reduction in traffic levels. The level of online shopping is likely to be higher than before the pandemic, due to consumers' experiences during periods of lockdown [Shaw *et al.* 2022]. A study carried out by [De Borger and Proost 2022] studied the effect of perceived virus contagion risk and teleworking, both changes caused by COVID-19, on public transport frequency supply and second-best optimal pricing, using a simple model and assuming that car use is undervalued. This study found that the increase in workers working from home declined the demand for both modes of transport.

One paper aimed to analyse the impacts of urban mobility restrictions, arising from the COVID-19 pandemic, and their GHG emissions, in Finland [Kareinen *et al.* 2022]. Furthermore, it focuses on the relationship between the reduction of GHG for future climatic goals and the role of teleworking in reducing emissions. They concluded that in the first wave of the pandemic, mobility rates in the city studied, Lahti, reduced by about 40%. Another aspect analysed in this study is global warming potential (GWP). GWP is defined as the relative potency of a GHG, taking into consideration the time the gas remains active in the atmosphere. In this case, the research shows that GWPs from urban mobility fell in the first wave by between 36%-50%. In fact, weekly GWPs related to mobility were 96% caused by passenger cars. However, these reductions are not sufficient to meet the 1.5°C goal in the urban mobility sector [Kareinen *et al.* 2022]. One of the factors that greatly influenced the results was, according to the authors, the role of teleworking, as it decreases the number of trips to work. In EU-27, about 14% of workers worked partially from home and 34% only from home in July 2020 [Kareinen *et al.* 2022]. In 2019 the percentage of workers working from home in the EU-27 was approximately 6%.

To get a sense of how the use of online meeting platforms has increased exponentially with the influence of the pandemic, there are some statistics. According to Google, the Google Meet platform reached a new target of 9 million new users every day in early April 2020. Regarding the Zoom Meetings platform, 10 million daily participants were recorded on 31 December 2019, 200 million on 31 March 2020 and 300 million on 31 April 2020 [Statista 2022b]. Another platform that is widely used to connect people and has been heavily used since the pandemic is Microsoft Teams. There were 20 million active users of the platform in 2019, compared to 145 million in mid-2021 [Statista 2022a].

A study that aimed to monitor, model and plan mobility in the city of Rome between March and June 2020, analysed transport modes including transit, car, bicycle and walking, but with a special focus on the subway [Carrese *et al.* 2021]. They concluded that occupancy in the subway and mobility on foot (in the historical centre) reduced by 95%. However, the observed reduction in private car use was only 70%. According to [Wang and Noland 2021], although the use of the underground and bike share system in New York City has experienced a sharp decline, underground use has not recovered in the same way as cycling, remaining well below pre-pandemic values. Another aspect considered in the study by [Zhou *et al.* 2021] is the fact that it is relevant to analyse the wage level of the inhabitants in the vicinity of the metro stations. In the case of the current pandemic, people with lower incomes, for example, are more likely to continue moving out of necessity.

In general, social distancing recommended or mandated by country authorities has been seen as a barrier to the use of public transport because of the risk of contagion. However, it can be seen from another perspective as a boost to the use of active modes of transport [Vallejo-Borda *et al.* 2022]. One such case is the bicycle. Even before the pandemic context, an increase in the use of this means of transport was already noticeable, through infrastructure investment or even financial incentives for users. However, it was during the pandemic that a more pronounced transition to non-motorized modes of transport, including the bicycle, was noted in many cities [Vallejo-Borda *et al.* 2022]. Indeed, cycle paths and temporary or permanent infrastructure were built during this phase. In addition to the bicycle being seen as a more efficient means of transport, the reason that led to this shift away from the public and shared transport (e.g., carpooling or ride-hailing) was that it allowed a greater social distance to be maintained and was therefore seen as safer [Hu *et al.* 2021].

The impact of COVID-19 on the Citi Bike sharing system and underground in New York City was studied by [Wang and Noland 2021]. They concluded that although both modes of transport experienced a reduction in use - 95% of underground and 70% of bicycle - bicycle use levels recovered more quickly. For example, by September 2020, underground trips were only 30% of the trips observed in the equivalent pre-pandemic period, against the trend of cycling. The fact that bike trips have almost returned to normal, and the metro has not, may indicate that many people have transitioned from metro to private cars. It also indicates that the metro is less resilient than the bike-share system.

Also in the United States, a study was conducted to examine changes in mobility patterns of the Divvy bike-sharing system in Chicago compared to other modes of transport during a pandemic context [Hu *et al.* 2021]. One of the conclusions is that the usage trend of bicycle sharing tends to follow an increase-decrease-rebound logic. Again, they state that the bicycle is a more resilient mode of transport than others (walking, public transport and driving). Furthermore, residential areas and wider spaces demonstrated a smaller decrease and a faster recovery of mobility. As an aside, when analysing mobility patterns during the pandemic, they found that the number of trips by members decreased dramatically while the number of casual trips increased vastly. Another aspect that changed with the pandemic context was the purpose of bike share trips. Most of the trips became leisure trips rather than commuting trips. Moreover, the relationship between public transport and cycling was also analysed, concluding that the bike-sharing system came to be seen as a substitute rather than a complement. The same impact of the pandemic on the use of bike-sharing systems was studied in Seoul, Korea [Kwak *et al.* 2021]. They found a relevant relationship between the spread of the virus and the use of the system. The number of bicycles rented per day increased 10,000 times when the social distance increased by only one level. In London, [Heydari *et al.* 2021] found that after a period of decline in rentals between March and April 2020, demand started to increase again from May 2020. Moreover, it remained at the expected levels that would be seen in a non-pandemic scenario, again indicating the resilience of this mode of transport.

It is also important to consider the influence of weather conditions on mobility patterns since it can cause a change in mode choice behaviour. To demonstrate this influence in Beijing city, [Otim *et al.* 2022] presented a study focusing on GPS itineraries. They state that GPS positioning data is a good alternative source of information, compared to the usual travel surveys used in various research. This enforces the idea of using data from different navigation applications in this study, such as Google Maps and Apple Maps. Moreover, one of the main conclusions is that distance of a trip is the most relevant circumstance when selecting a transport mode. When it comes to the impact of weather conditions directly (precipitation, wind velocity, temperature and relative humidity), the conclusion is that temperature is the most influencing condition. For instance, if the temperature is above 25ºC, bike mobility can decrease by about 21% and walking mobility can increase by 27% [Otim *et al.* 2022]. Apart from the weather, it is also significant to study the effect of special events on mobility, specifically walking. A study conducted by [Eom and Nishihori 2021] explored pedestrian activity, by using pedestrian distribution indexes (PDIs), to understand how situational dynamics related to special events and weather conditions affect PDIs. Once more, weather circumstances proved to influence the magnitude of pedestrian activities, besides the temporal and spatial distributions.

Some authors agree on the noticeable shift in modal shares, especially during the first COVID-19 outbreak [Kareinen *et al.* 2022]. The proportion of mobility by bicycle and pedestrian increased from 9% to 22% while car use grew from 64% to 70%. On the other hand, public transport, one of the most affected transport modes, declined from 27% to 9%, in Finland. In the city of Budapest, Hungary, the split of passenger vehicles suffered an increase of approximately 22% while public transport suffered a reduction of 25%, in March 2020 [Bucsky 2020]. A study conducted by [Khadem Sameni *et al.* 2021], in Theran city, focused on the mode choice change from metro to other transportation options. According to their results, private car had the major increase and metro had the major decrease since it was observed a shift from subway, bus and bus rapid transit to private cars and taxis. Another study investigated if the loyalty to public transportation had changed since the COVID-19 outbreak [Esmailpour *et al.* 2022]. They focused on studying the relation between service quality, passenger loyalty and customer satisfaction in Theran's bus system, by using a cross-sectional survey. The conclusions are that with the pandemic, although the loyalty to public transportation has decreased, the feeling of service quality and customer satisfaction increased. The cause was mainly the improved safety, information, trustworthiness, and comfort (and crowding) of the bus system. In reality, the financial and psychological costs of using passenger cars were not enough to encourage commuters to ride the bus, particularly due to the perception of appeal towards the private car.

An analysis based on inter- and intra-individual modifications in transport mode choice and user's viewpoints concerning cars, bicycles and public transport was made in Germany [Eisenmann *et al.* 2021]. The study revealed a very good feeling towards the car during the strict lockdown period, while the bicycle perceptions were dispersed, and public transport was perceived as negative. Another interesting aspect regarding the psychological effects that decrease the usage of motorised modes is the fact that people find themselves free and stress-relieved from the lockdown by using non-motorised transport [Aaditya and Rahul 2021].

In general, it is important to note that before the pandemic phase, there were already various negative consequences and externalities related to the transport sector. For instance, the high levels of congestion and accidents, deterioration of air quality, a boost in noise levels, contribution to climate changes and even health impacts [Verma *et al.* 2020]. However, it is known that the COVID-19 pandemic had, and is still having, a lot of impact on mobility patterns, generating variations in different environmental indicators such as noise and pollutants emissions.

Regarding noise levels, according to the EEA, the major cause of environmental noise in Europe is due to road transport, followed by railways, airports, and industries. Exposure to high noise levels can have diverse severe consequences on human health such as temporary hearing problems, sleep disorders, anxiety, depression, or even cardiovascular problems [Pascale *et al.* 2022]. During the lockdown period, since fewer vehicles were circulating and people were having fewer outdoor activities, noise levels showed a decrease. For instance, China, Spain, France and Italy had verified a decrease in noise levels. In Dublin, Ireland and Stockholm, Sweden, a reduction in the noise levels was also felt by the monitorisation campaigns, during the pandemic phase [Pascale *et al.* 2022]. In Rome, Italy, the studies showed approximately a 65% reduction in traffic and noise emissions during the lockdown period. Another interesting aspect is the fact that traffic-related and outside movements allow for reducing noise levels but, on the other hand, other forms of noise can be generated due to people staying at home [Yildirim and Arefi 2021]. There is no doubt that the lockdown measures impacted traffic patterns. As previously mentioned, a significant difference that can be highlighted is regarding the improvement in noise levels associated with the road traffic decrease.

Another equally important issue, which also affects human health is related to air pollution. Exposure to pollution is a risk factor for respiratory and cardiovascular complications [Berman and Ebisu 2020]. Besides this, air quality can also affect the ecosystems and the climate, contributing to climate change due to greenhouse gases (GHG). For instance, [Kareinen *et al.* 2022] stated that CO_2 emissions plunged by around 50%, in the EU-27 and UK, in April 2020. This percentage is related to surface passenger transports only. Since people's mobility behaviour experienced changes during the pandemic, air quality also experienced some variations. In the United States, for example, studies show a reduction in nitrogen dioxide (NO_2) of around 26% and also a decrease in PM 2.5 (particulate matter with an aerodynamic diameter less than 2.5 m) levels. However, these reductions were more significant in urban areas and in towns where the closing of non-essential businesses was imposed in the early stages of the pandemic. In addition, and according to National Aeronautics and Space Administration (NASA), if we compare 2019 concentrations of NO_2 in China with the same period of 2020, it is notable a 10-30% reduction [Berman and Ebisu 2020]. The EEA concluded that in European cities the air pollution had decreased as well. For instance, in Bergamo, Italy and Barcelona, Spain, it was confirmed a reduction of 50% approximately in NO_2 levels, compared with 2019 - 2020 [Berman and Ebisu 2020]. Another research regarding four Southern European Cities (Nice, Rome, Valencia and Turin) and one Chinese city

(Wuhan) took the general conclusion that the imposed lockdowns led to a 56% of reduction in NO_x [Sicard *et al.* 2020]. However, concerning the PM emissions, the reduction was much lower in Europe (8%) if compared with the reduction felt in Wuhan (42%). In the case of ozone, O_3, it was noted a growth of its level in all the studied cities (17% in Europe, 36% in Wuhan). In conclusion, besides the health crisis generated by COVID-19, this period had a positive consequence an unseen anthropogenic emission decrease from manufacturing and traffic sectors, and the implemented lockdowns [Le *et al.* 2020]. Nevertheless, it would be fundamental to investigate the changes in mobility patterns with a clear perspective of overall impacts regarding noise and pollutant emissions, and provide a comparative evaluation considering different European cities, so that specific guidelines can be set to support policymakers to better design mobility strategies.

On road congestion, and the influence of the pandemic context on its evolution, it can be said that a portion of public transport users preferred to drive their own car [Xu *et al.* 2022]. This change in behaviour caused the dynamics of vehicle flow on roads to change, worsening congestion patterns as well [Xu *et al.* 2022]. One of the findings of this Shanghai-focused study is that pandemic constraints are reflected more in central city areas compared to suburban areas. They also found that congestion levels recovered or even surpassed pre-pandemic levels when face-to-face work and school activities started to take place. In fact, in the questionnaire carried out by the authors, 82% of the participants, where a large share was already public transport users, switched to private modes of transport. A way to make congestion-related charges more accurate, using an artificial intelligence algorithm, was studied by [Yu *et al.* 2022]. They report that the increase in the number of private car trips was due to the decrease in public transport use, since the COVID-19 outbreak, and it seems to last in recent times. This finding suggests that the new normality mobility patterns can entail some specificities that may change the previously known patterns.

COVID-19 deeply impacted the mobility of people and goods around the world and was even considered a 'mobility crisis' by World Bank 2020 [Khadem Sameni *et al.* 2021]. Thus, it is important to study these changes closely in order to know how to best manage resources in future situations.

As one of the aims of this dissertation is to carry out a comparative analysis, three different European cities were chosen. The way each of the authorities managed the pandemic situation in the country, implementing lockdowns at different times and different levels of restrictions on mobility, makes the results vary as well [Jiao *et al.* 2022], enriching the study. According to [Borkowski *et al.* 2021], different levels of perception of the severity of the pandemic situation, the risk of contracting disease and the exposure itself influence how daily mobility is affected by the pandemic in different socio-demographic groups. This is one of the reasons that show the importance of a comparative study, in this case between Lisbon, Bucharest and Stockholm. These cities have as a common point the fact that they are capitals of countries within the European context, however, they have several differences between them. On the other hand, the period chosen for the analysis is relatively long (March 2020 to October 2021), encompassing a short period not officially affected by the pandemic, a more severe pandemic period (spring 2020) and periods of less constraint. This last period already encompasses a period of possible adaptation and coexistence with the "new normal", that is, in which some of the new habits, behaviours, and patterns brought by the pandemic and its restrictions remain present in daily life.

Although all modes of transport have undergone changes in their demand and supply since the outbreak of the pandemic situation, the consequences have not been identical for all of them. It was also found that different cities/countries imposed different strategies in terms of mobility systems, which obviously yielded different impacts. Another research gap seems to be related to the external costs of road transport during this period of the pandemic. In this dissertation, we will tackle these issues and the focus is on exploring the mobility patterns changes for the dominating road transport categories such as light-duty vehicles, both passenger and freight. This choice was made also because they are the most polluting group of vehicles, and secondly, because most of the existing studies on the impact of the pandemic on mobility and the transport sector focus on public transport. Thus, we hope to contribute to a better understanding of the impact these categories have been posing in the last few years.

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Chapter 3

Methodology

The research work seeks to present an assessment of the mobility challenges and associated environmental and road safety impacts related to the current pandemic situation, considering different European regions. Under the context and considering the work objectives, the research is conducted applying the methodology illustrated in Figure 3.1:

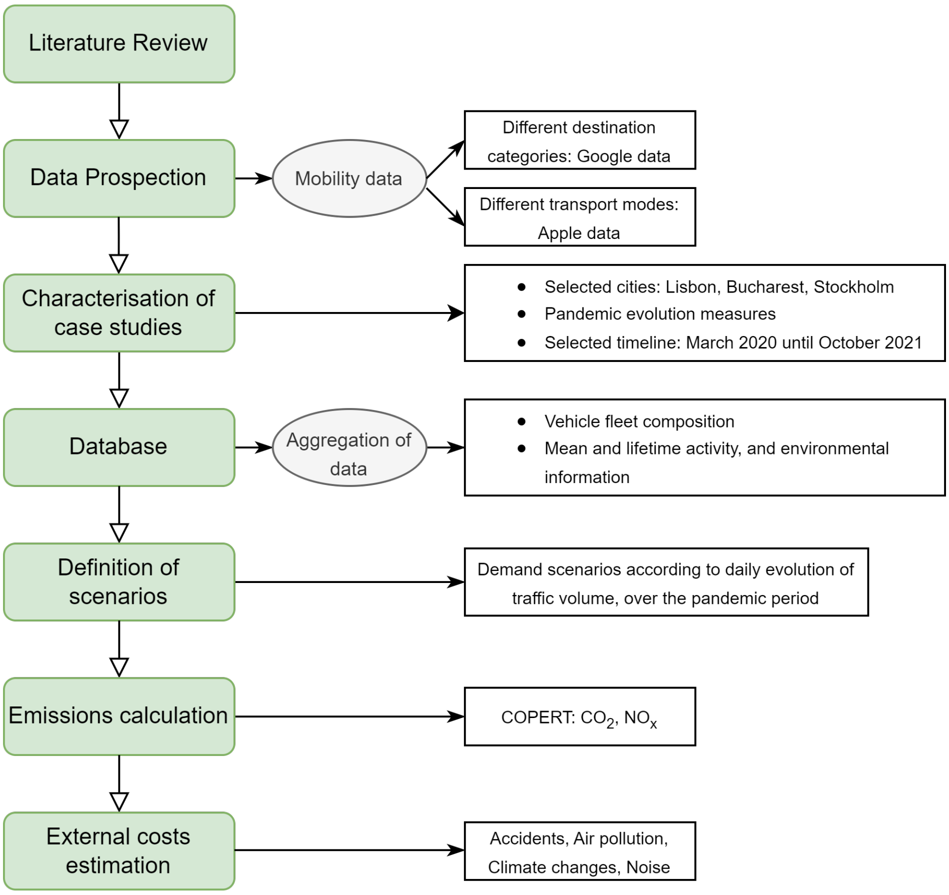


Figure 3.1: Methodology's flow chart

In the first step, it is necessary to understand what conclusions were taken from previous studies on externalities associated with road traffic and, especially, how they relate to the effects of the pandemic.

Regarding the exploitation of data, the focus in this study is on data from Google Mobility Reports [Google 2022] and Apple Mobility Trends Reports [Apple 2022]. They both deliver statistical data concerning the percent change of movement, compared to a baseline pre-pandemic value. However, while Google provides information about the change in visitors over time, by category of destinations, Apple presents information regarding the change in the volume of people driving, in transit, or walking.

At a later stage, a preliminary study is performed to identify case cities upon the availability of relevant data for the proposed study. The set of countries initially defined for this study is based on the country consortium of the PriMaas Interreg Europe Project [EU 2022]. In addition, the availability of official data also influenced the choice of the three case cities: Lisbon, Bucharest and Stockholm. Also in this phase, the time period for the study of externalities associated with different pandemic periods is selected. In this case, the chosen period was from March 2020 to October 2021.

To create the database, information regarding the composition of each city's vehicle fleet, speeds, mean activity, among others, is filtered and aggregated. Moreover, data concerning the daily evolution of traffic volume during the selected period is also included in the database.

Concerning the definition of scenarios part, Apple's driving daily mobility data is used to the vehicle fleet composition of the city to be analysed, to define different daily demand scenarios over the pandemic period.

Then, we end up with another of the objectives of this study which is to estimate the emissions of CO_2 and NO_x originated by each vehicle fleet, during this period, and how it is related to the mobility patterns observed by Google mobility reports.

Following the estimation of emissions and the daily evolution of traffic volumes in each city, we will explore the associated external costs, which will allow us to understand the real impact these changes in mobility patterns due to the pandemic posed.

3.1 Major tasks under the study

The fundamental steps of this study can be described in 6 main tasks, namely:

Task 1 - Methodology of the work and literature review

The first task contemplates the literature review focusing on externalities associated with road traffic, methodologies for calculating emissions, general evolution of the pandemic at the European level regarding traffic volumes and use of public transport . Based on the revision of relevant literature, the methodology to be followed in the study will be derived.

Task 2 – Selection and characterisation of the case studies

Preliminary study to identify case cities upon the availability of relevant data for the proposed study. Selection and characterisation of case studies and preliminary assessment of mobility patterns. Heterogenous regions will be selected to be able to establish some comparison evaluation.

Task 3 – Database creation

Mobility data was collected in platforms such as Apple mobility trends and Google Mobility Reports, as well as European Commission reports. Collection of data related to vehicles fleet and volumes in pre- and post-pandemic periods, for different cities or regions, will be made. Collect all the good practices implemented within the selected regions to better cope with the mobility and citizen safety challenges related to the pandemic. Pre-processing of the data and aggregate construction of a database (two-dimensional data set) of the vehicles fleet, as well as evolution in terms of daily traffic volumes in several cities, will be made. Depending on the availability of data, information regarding the mobility levels in the selected cities may not be equal for all case studies.

Task 4 – Definition of scenarios

Based on data regarding changes in mobility patterns, define different demand scenarios that will serve as a basis for estimating road traffic externalities. This will be done using the Apple mobility trends report.

Task 5 – Analysis of the impacts of the COVID-19 pandemic on road emissions

Application and adjustment of methodologies to assess changes in road traffic-related emissions for various scenarios (using specific software such as COPERT with MATLAB integration).

Task 6 – Study and analysis of the external costs of the achieved mobility patterns for each scenario

Based on the scenarios defined previously, the external costs associated the obtained mobility patterns for the cases under study were estimated. A comparative assessment of the results obtained for each selected case study was performed for specific time periods.

3.2 Data gathering and management

In this section, the aim is to retrieve and pre-process data that can be used to extract relevant information for this study.

3.2.1 Information regarding COVID-19 implemented measures

The data regarding the measures applied by each city in terms of mobility restrictions must be collected. This can be obtained by decrees, reports, and official web pages, for instance. This information will be crucial for interpreting the data and calculations we will perform concerning emissions and external costs.

In particular, authorities may have recommended against travelling abroad because of contagion rates from other countries or continents. For example, between March and June 2020, the European Commission recommended that country authorities implement such a measure [Schneider *et al.* 2021]. In more extreme cases, crossing borders was prohibited, except in very specific cases. Another type of measure adopted was the obligation to submit negative tests to COVID-19 before travelling or even quarantine upon arrival at the destination. The filling of passenger locator forms was also implemented by several authorities, in order to obtain information on the possible location of the traveller, in case he is involved in a chain of contagion. In addition to not recommending or banning movement across borders, many governments opted for similar restrictions between districts or counties in their country.

In general, these measures made free movement, especially across borders, more restricted and difficult. However, there have always been exceptions to the measures implemented. These exceptions could apply to citizens of one's own country, residents or workers, transit passengers, etc. At a later stage, some measures were lifted and the

COVID-19 certificate was created, proving the passenger's previous vaccination, testing or infection [Schneider *et al.* 2021].

Since each country and its authorities have the autonomy, to a certain extent, to implement the measures they consider appropriate, the gathering of this type of information is crucial to understand how each country dealt with the situation and how this affected mobility in that region.

3.2.2 Mobility-related data

The data we need is provided by different platforms and we only relied on data provided as publicly available. The focus was on the mobility data and reports provided in Google [Google 2022], Citymapper [Citymapper 2022], TomTom [Tom Tom 2022] and Apple [Apple 2022] web-based platforms. However, some of these data were not open to the general public, thus, only the data reported in the mobility reports from Google, Citymapper and Apple, were used.

The Community Mobility Reports from Google provide insights regarding the perception that communities have about the COVID-19 pandemic. These anonymous and aggregated statistical data showed to be crucial to health organisms and policymakers around the world, demonstrating how populations react according to the measures installed by governments. It is important to bear in mind that this information provided by Google respects and protects the privacy of individuals, with no disclosure of personal information such as individual location or contacts. For example, when there is not enough information to maintain the privacy and anonymity policy, there is a gap in the reports. More specifically, the reports present the mobility trends in different regions over time by registering the percent change in visitors, dividing them by destination categories such as retail and recreation, grocery and pharmacy, parks, transit stations, workplaces, and residential. The values presented in these reports are a comparison between the number of visitors in that day and the number of visitors of the respective baseline day. The baseline days characterizes a "normal value" of mobility for that specific day of the week and is the median of the number of visitors in the five-week period January 3rd - February 6th of 2020, considered to be pre-pandemic. For every region, there are 7 different baseline values, each corresponding to a different day of the week. However, seasonality is not considered. The only category of destination that presents a specification is the Residential since it shows a change in duration (hours) spent in this place instead of a change in number of visitors [Google 2022]. This mobility information from different cities, provided by Google in its raw form, was aggregated in a database in order to be more easily analysed.

Concerning the Citymapper platform, its main focus is the public transit and also providing mapping services in various modes of transportation including walking, cycling, driving and even public transport. However, on the opposite of Google reports, Citymapper does not provide information regarding the change on mobility trends during the pandemic, for different locations. For this reason, data from this platform could not be used for this study [Citymapper 2022].

Another mobility platform prospected in this study was TomTom. It provides geolocation information which can be used by drivers, companies or developers. For instance, TomTom publishes every year the TomTom Traffic Index, which is a study that presents how traffic congestion changed over that year and its impacts, in different cities around the world. However, the data used for the development of this Index are not easily accessible and therefore it was not possible to include them in the created database [Tom Tom 2022].

Concerning the data from Apple, it is based on an Apple Maps tool they released with the aim of providing insights to health authorities about mobility of populations. Specifically, they show the changing volume, in percentage, of people who drive, walk, or use public transportation in their communities. This mobility trends aggregated data is collected by Apple Maps, regarding various cities and countries. Similarly to Google, the information provided by Apple does not have an associated individual ID or the user's movement history, thus ensuring privacy. The values Apple presents are based on the number of requests for directions, made to Apple Maps, and then compared to a baseline value only, generating a relative volume. The baseline value in this case corresponds to the volume observed on January 13th, 2020. This database provided by Apple is in fact more complete, allowing from here to build the scenarios of mobility evolution - described in the following sections - throughout the pandemic period [Apple 2022]. In conclusion, the database developed was based mostly on data provided by Google and Apple.

3.2.3 City-level vehicle fleet data

Regarding the information on the composition of the passenger vehicle fleets of the three selected cities, these were acquired from [EMISIA 2022]. Emisia provides detailed data on vehicle stocks for all the EU-27 countries and has been supported by the EEA and the Joint Research Centre on developing reliable datasets and emission estimation tools for emission inventories.

The datasets include several variables, including vehicle stock data (divided into categories, fuel, segments, and Euro standard), mean activity (with average information on the kilometres travelled), and lifetime cumulative activity. Environmental properties, fuel and speed specifications, and share of activity in urban, rural, and highway conditions are also available. In this study, this data is considered enough for exploring the emission impacts for different mobility patterns at the city level. Since these data provide information for the national vehicle fleet composition, an adjustment had to be made to contemplate the specific vehicle composition circulating in each city under study. For this purpose, several mobility reports were explored and the proportion of the number of vehicles within each category was computed, i.e., from the total number of circulating vehicles in each country, the cities' vehicle stock composition was estimated. Moreover, since we are interested in daily evolution analysis, the data regarding mileage had to be (roughly) adjusted to a daily average instead of a year-based.

3.3 Mobility scenarios

The pandemic scenarios were constructed according to the following:

- for the city-level adjusted vehicle fleet data in terms of stock and mileage, pre-pandemic data were set as the baseline scenario;
- daily scenarios were generated by multiplying the baseline number of vehicles in each city by the driving daily percent change provided by Apple mobility data

[Apple 2022].

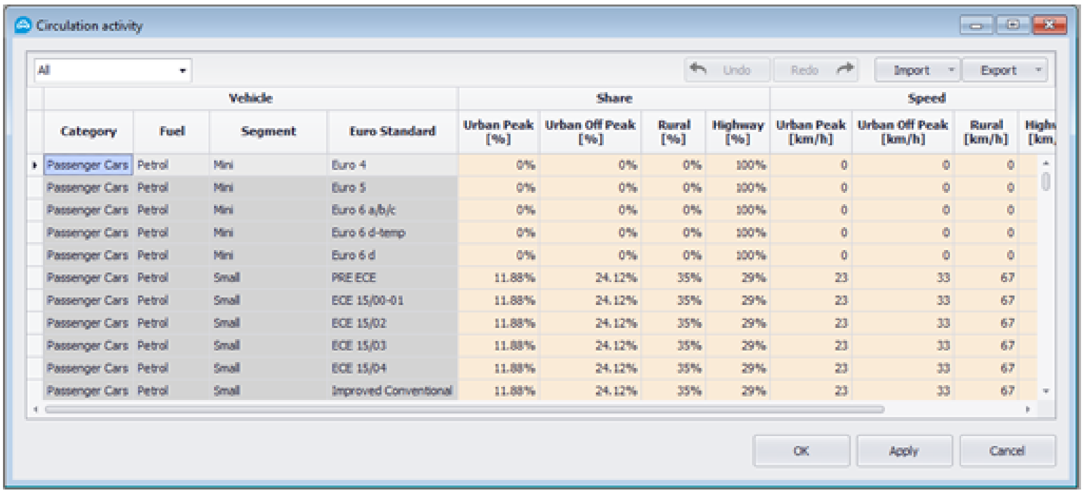
This was made to obtain the number of vehicles that circulated on a specific day of the months considered in the study. It is important to note that for all information regarding the vehicle fleet of the given city, except the stock and mileage, it was assumed that other variables remained with the same values throughout the selected period for the analysis. For each mobility change scenario, only the vehicle stock information varies over the days due to the pandemic situation present in each of the cities.

3.4 Emission estimation

To estimate the pollutants emissions associated with the created scenarios , COPERT software is used. It is considered by EU the standard vehicle emissions calculator and estimates emissions considering the vehicle population, mileage, speed and other information including environmental properties of the region to be studied. Although the software was initially created for official road transport emission inventory preparation, in EEA, it can be applied for academic or scientific purposes. The obtained results of emissions are concerning the main pollutants involving toxic species, GHG and air pollutants [EMISIA 2022].

Since the vehicle fleet information of each region is very extensive, the used method was to directly input the Excel files with the required information into COPERT and then, after verification of data, to calculate the emissions results of CO_2 and NO_x for the selected period. The present study emphasizes these two pollutants since CO_2 is the reference gas for the greenhouse effect that contributes the most to global warming and NO_x impacts negatively human health when inhaled.

One of the most important information to enter in the COPERT software is the Stock and Activity Data, on the Vehicles tab. In addition to Stock, the user must insert information about Mean Activity (km/year) and Lifetime Cumulative Activity (km). Also in the Vehicles tab, it is possible to enter data on Circulation Activity, i.e., data on the average speed in urban areas (peak and off-peak hours), rural areas and highways. Figure 3.2 presents the Circulation Activity window in COPERT workspace.



Vehicle				Share				Speed			
Category	Fuel	Segment	Euro Standard	Urban Peak [%]	Urban Off Peak [%]	Rural [%]	Highway [%]	Urban Peak [km/h]	Urban Off Peak [km/h]	Rural [km/h]	High [km,
Passenger Cars	Petrol	Mini	Euro 4	0%	0%	0%	100%	0	0	0	
Passenger Cars	Petrol	Mini	Euro 5	0%	0%	0%	100%	0	0	0	
Passenger Cars	Petrol	Mini	Euro 6 a/b/c	0%	0%	0%	100%	0	0	0	
Passenger Cars	Petrol	Mini	Euro 6 d-temp	0%	0%	0%	100%	0	0	0	
Passenger Cars	Petrol	Mini	Euro 6 d	0%	0%	0%	100%	0	0	0	
Passenger Cars	Petrol	Small	PRE ECE	11.88%	24.12%	35%	29%	23	33	67	
Passenger Cars	Petrol	Small	ECE 15/00-01	11.88%	24.12%	35%	29%	23	33	67	
Passenger Cars	Petrol	Small	ECE 15/02	11.88%	24.12%	35%	29%	23	33	67	
Passenger Cars	Petrol	Small	ECE 15/03	11.88%	24.12%	35%	29%	23	33	67	
Passenger Cars	Petrol	Small	ECE 15/04	11.88%	24.12%	35%	29%	23	33	67	
Passenger Cars	Petrol	Small	Improved Conventional	11.88%	24.12%	35%	29%	23	33	67	

Figure 3.2: Circulation activity in COPERT workspace

When introducing the data in the software, the Tier 3 emissions estimation calculation method was used. In this method, exhaust emissions result from the combination of activity data (total vehicle mileage) and technical data (emissions factors) [EEA 2019a]. Total exhaust emissions are given by the following formula.

$$E_{\text{total}} = E_{\text{hot}} + E_{\text{cold}} \tag{3.1}$$

Hot emissions correspond to emissions when the engine is running at normal operating rhythm, at the normal temperature of that condition. Cold emissions are associated with the emissions released when the vehicle is in a warming-up phase, which is transient thermal engine operation (cold start). The latter type of emissions is usually higher than the hot emissions. Therefore, the total emissions are considered in this study.

3.5 External costs

An externality, or external cost, can be defined as the effect that an activity (economic or social) of one group of people has on another group of people, without the interests and impact on the second group of people being taken into account intentionally [EC 2019]. However, externalities are not necessarily negative. In the case of positive externalities, the collective benefit must be greater than the private benefit of the individual who takes the action [Belhaj and Fridell 2008]. Regarding negative externalities, the opposite is true. For example, the emissions of pollutants from a vehicle have an impact on human health, generating a negative external cost, as this impact has not been taken into account by the driver of the vehicle.

As was already mentioned, the major externalities associated with transportation include accidents, air pollution, climate change, noise, traffic congestion, habitat degradation, and other factors. The first four mentioned are the ones this study focuses on. Additionally, light passenger vehicles and light-duty vehicles, both used for road transportation, are among the vehicle categories analysed. In fact, and according to the Handbook of external costs 2019, road transport generates the highest external costs, taking up around 83% of total costs if these include sea and air transport. The costing methodology in this document is based on the one outlined in the Handbook of External Costs, followed by the EU [EC 2019]. This means that the standard marginal cost figures [€/vkm], used for the final calculation of external costs, can be found in the Excel document annexed to the Handbook. They articulate the monetary values with transport externalities, for each country of the EU, for each type of vehicle, and each type of road the trip occurs.

3.6 Case studies

Since this dissertation was supported by PriMaaS InterregEurope Project PGI05830, the aim was to select regions within the country's consortium, such as Portugal, Italy, Germany, Romania, Finland, Sweden and Scotland. Thus, the selected cities as case studies were Lisbon, Bucharest, and Stockholm – capitals of Portugal, Romania and Sweden, respectively - due to the fact that they are very heterogeneous countries when it comes to Eco-innovation. Figure 3.3 represents the 2019 Eco-Innovation ranking [EIO 2020]. This ranking is developed by the Eco-Innovation Observatory to assess the performance of all European Union Member States, and it shows the different clusters these countries are in. While Portugal is considered an Average Eco-I performer, very close to the EU average, Romania is classified as a country catching up with Eco-I. Regarding the performance of Sweden, the ranking shows this country is in the cluster of Eco-I leader. In addition, the amount and quality of data available regarding these three countries, especially official data concerning the national fleet composition, is another reason for this selection.

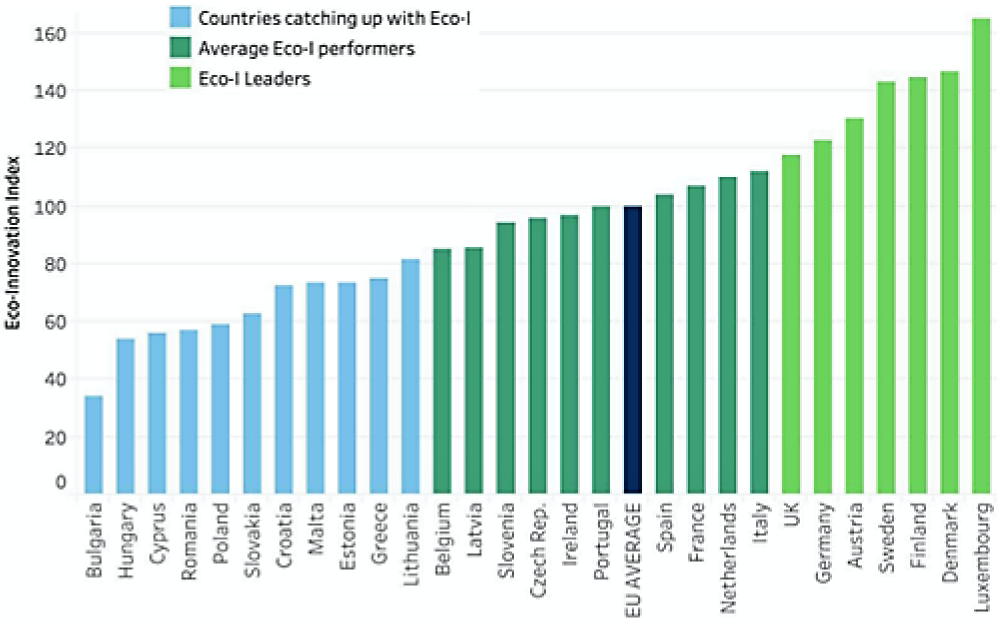


Figure 3.3: Eco-Innovation Index 2019 [EIO 2020].

Chapter 4

Results analysis and discussion

This chapter is devoted to the presentation of results and discussion of the findings. These are presented in different subsections. Notice that in all the performed analyses, the period defined as relevant is from March 2020 to October 2021.

4.1 City-level mobility data

After selecting the case studies, specific data was collected for each of the major cities, namely, Lisbon (Portugal), Bucharest (Romania), and Stockholm (Sweden).

First, it was gathered information regarding the passenger and light-duty commercial vehicle fleet of each country. In this study, information regarding the composition of the vehicle fleet in the three selected cities is derived from data acquired from the company EMISIA. It was found that only 2019 (for Portugal) and 2014 (for Romania and Sweden) data were available (EMISIA data), and thus, due to some unavailability of data, the data assumed for this study are for different years. Such data were considered as the baseline of the pre-pandemic period. At this point, information in terms of stock, mileage, etc at a national level was available. Then, these must be adjusted to the local vehicle fleet for considering the circulating parking in each of the cities under study. Thus, based on the data reported in various documents such as [Lisbon 2020] and [Trafikanalys 2015], we were able to obtain an estimate of the local vehicle fleet composition in terms of stock. The next step involves the assumption of daily analysis. Since the fleet data acquired from EMISIA presented the average annual activity in kilometres and we are interested in estimating emission impacts on a daily basis, so data regarding mileage (km/year) had to be transformed to account to daily kilometres travelled.

Afterward, the daily scenarios to account for the daily evolution of the pandemic were generated by multiplying the baseline number of vehicles in each city by the driving daily percent change provided by Apple mobility trend report, which allowed us to estimate the variability in the number of vehicles circulating on a specific day.

After analysing in detail the fleet composition of each country, it was found that they were indeed heterogeneous and therefore it would make sense to carry out this study on a comparative basis. As previously mentioned in the Introduction chapter, in this study the focus relies on light passenger and light-duty vehicles only. This happens since the major impact of driving on-road emissions is caused by those vehicles, as shown in Figure 1.2. Therefore, Figure 4.1 shows the aggregate characterisation of the light vehicle fleets for each of the three countries, based on the data acquired from EMISIA.

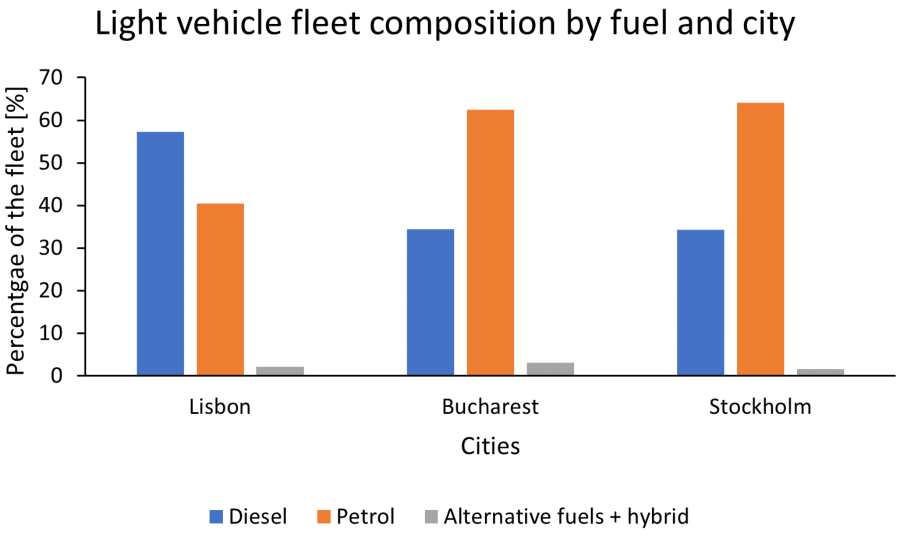


Figure 4.1: Light vehicle fleet composition by fuel and city.

Since the aim is to make a comparative study of the impacts of the pandemic on road externalities in different regions, the selection of cities also considered the evolution of the pandemic situation in each country over the study period.

4.2 Mobility restrictions due to the pandemic

In the case of Lisbon, face-to-face teaching activities were suspended on 12 March 2020, however, the state of emergency and consequent lockdown only began on the 18th. Then, it was only in mid-June that the city of Lisbon was able to ease the special restricting measures, unlike the rest of the country which had already started this relief earlier. However, by the end of the month, the number of new cases of virus infection in Lisbon led to new and more restrictive measures being applied. In September, face-to-face classes resumed but quickly came to a halt as a new state of emergency began in Portugal in November. This state of emergency lasted until the end of 2020, making December a very critical month in terms of mobility. Then, in January 2021, the pandemic situation remains very similar to December 2020, with various restrictions to circulation. In March 2021 the pandemic situation improves slightly, making the measures more flexible and allowing face-to-face teaching activities to resume in April. However, by mid-June, the situation worsens again, with weekend traffic restrictions in Lisbon and teleworking recommended whenever possible, making July a month with tighter restrictions again. Later, from August onwards, a new phase begins characterised by even more flexible measures and a return to a life closer to the pre-pandemic situation. This means that by September and October 2021 mobility was already somewhat close to pre-pandemic levels because there were no longer such tight restrictions, at various levels.

In the case of Bucharest, the measures implemented by the authorities were initially similar to those of Lisbon, however, as time went by, they were more rapidly relaxed.

For example, the first lockdown started in March 2020, when the pandemic officially began, followed by a period of relief measures in May. In June, this phase of opening establishments and easing various restrictions will continue, leading to a possible increase in mobility levels. At the end of the year, from November, a new curfew is implemented. This period is coincident with the period in which there was the highest peak in the number of new cases of coronavirus infection during 2020, around 8,500. Then, at the end of January 2021, the measures are relaxed again due to a significant decrease in new cases of infection - about four times fewer cases. However, in March some measures regarding catering and entertainment venues are brought back, due to a further increase in infections. After a controlled period of the pandemic situation in Romania, a new peak of infections starts in September, reaching a maximum of 15,000 new daily cases in October. This was the highest peak in 2021 and prompted new measures to be implemented to halt the advance of new infections. October 2021 was apparently considered a critical phase in Romania's pandemic management, while in Lisbon, for instance, this month was characterised by an easing of restrictions and a near return to normality.

Lastly, in the case of Stockholm, this city applied the most flexible measures of the three cities. Compared to other European countries, Sweden has adopted a different approach to the pandemic, trying to balance the management of hospital capacity with the country's economy. Thus, the measures implemented by the government essentially involved restrictions on gatherings of people - to promote social distancing - and on travel. Besides that, it was recommended that secondary and higher education schools be taught remotely, from March 2020. In October 2020 some of the restrictions targeting the most vulnerable public, namely the elderly, are even lifted. Only in December 2020 were more stringent restricting measures implemented, such as the recommendation to wear masks and limit the number of passengers on public transport. This period is coincident with the highest peak in the number of new cases of infection, around 7,000. Then, in January 2021, a new pandemic law was passed allowing the implementation of lockdown measures and restrictions on gatherings. This phase is considered by many to be a turning point in Sweden's approach to the pandemic, as other European countries implemented similar measures at the very beginning of the pandemic. Finally, the first phase of lifting measures took place in June. Measures aimed at slowing the advance of the number of contagions continued to be more relaxed in July 2021, with more participants being allowed at events and establishments. At the end of September phase 4 of restriction relief takes place, with teleworking no longer being recommended. This meant that from this time onwards, populations were freer to move around the territory [Mathieu *et al.* 2020] [Global monitoring 2020]. Table 4.1 presents a summary of these measures along a temporal line.

These differences in the way authorities and governments dealt with the pandemic situation had direct consequences on population mobility trends. This means that in a city where measures restricting movement, for example, were more restrictive, fewer people moved to certain places. This association can be proven by the graphs presented in Section 4.3, which represent the difference in the number of visitors, in percentage, based on mobility data from Google.

Cities	Face to face teaching activities suspended	Lockdowns	Restrictions relief	Stricter measures
Lisbon	12/03/2020	18/03/2020	mid-June 2020; mid-March 2021; August 2021	end-June 2020; Nov 2020; mid-June 2021
Bucharest		March 2020; Nov 2021	May 2020; end-Jan 2021	March 2021; Oct 2021
Stockholm		mid-Jan 2021	June 2021	Dec 2020

Table 4.1: Key moments of the pandemic for the three selected cities.

4.3 General mobility patterns

In this sub-section, charts are presented that were designed from the driving datasets of Google mobility reports. It is possible to observe the mobility curves between the three cities, Lisbon, Bucharest, and Stockholm, for sub-periods March 2020-December 2020 and January 2021-October 2021. A comparison can be made by taking into account the different ways of dealing with the evolution of the pandemic situation in each location, i.e., the change in drivers' behaviour at critical times of the pandemic should be reflected in the mobility graphs. For example, looking at the following 6 graphs, it is noticeable different mobility patterns, many of them influenced by the pandemic.

The plateau observed in the Residential curves corresponds to weekdays, while the minimums correspond to weekends. Taking into account the characteristics of the data, it makes perfect sense that the percentage change in the time spent at home is lower at weekends, given that people usually spend a lot of time at home compared to weekdays.

In a brief comparison of mobility patterns in 2020, the same behaviour is observed in the Residential curve trend for Lisbon, Figure 4.2, and Bucharest, Figure 4.3. This is, a significant decrease from mid-April until June and then an increase in mid-October. In the case of Stockholm, in Figure 4.4, the behaviour of the curves is different, especially the Parks curve which reaches much higher values than in Lisbon and Bucharest. However, the very sudden and almost vertical decrease of the remaining curves in Lisbon, in March, is different from what is observed in the other cities. Moreover, Lisbon is the city that manages to keep for longer its curves in negative values, except Residential, indicating the possibility that the restrictions imposed have been more influential in people's mobility.

In 2021 it is possible to notice that, until June, all the Lisbon curves except Residential present values that are the furthest from zero, as shown in Figure 4.5. This is related to the the restrictions relief period that happened in the Summer of 2021. In comparison, Figure 4.6 presents Bucharest's mobility patterns for 2021. In the end of January, most curves approach 0% change, coinciding with a period of easing of restriction measures. Then, in October it is possible to verify a reduction in the percent change, due to new and more strict measures. In general, Stockholm is the city that maintains its curves more constant throughout the year, revealing that the different measures imposed in the country did not reflect so much on people's mobility, as shown in Figure 4.7.

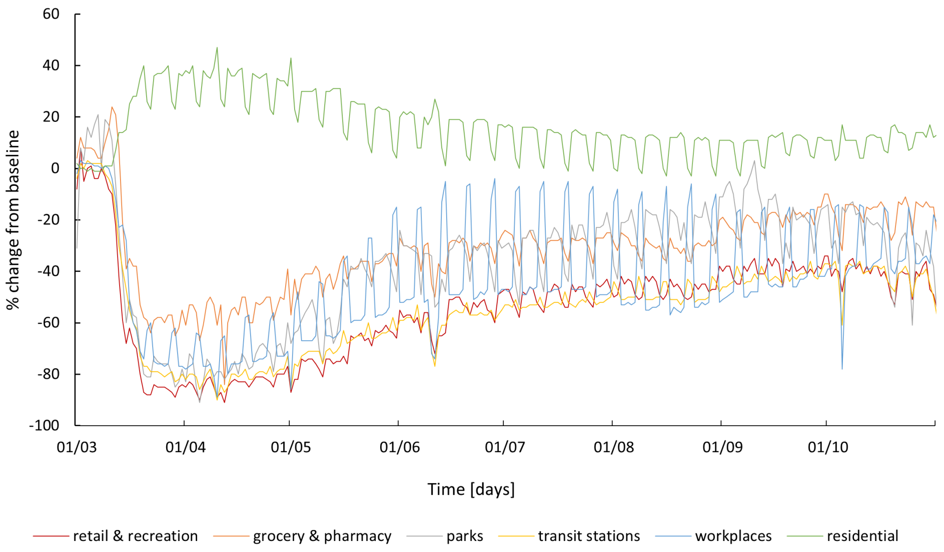


Figure 4.2: Movement trends over time, across different categories of places, Lisbon 2020 [Google 2022]

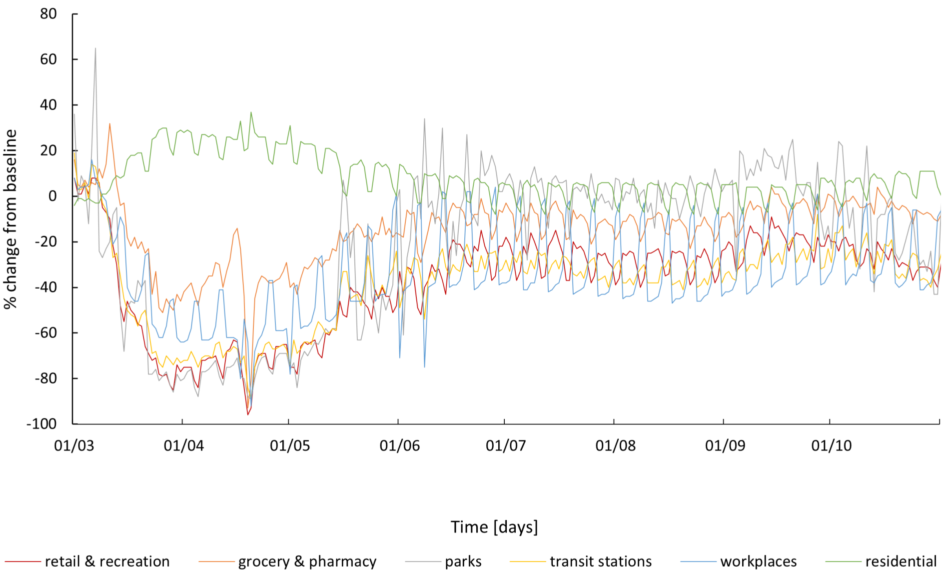


Figure 4.3: Movement trends over time, across different categories of places, Bucharest 2020 [Google 2022]

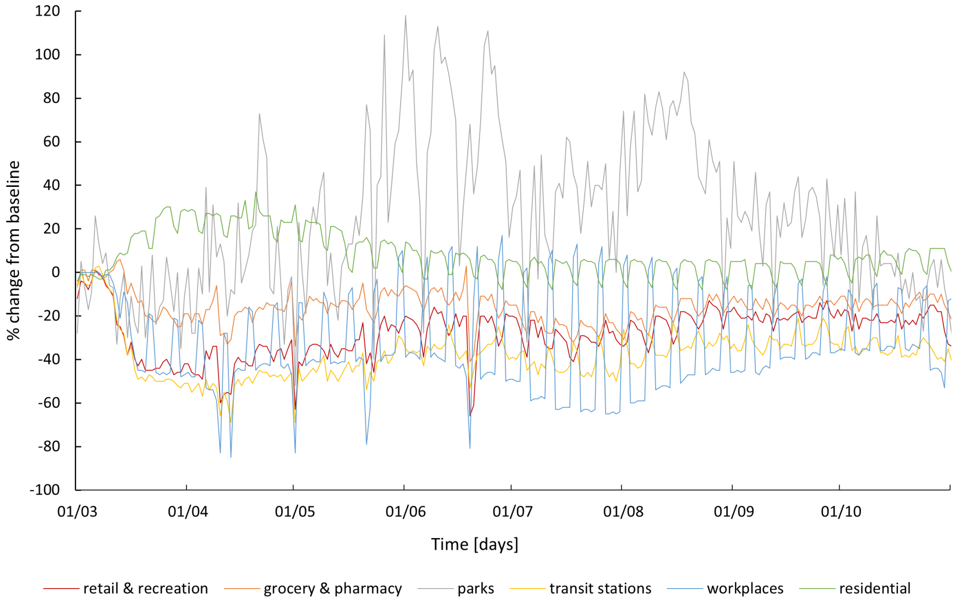


Figure 4.4: Movement trends over time, across different categories of places, Stockholm 2020 [Google 2022]

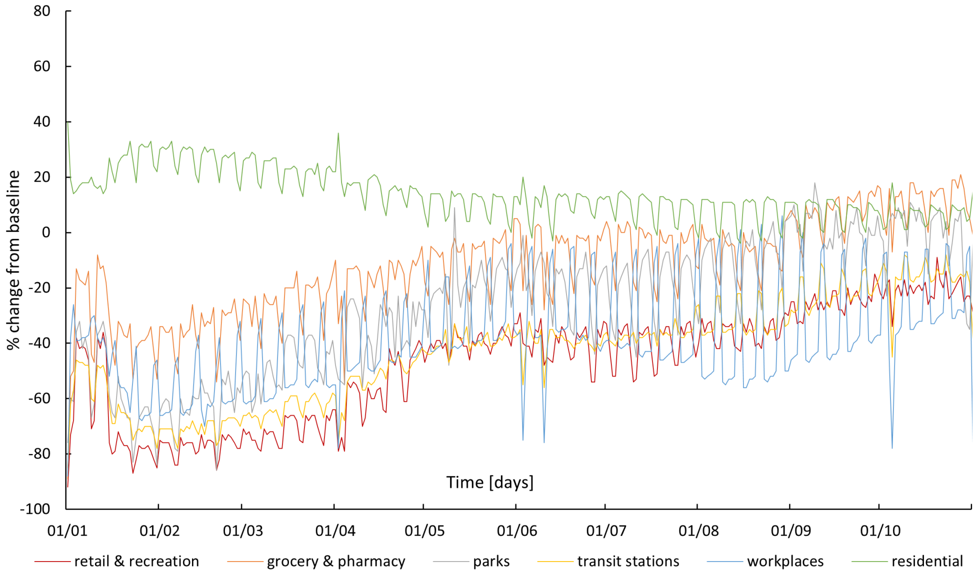


Figure 4.5: Movement trends over time, across different categories of places, Lisbon 2021 [Google 2022]

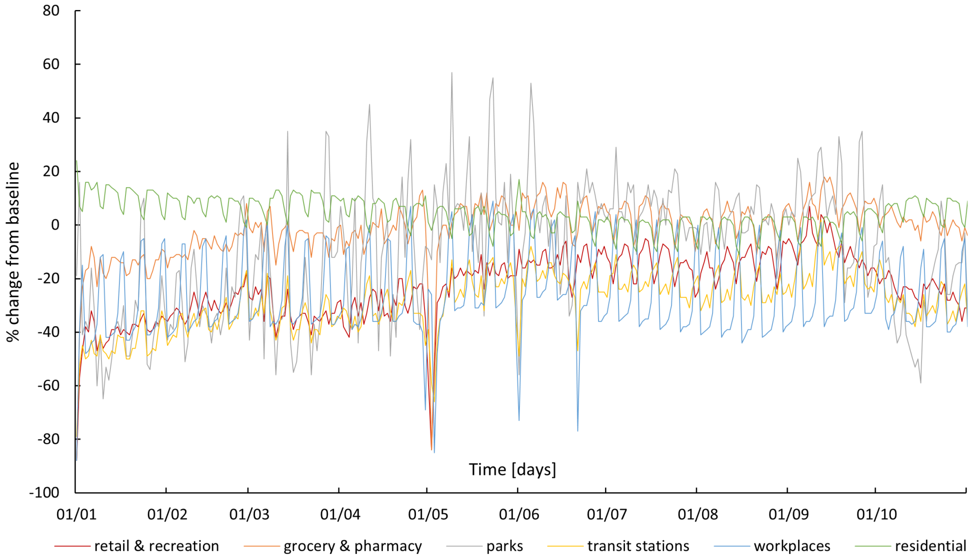


Figure 4.6: Movement trends over time, across different categories of places, Bucharest 2021 [Google 2022]

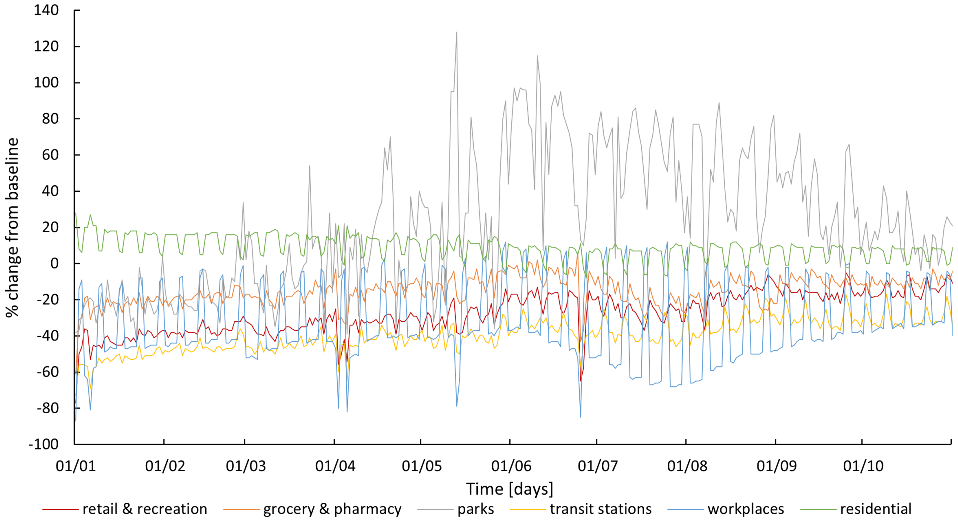


Figure 4.7: Movement trends over time, across different categories of places, Stockholm 2021 [Google 2022]

4.4 Emissions analysis

This section aims to analyse in detail each city under study to interpret and justify the results of CO_2 and NO_x emissions obtained. This analysis will consider the evolution of the pandemic situation in a given city, the mobility patterns on foot and by car observed in that period (Apple mobility) and also the mobility destinations of the populations (Google mobility). The calculation and consequent analysis of emissions are made based on the pandemic scenarios previously created and imported into the COPERT software.

4.4.1 Lisbon

Analysing the light-duty vehicles fleet in Lisbon, it can be concluded that 57.32% is made up of diesel vehicles, 40.50% of petrol-driven vehicles and 2.17% of vehicles powered by alternative fuels, as shown in Figure 4.1. This class of alternative fuels includes battery electric, Compressed Natural Gas (CNG) bifuel, flexi-fuel, fuel cell electric, Liquefied Petroleum Gas (LPG) bifuel. As the alternative fuel class is still quite residual in the total vehicle fleets, its influence on CO_2 and NO_x emissions is expected to be minor when compared to the remaining types. The measures to tackle COVID-19 referred to hereafter are based on the Communications from [Conselho de Ministros 2022].

March 2020

As noted in the earlier chapters, March 2020 corresponds to the time when the WHO declared COVID-19 to be a pandemic. In the city of Lisbon, measures to combat the spread of the virus were immediately implemented, which are explained in the methodology chapter. Figure 4.8 shows a decrease on March 12th, 2020, assuming a relative volume of mobility of 82.6%, due to the suspension of classroom activities in most schools in the country. On the 18th of March, the observed value is lower, 74.7%, due to the declaration of a state of emergency in Portugal. It is interesting to note that before this date, the values of mobility on foot were higher than those of mobility by car. However, with the implementation of the state of emergency and consequent first lockdown, walking mobility decreases due to people not being allowed to stay in the street without an essential reason. The destinations where an immediate decrease in trips or dwell time was observed in places after March 11 were Retail and recreation (minimum value of -89%), Parks, Workplaces and Transit stations (Figure 4.9). Regarding Grocery and Pharmacy, this destination did not reach such low values (minimum value of -65%) since this category of shopping is considered essential and, therefore, was part of the allowed trips. Thus, the only destination where dwell time increased throughout the month was Residential due to the lockdown imposed, reaching its maximum value of 40% at the end of the month.

Concerning CO_2 and NO_x emissions by the light vehicle fleet in Lisbon, the graphs presented are based on the results obtained in the COPERT software. In Figure 4.10, a sharp decrease is noticeable on March 12, especially in emissions by diesel and petrol vehicles. There is also a significant decrease in CO_2, around 21%, between the 13th and 14th, matching with the suspension of the face-to-face classes, mentioned above. At the end of the month, after the implementation of mandatory lockdown, emissions stabilise, remaining almost constant at 500 [t] for CO_2 and 2 [t] for NO_x, both values for diesel cars. Being that March was the month that marked the beginning of the pandemic and therefore major changes in mobility patterns, it is proven by the graph that at the beginning of the month the value of CO_2 emissions (diesel) was 2834 [t] and at the end of the month, this value was 507 [t].

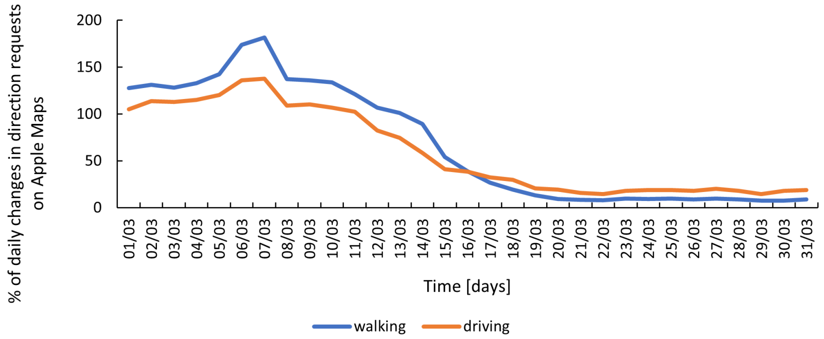


Figure 4.8: Apple mobility patterns, March 2020, Lisbon.

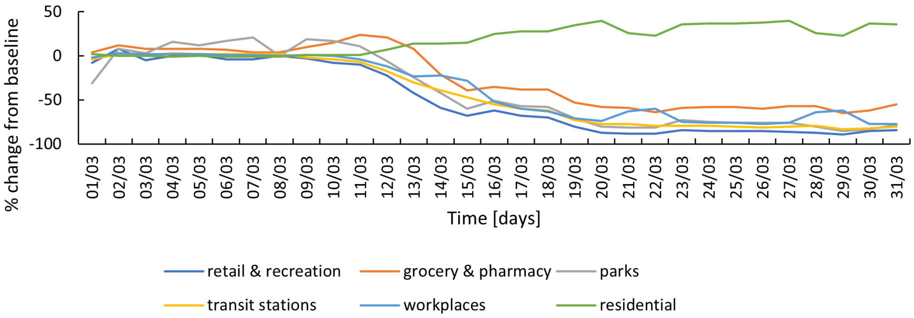


Figure 4.9: Google mobility patterns, March 2020, Lisbon.

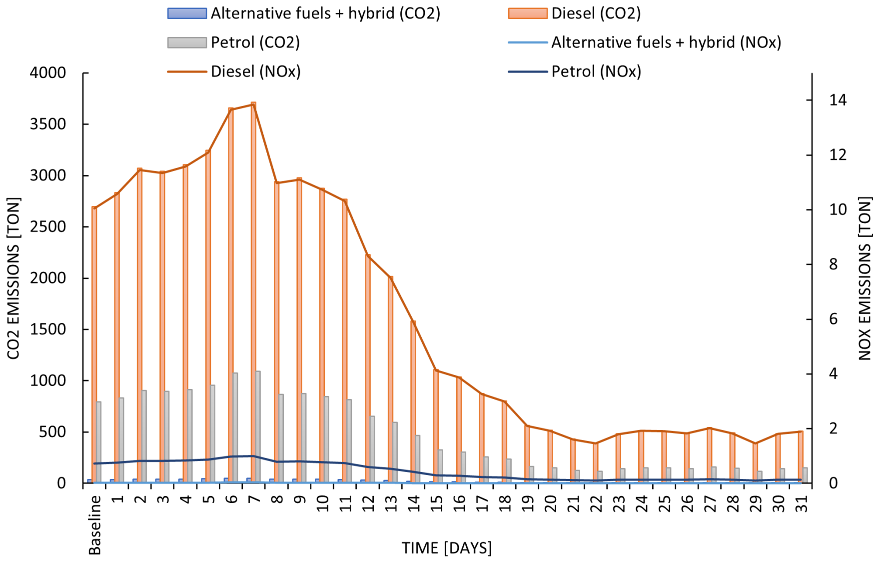


Figure 4.10: CO_2 and NO_x emissions, March 2020, Lisbon.

June 2020

The state of emergency previously implemented ended in May and so from then on the first phases of lifting lockdown measures in Lisbon city. This meant that in June the movement of people was greater. For example, the levels of mobility on foot and by car at the end of March were approximately 10% and 20% respectively. However, in June (Figure 4.11) these figures were approximately 32% and 61%, respectively. It is noticeable that the minimum values coincide with the weekends or national holidays (for instance, the 10th and 11th), which would be expected. Figure 4.12 also shows the influence of weekends. For example, in relation to the Residential destination curve, the minimum values are close to zero. This means that the difference between the mobility levels of these June weekends differs little from the weekend levels taken as Baseline (in a pre-pandemic period). In other words, if people normally already spend a significant part of the day at home, no major change related to the pandemic COVID-19 would be expected. The same kind of logic can be done with the Workplaces category. Given that on 15 June Lisbon moves to a new phase of confinement measures lifting, the percentage of daily change in the request for directions on the Apple Maps application increases slightly (Figure 4.11). This increase is also observed in the Retail and Recreation curve in Figure 4.12.

In Figure 4.13, which represents the total CO_2 and NO_x emissions for 3 categories of fuel, the increase in emission levels is perceptible. In the case of petrol-powered cars, CO_2 emissions throughout this month are around 514 [t] and NO_x 0.47 [t]. However, in March after the state of emergency was implemented, the equivalent values were 150 [t] and 0.13 [t], representing an increase of about 2,5 times.

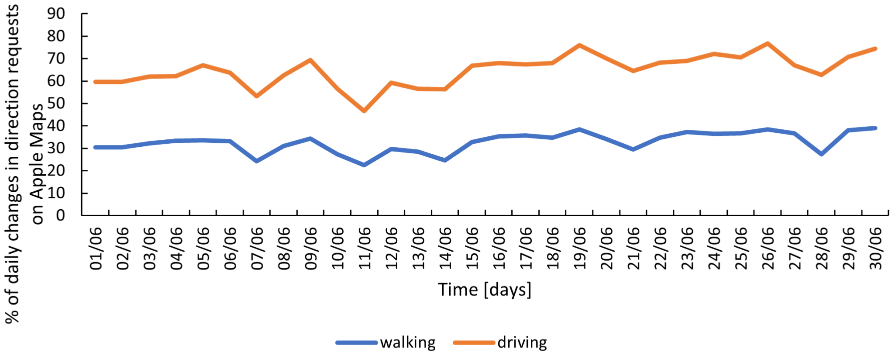


Figure 4.11: Apple mobility patterns, June 2020, Lisbon.

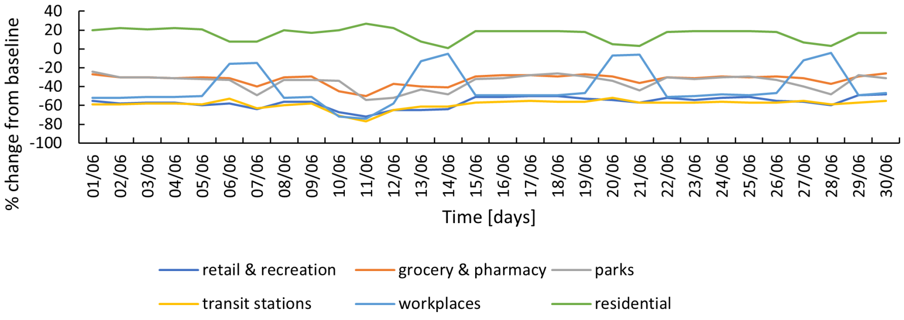


Figure 4.12: Google mobility patterns, June 2020, Lisbon.

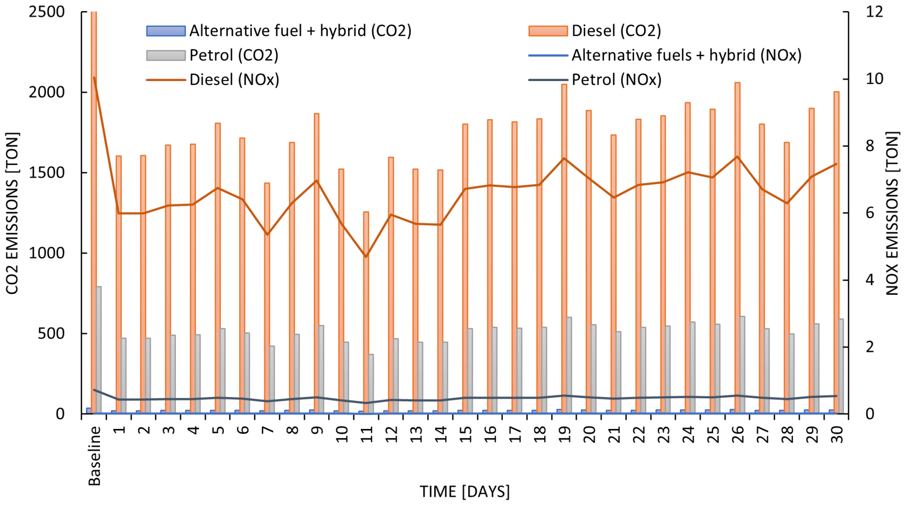


Figure 4.13: CO_2 and NO_x emissions, June 2020, Lisbon.

September 2020

At the end of August, the state of contingency in Lisbon [Conselho de Ministros 27 agosto 2020] was extended due to the increase in cases of contagion by the virus. Although teleworking is still present on a rotating basis in many services, the beginning of the in-person school year and a greater circulation of people in public transport, for example, would be expected. These movements are confirmed by Figure 4.14 in which the values for driving are above 100% (110%) and those for walking are around 85%, i.e., they are beginning to approach pre-pandemic mobility levels. In Figure 4.15, referring to Google Mobility data, the oscillations in mobility levels are not significant, compared with the month previously analysed. Only the Transit stations category stands out, which, as expected, increased its percentage by approximately 10%. In Figure 4.16, there is a significant change in CO_2 emissions especially. Throughout September, many of the days show CO_2 emission values that not only reach the values verified in a non-pandemic situation but exceed them. For example, the maximum CO_2 value for diesel vehicles (3586 [t]) on 4 September is about 33% higher than the baseline value (2695 [t]).

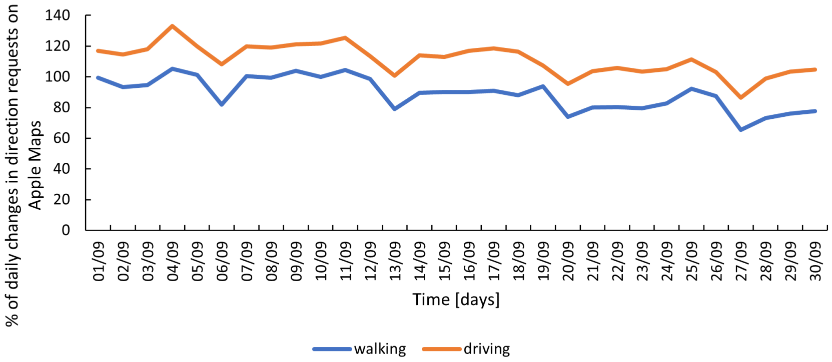


Figure 4.14: Apple mobility patterns, September 2020, Lisbon.

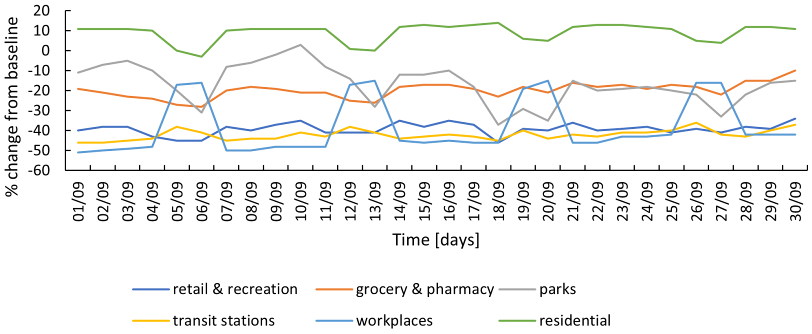


Figure 4.15: Google mobility patterns, September 2020, Lisbon.

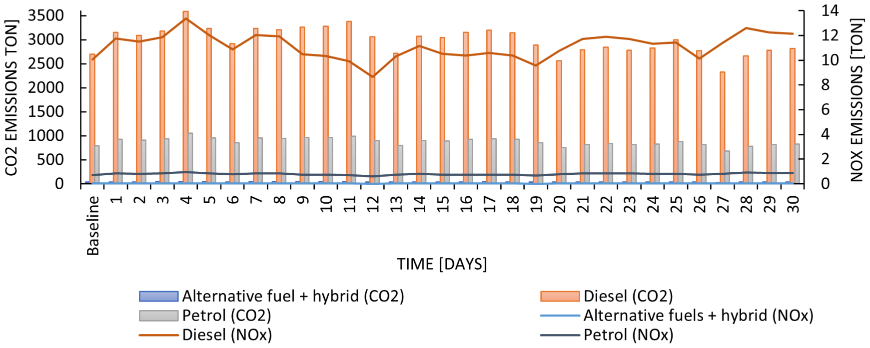


Figure 4.16: CO_2 and NO_x emissions, September 2020, Lisbon.

December 2020

At the end of November, there was a peak of new contagious cases in Portugal and therefore a new state of emergency was implemented, until the end of 2020. Thus, the month of December presented measures restricted to the displacement and concentration of people. Figure 4.17 shows a less constant trend than the previous months of 2020. In this case, the maximum driving values are close to 80% while the minimum values are around 50%, corresponding to weekends or national holidays. When comparing Figure 4.18 of this month with the equivalent of September, it may be concluded that the trend in the Residential category is very constant, the influence of weekends being less. The three oscillations which stand out correspond to days 1, 8 and 25, all national holidays. The remaining categories show lower values on weekends. At the end of the month, there is also a large decrease due to the Christmas festivities.

Regarding emissions, in Figure 4.19, the values for CO_2 and NO_x are once again lower than the baseline values, indicating that the state of emergency and the restrictions on travel had a real impact on mobility and emissions of pollutants. As in the previous charts for this month, the influence of weekends and holidays is noticeable, with a decrease of approximately 47% compared to weekdays.

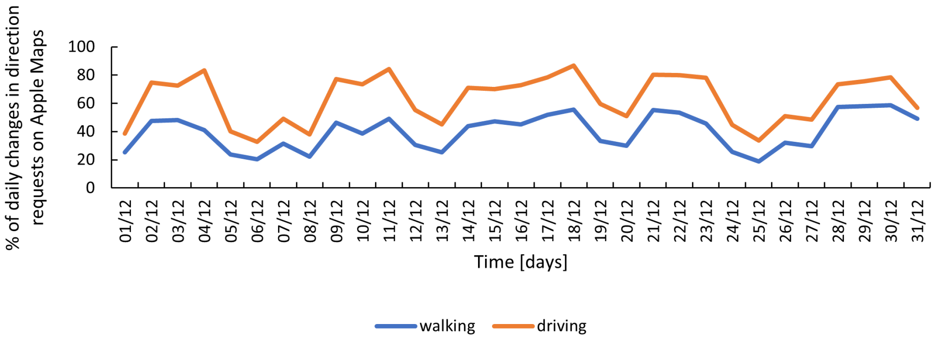


Figure 4.17: Apple mobility patterns, December 2020, Lisbon.

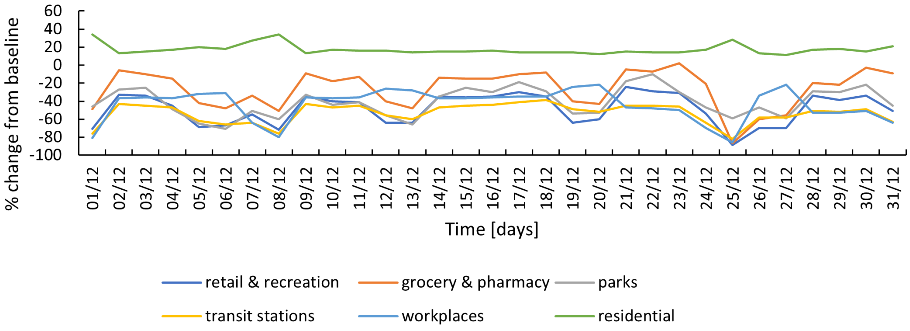


Figure 4.18: Google mobility patterns, December 2020, Lisbon.

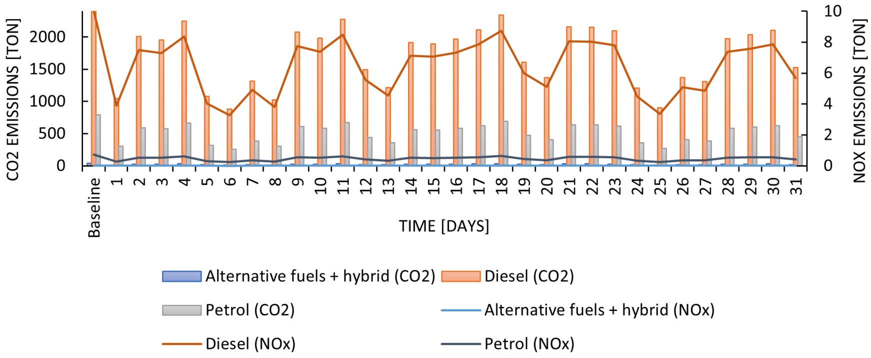


Figure 4.19: CO_2 and NO_x emissions, December 2020, Lisbon.

January 2021

At the beginning of the year the country remains in a state of emergency. Furthermore, on day 1 and weekend days 9-10 lower values of mobility, both driving and walking, would be expected due to the holiday and specific travel restrictions, respectively. Figure 4.20 proves this. In the second half of the month, the trend of the curves is more constant, with oscillations only on weekends.

Given the suspension of retail trade activities between 15 and 30 January, it was expected that the Retail and Recreation curve in Figure 4.21 would take lower percentages, which is the case. In addition, school and non-school activities are also suspended between 22 January and 5 February. All these reasons led to lower levels of mobility in January. As for Figure 4.22 representing emissions, the trend in the columns and lines follows the trend in Figure 4.20. In general, the absolute values are lower than those observed in December 2020.

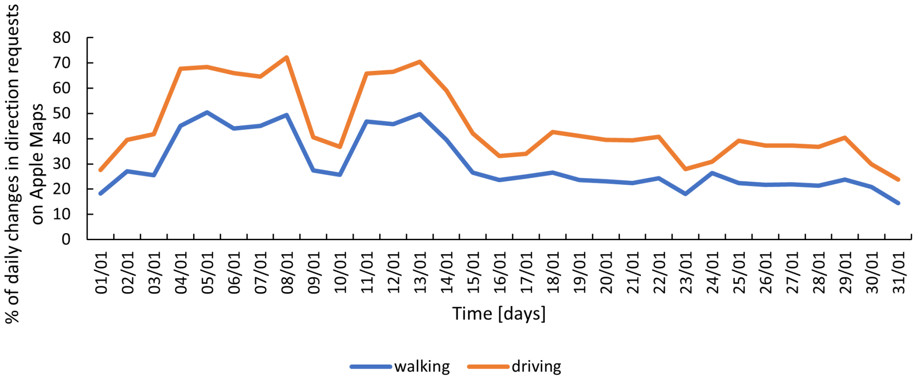


Figure 4.20: Apple mobility patterns, January 2021, Lisbon.

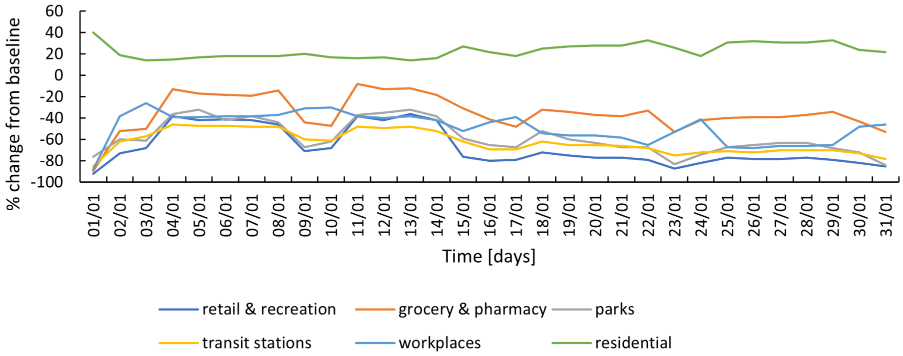


Figure 4.21: Google mobility patterns, January 2021, Lisbon

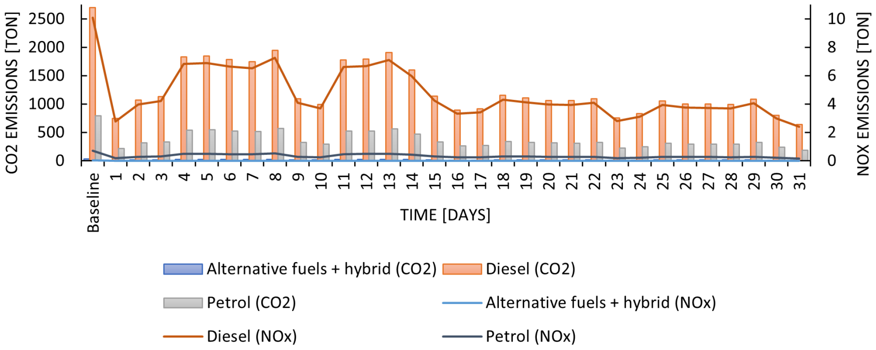


Figure 4.22: CO_2 and NO_x emissions, January 2021, Lisbon

April 2021

In April, most of the face-to-face teaching activities had resumed, except for those in higher education which only resumed on 19 April. In other words, the measures implemented were less restricted. In addition, shopping centres and concert halls also opened, meaning a gradual increase in people moving around. Mobility patterns from Apple and Google, for April 2021, are shown in Figure 4.23 and Figure 4.24, respectively. Figure 4.25 shows a slight increase from 19 April, especially for CO_2 emissions from diesel vehicles. Comparing the day with the highest number of emissions, day 30, with the initial Baseline value, there is a decrease of about 12%. That is, the values of emissions in April 2021 were very close to the values for a pre-pandemic period.

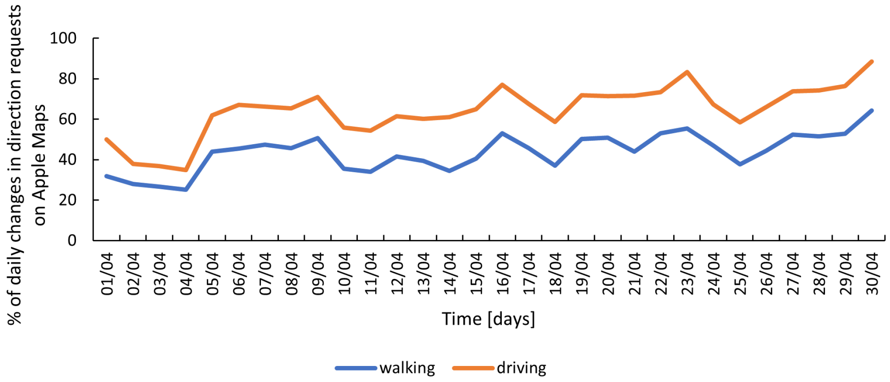


Figure 4.23: Apple mobility patterns, April 2021, Lisbon.

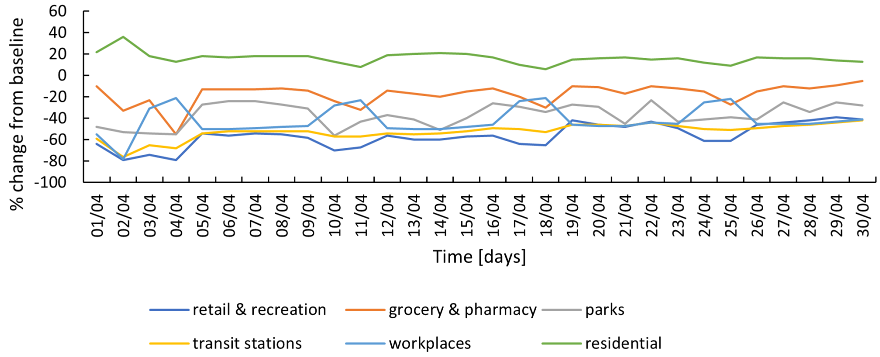


Figure 4.24: Google mobility patterns, April 2021, Lisbon.

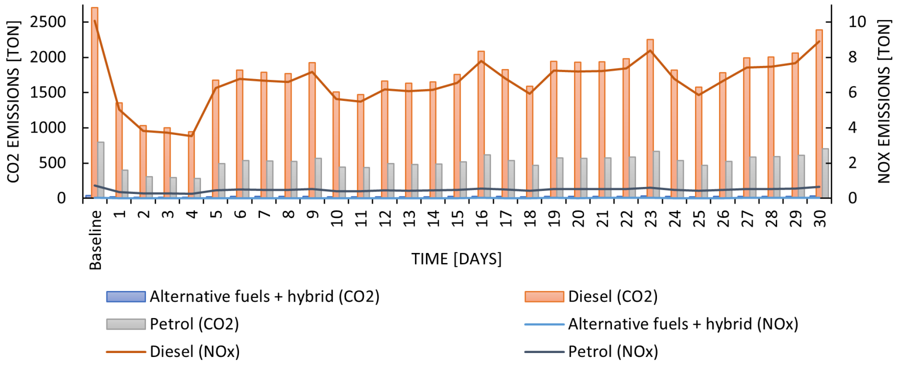


Figure 4.25: CO_2 and NO_x emissions, April 2021, Lisbon.

July 2021

Given the worsening of the pandemic situation in the Lisbon region, measures are implemented restricting circulation on weekends and holidays. For example, at weekends in April the driving mobility figures were approximately 58% while in July the equivalent figures are around 90% (Figure 4.26). Concerning Figure 4.27, we can observe that July is the first month in which the curve corresponding to the Grocery and pharmacy category takes on positive values. This phenomenon occurs on weekdays, indicating that the number of trips to this type of destination was very close to the baseline, on these days.

In Figure 4.28, besides the influence of the weekends (especially Sundays), it can be noticed that on the great majority of the days, the value of CO_2 and NO_x emissions exceeds the Baseline value.

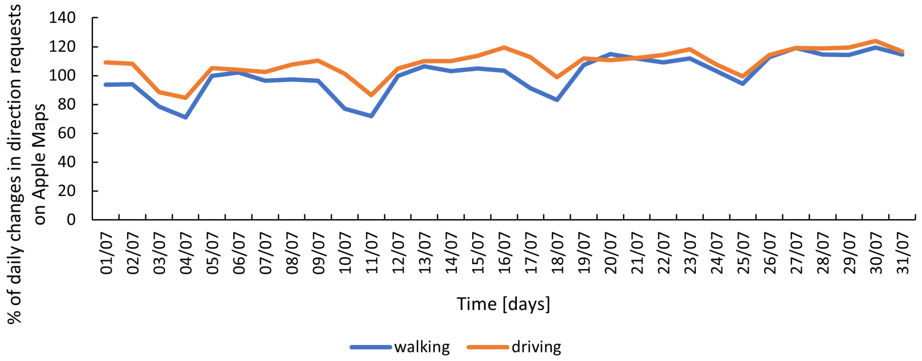


Figure 4.26: Apple mobility patterns, July 2021, Lisbon.

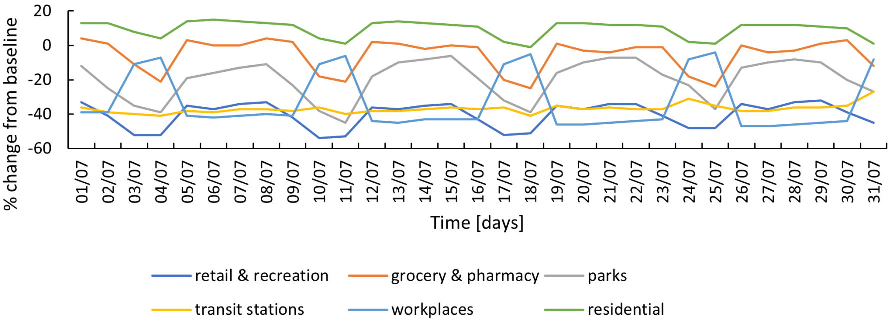


Figure 4.27: Google mobility patterns, July 2021, Lisbon.

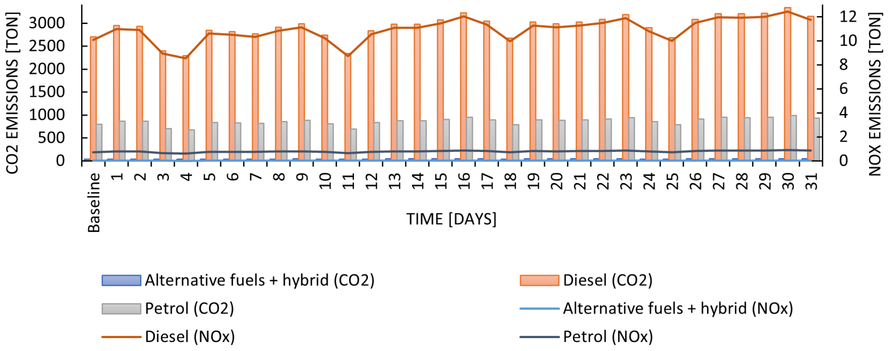


Figure 4.28: CO_2 and NO_x emissions, July 2021, Lisbon.

October 2021

It was at the beginning of October that Portugal reached 85% of the vaccinated population. Thus, a gradual lifting of measures to combat the virus took place. The elimination of the recommendation of teleworking, a measure that kept many workers at home, stands out. Figure 4.30 shows the highest figures for Workplaces (approximately -29%), i.e., people actually moved more to their workplaces this month. By way of comparison, in March 2020 the equivalent figures tinged at -89%.

The percentage of daily change in the number of requests for directions in the Apple Maps app reaches maximum values between the months analysed, in driving (190%) and walking (233%), in Figure 4.29. Not even in early March 2020, before COVID-19 was declared a pandemic, these values were so high. This indicates that the population in Lisbon was already moving ”normally”. Regarding Figure 4.30, the only oscillation outside the weekend pattern corresponds to the bank holidays of 5th October. On this day, the values for all curves except for the Parks and Residential category show lower values than usual. Note that this is also the first month in which there are positive values in the Parks curve, on weekdays, after March 2020.

Regarding the emissions, Figure 4.31, the values for day 8, 5.15E03 [t] for CO_2 (diesel) and 19.18 [t] for NO_x (diesel) are highlighted. These values contrast greatly with the baseline value, translating into an increase of 90% for both cases, approximately.

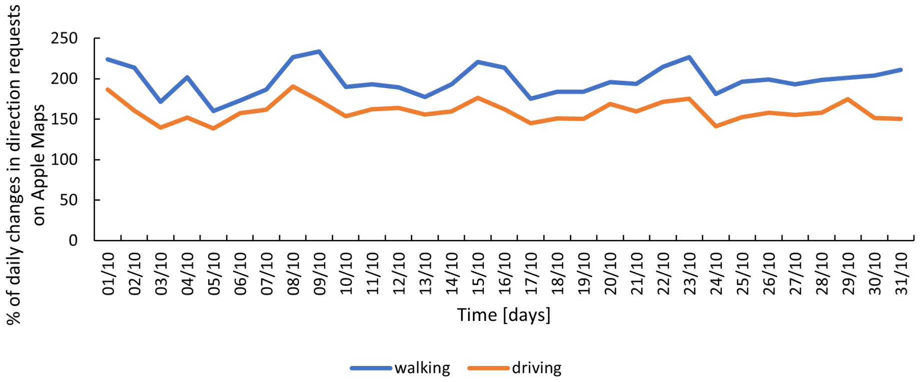


Figure 4.29: Apple mobility patterns, October 2021, Lisbon.

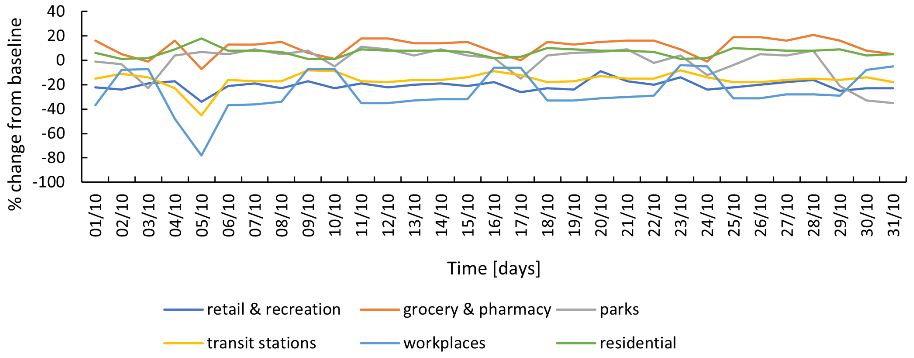


Figure 4.30: Google mobility patterns, October 2021, Lisbon.

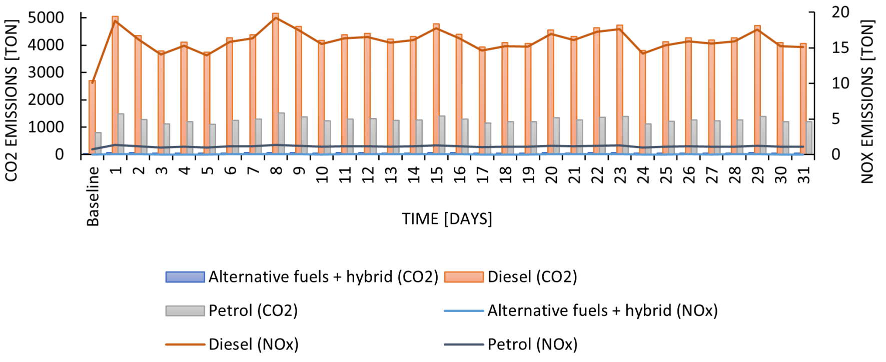


Figure 4.31: CO_2 and NO_x emissions, October 2021, Lisbon.

4.4.2 Bucharest

When analysing the light vehicle fleet in Bucharest, it can be seen that 62.43% consists of petrol vehicles, 34.46% of diesel vehicles and 3.11% of alternative fuel vehicles, as shown in Figure 4.1. As the alternative fuels class is small in the total fleet, its influence on emissions is expected to be minimal. The following analysis was based on [Crisis24 2021], [Global monitoring 2021], [ECDC 2022] and [UNECE 2022].

March 2020

Although the first case of COVID in Romania was reported at the end of February, the state of emergency was decreed only on 16 March. Teleworking was recommended and teaching activities were suspended. As a few days passed, more restrictive measures were added, such as the closure of entertainment venues and gyms. On 21 March, shopping centres closed, except for essential shops.

It is possible to observe in the charts relating to Apple's data the patterns of driving and walking mobility. Despite some oscillations at the beginning of the month, the curves decrease from the 9th and assume an almost constant behaviour from March 22nd onwards (20% for driving), and there is no longer such a significant influence of the weekends (Figure 4.32). Figure 4.33 shows a peak in the curve for Grocery and pharmacy on March 11th and then the curve begins to assume negative values from March 14th onwards. Regarding the Residential curve, despite the decree of lockdown on March 25, it did not undergo any major changes, remaining relatively constant on weekdays and taking on values of around 30%. Most of the curves become negative as of March 9, the date on which the first restrictive measures were adopted in Romania.

Regarding CO_2 and NO_x emissions, Figure 4.34, the data trend follows the trend of Figure 4.32. A decrease can be noticed from the middle of the month and the difference in the level of CO_2 emissions between the last day of the month and the baseline is -78% while in Lisbon the equivalent value was -81%.

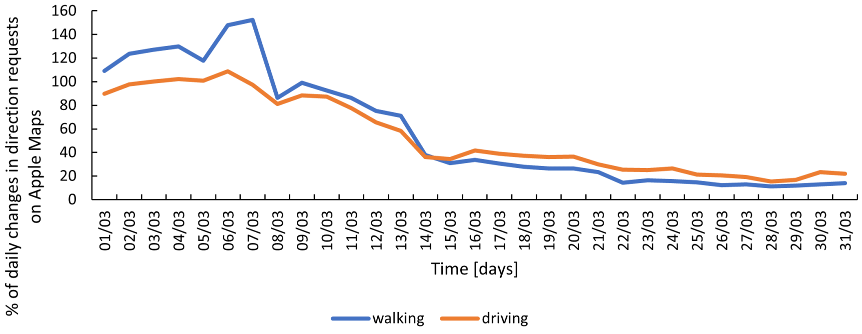


Figure 4.32: Apple mobility patterns, March 2020, Bucharest.

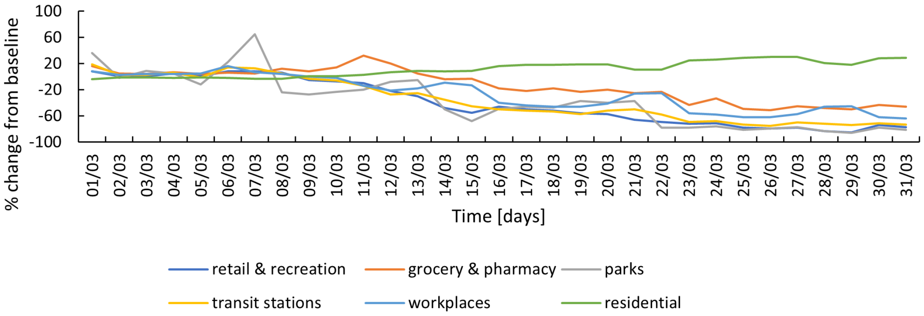


Figure 4.33: Google mobility patterns, March 2020, Bucharest.

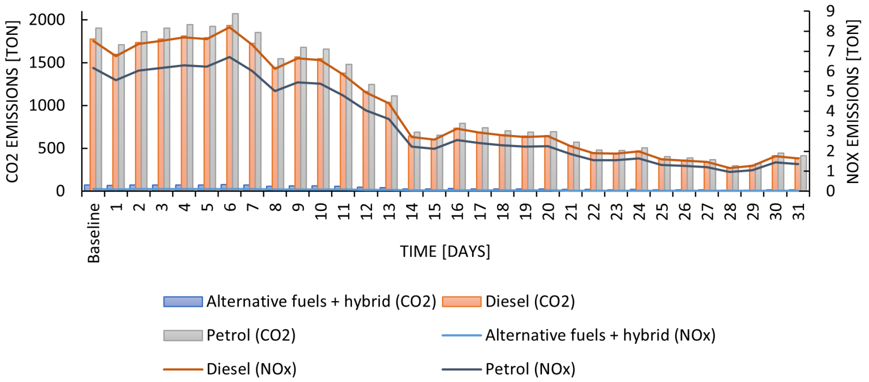


Figure 4.34: CO_2 and NO_x emissions, March 2020, Bucharest.

June 2020

By mid-May the measures became less stringent with movement restrictions outside the locality/metropolitan area being lifted in early June. Although schools remained closed, in the first two weeks of June some specific years were allowed back onto the premises. This means that June could be expected to have higher levels of mobility compared to the end of March 2020, for example. In this case, the levels for driving increased 242% if we compare 31st March with 1st June (Figure 4.35). In the case of walking, it increased by 379%. However, it is necessary to take into account the fact that the weather conditions are better at this time of the year, which leads people to walk more outdoors. Once again, the influence of the weekends is noticeable, with Sunday corresponding to the lowest values on the curve. Although on weekdays the curves are almost constant, there is a subtle increase throughout the month. As for the graph representing the change in the number of trips or time spent at certain places, Figure 4.36, the graph for June indicates that people spent less time at home since the Residential curve values are around 9% on weekdays and close to 0% on weekends.

Looking at Figure 4.37, which shows CO_2 and NO_x emissions, it can be seen that it follows the same trend as Figure 4.35, i.e., shows a slight increase in the last weeks of the month. For example, on the 24th a NO_x emission value (for diesel vehicles) higher than the baseline value is registered. In addition, the total emission values on weekends are also increasing throughout the month. In an overview of June, comparing day 1 with day 30, there is an increase of 36.9%.

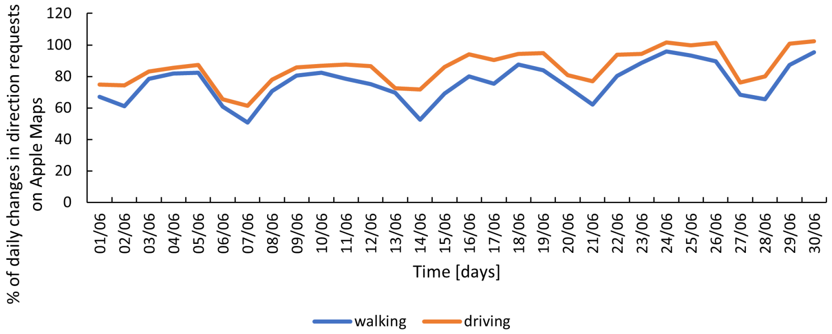


Figure 4.35: Apple mobility patterns, June 2020, Bucharest.

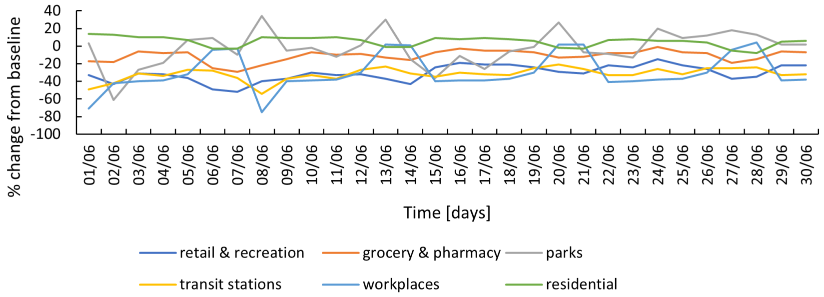


Figure 4.36: Google mobility patterns, June 2020, Bucharest.

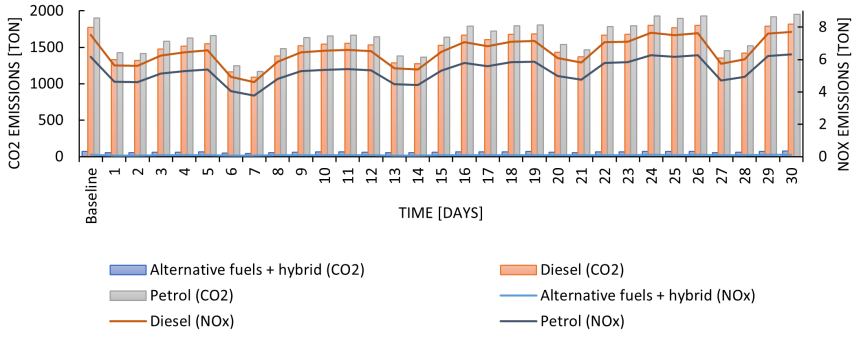


Figure 4.37: CO_2 and NO_x emissions, June 2020, Bucharest.

November 2020

At the beginning of October, the number of new cases of COVID-19 infection rises again, reaching a peak of 2020 on 18 November. This increase led to new measures being implemented, such as a night curfew starting on the 9th and lasting for 30 days. With this measure, primary and secondary schools were closed, with teaching activities going online. Despite this, in Figure 4.38 there is no notable significant change from this date onwards. In general, the values taken by the driving and walking curves are slightly lower than in June, by about 20%. In Figure 4.39, on the other hand, the behaviour of the curves is not altered on a weekly basis. The only different oscillation in this graph, on day 18 and the Parks curve, coincides with the peak in the driving curve in the previous graph. Compared to June 2020, the Parks curve assumes lower values, no longer assuming positive values.

Regarding emissions, shown in Figure 4.40, the panorama is significantly different from that observed in June. While in June the emission values exceed the baseline values, in November they decrease again. For example, on day 1, compared to the baseline, there is a decrease of about 35% in CO_2 emissions by diesel vehicles. Furthermore, in the three graphs, it can be seen that on 30 November a different behaviour occurs, corresponding to a bank holiday. For example, in Figure 4.38 the lowest driving and walking values occur on that day and in Figure 4.39 we also observe that people spent more time at home (Residential curve) and less time than usual at workplaces (Workplaces curve). In the emissions, Figure 4.40, the lowest value of emissions also occurs on this day. All this proves the influence of a public holiday on mobility patterns and the amount of CO_2 and NO_x emissions by the circulating fleet on that day.

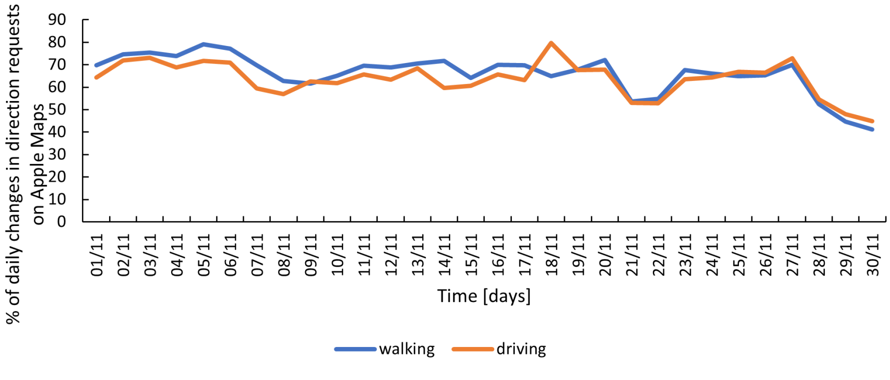


Figure 4.38: Apple mobility patterns, November 2020, Bucharest.

Figure 4.39: Google mobility patterns, November 2020, Bucharest.

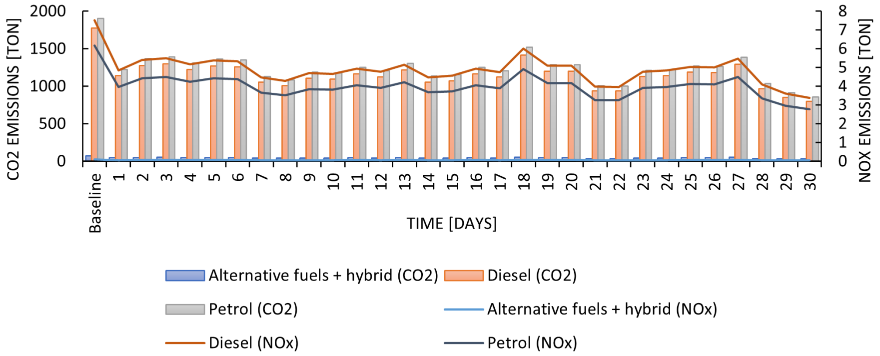


Figure 4.40: CO_2 and NO_x emissions, November 2020, Bucharest.

December 2020

In December the alert state imposed in November is extended until mid-January 2021. This means that mobility patterns are expected to remain similar to the previous month, despite the influence of the Christmas holiday season. Although the influence of the weekends is noticeable, there is a greater decrease between the 23rd and 28th of the month. At the end of the month, on the 31st, there is a decrease once again, reaching values close to those verified on the 1st of December, a bank holiday. As regards Figure 4.42, December shows more oscillations and less constant behaviour than November. Whereas in November the Grocery and pharmacy curve was only negative, now it is sometimes positive, with a peak (12%) on the 23rd.

Concerning emissions, Figure 4.43 shows a similar trend to Figure 4.41, i.e., the influence of weekends and holidays or festive periods. For example, a higher amount of CO_2 and NO_x emissions were emitted on day 18. However, this is still lower than the baseline, proving that the levels of traffic on Bucharest's roads were not yet ”normal”.

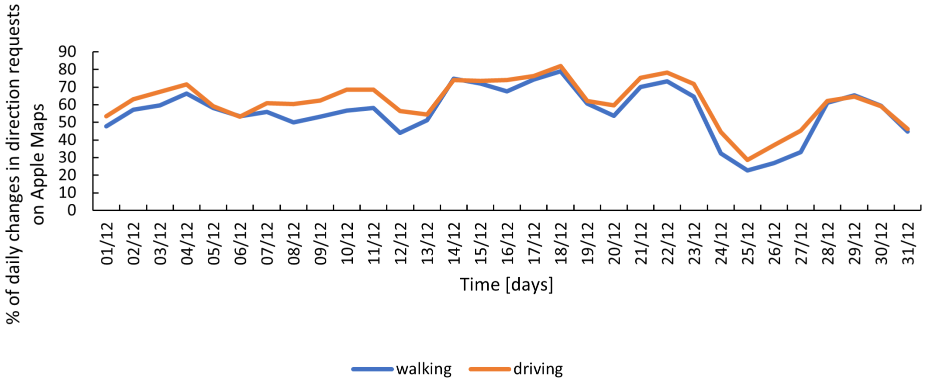


Figure 4.41: Apple mobility patterns, December 2020, Bucharest.

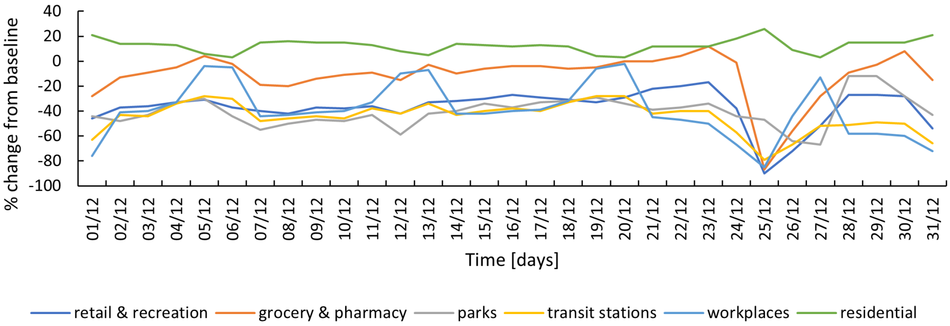


Figure 4.42: Google mobility patterns, December 2020, Bucharest.

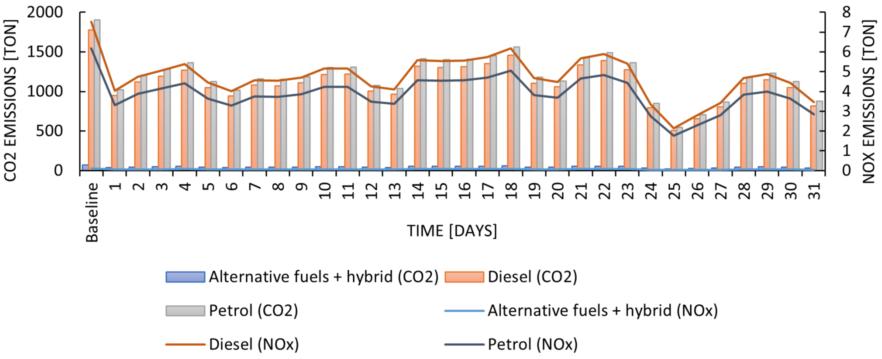


Figure 4.43: CO_2 and NO_x emissions, December 2020, Bucharest.

January 2021

Although at the national level the state of alert was extended until 12 February, the picture in Bucharest was more flexible. From 25 January the measures in Bucharest were eased, with changes focused on restaurants, cafes and entertainment venues and cultural events.

Figure 4.44 shows that the day with the lowest percentage of changes in the Apple Maps directions request was the 1st of January, which corresponds to a national public holiday and therefore, regardless of the pandemic, many people would stay at home. Despite some influence from weekends (smaller than the one verified in December 2020), the percentages relative to weekdays are very similar to each other. After 25 January, the trend of the curves does not change significantly, indicating that in practice this measure was not reflected as expected.

The Residential curve, Figure 4.45, assumes almost constant values, with no such large oscillations on weekends as was the case in previous months. In other words, the time spent at home by people was approximately the same during the month. The remaining curves, except Workplaces and Parks, present a behaviour similar to Residential in what concerns the absence of great oscillations.

Concerning CO_2 and NO_x emissions, we can see in Figure 4.46 that they do not vary much throughout the month. Again, the lowest value of emissions is registered on day 1, with a 67% decrease in CO_2 emissions by diesel vehicles, when compared with the baseline.

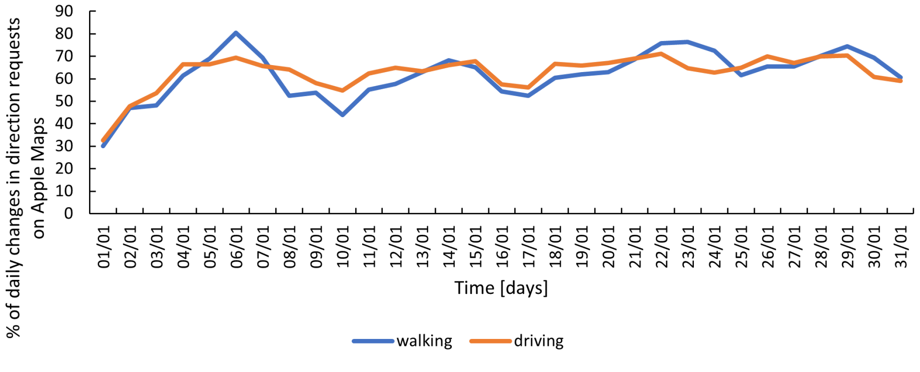


Figure 4.44: Apple mobility patterns, January 2021, Bucharest.

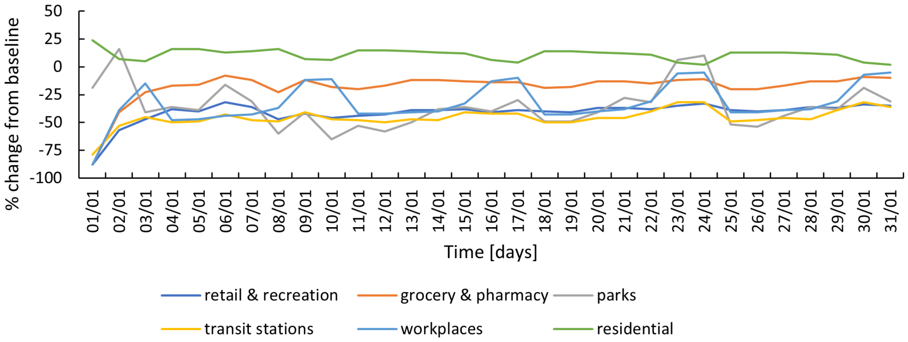


Figure 4.45: Google mobility patterns, January 2021, Bucharest.

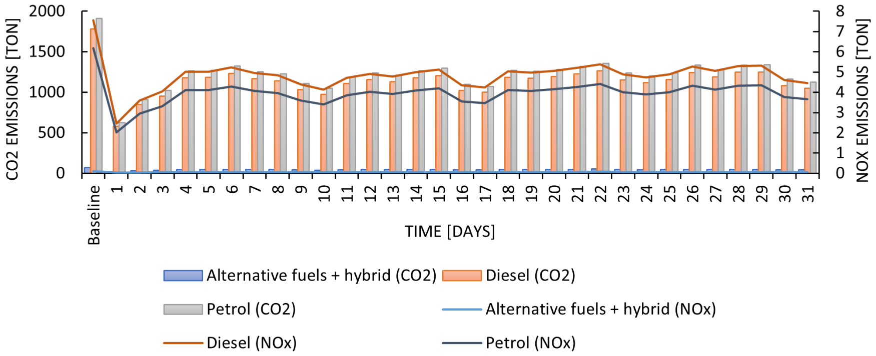


Figure 4.46: CO_2 and NO_x emissions, January 2021, Bucharest.

March 2021

At the end of February, the number of new infections increases, with a peak in the last two weeks of March. Therefore, the government decided to implement more restrictive measures regarding the circulation of people and attendance in public spaces from the second week of the month. At the end of March, schools were still not providing face-to-face classes. In addition, the state of alert is extended until mid-April, continuing the night curfew as well. However, the measures implemented depended on the severity of the pandemic situation in each region of the country.

According to Figure 4.47, the percentage of change in the levels of mobility on foot reach values greater than 100%, indicating that people were already moving on foot more than in the pre-pandemic period. This peak is reached on the 5th of March. On the following day, a large decrease is registered, with this value becoming 61%. In the rest of the month, there are some oscillations, most of them coinciding with weekends.

In relation to Figure 4.48, it can be seen that, in comparison with the previous months, the curve for Grocery and pharmacy is very close to 0% indicating that the mobility of people was very close to the one registered in the pre-pandemic period, even exceeding that value. The Parks curve is the one that shows the greatest oscillations, especially on the 14th, which is a Sunday, and on the weekend 27-28. In Figure 4.49, it can be seen that CO_2 and NO_x emission levels were closer to baseline levels compared to previous months.

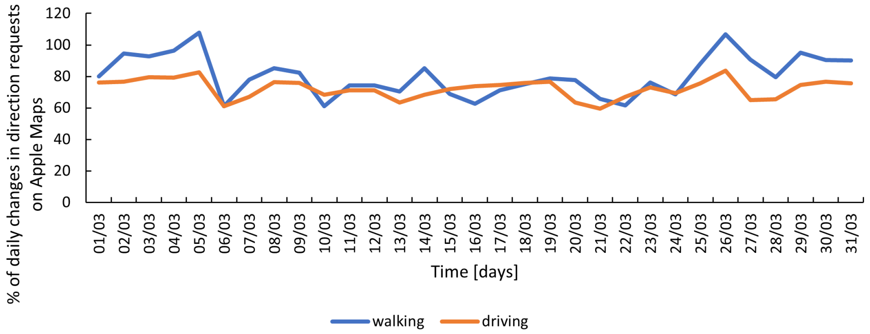


Figure 4.47: Apple mobility patterns, March 2021, Bucharest.

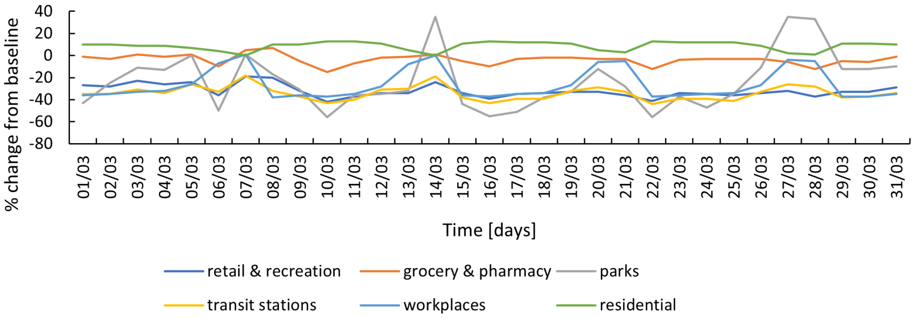


Figure 4.48: Google mobility patterns, March 2021, Bucharest.

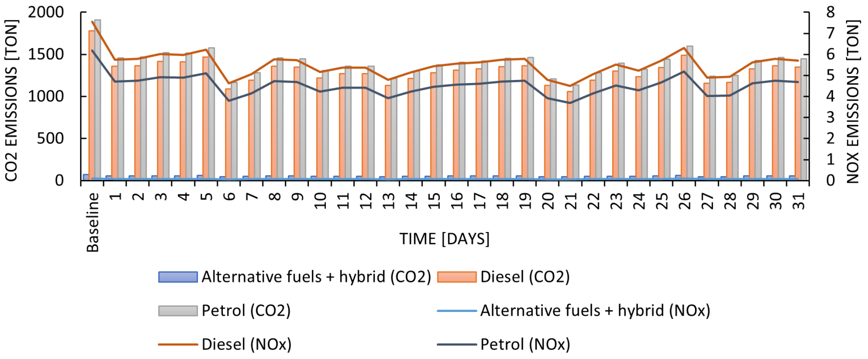


Figure 4.49: CO_2 and NO_x emissions, March 2021, Bucharest.

July 2021

In June, the pandemic situation in Romania was calmer as the number of new infections was lower. Therefore, the measures that had been implemented before were further relaxed in July, notably concerning catering services, and the number of participants in events and sports facilities. However, the state of alert would be extended until mid-August.

For the first time in 2021, the percentage change in the number of requests for directions in Apple Maps, Figure 4.50, reaches values above 110%, registering 113.91% for driving and 137.12% for walking. After March 2020 the only time values above 100% were recorded in June 2020. Once again, the influence of weekends is observed, whose mobility levels are lower, and throughout the month the curves tend to increase.

As far as Figure 4.51 is concerned, the change in the behaviour of the curves between March and July 2021 is highlighted. In this case, the Parks curve assumes higher and almost always positive values, indicating that in fact, people circulated more in parks. This would be expected given the improvement in weather conditions. Regarding the Transit stations curve, an increase of approximately 10% is also observed, when compared with the previous month.

Regarding CO_2 and NO_x emissions (Figure 4.52), the general picture is very different from that observed in March 2021. In July 2021, on most days the amount of emissions by the circulating fleet on that day is higher than the baseline value. On July 20th, the day of the month with the most emissions, the CO_2 value (diesel vehicles) is 36% higher compared to the baseline. In general, only at weekends, the value is close to the baseline value.

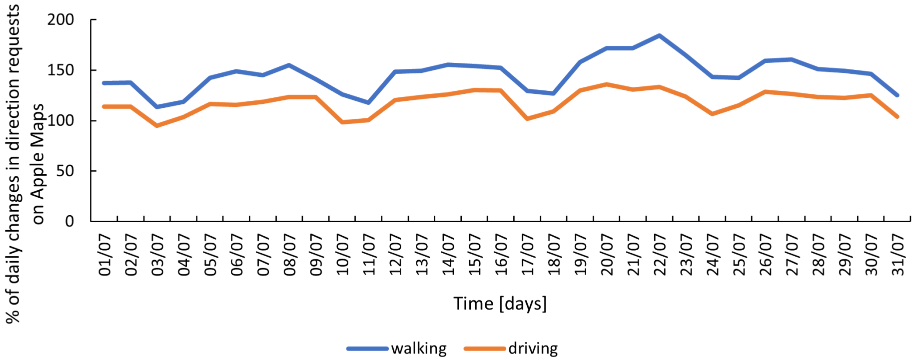


Figure 4.50: Apple mobility patterns, July 2021, Bucharest.

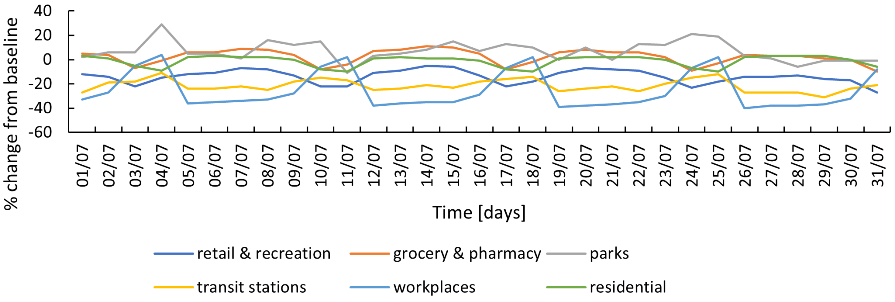


Figure 4.51: Google mobility patterns, July 2021, Bucharest.

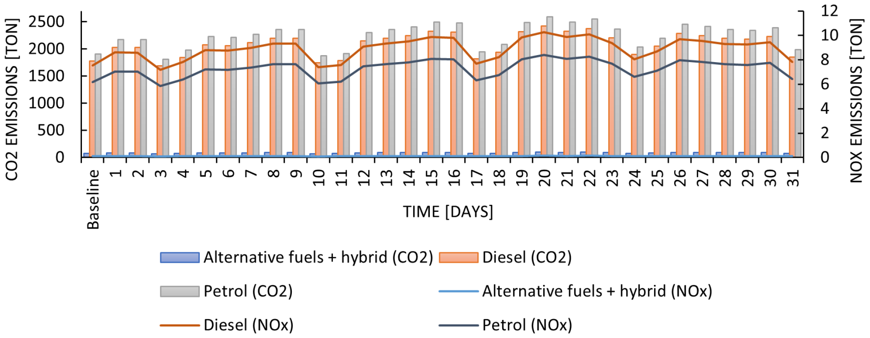


Figure 4.52: CO_2 and NO_x emissions, July 2021, Bucharest.

October 2021

In October the situation was more worrying as rates of infection with COVID-19 increased. The second-highest peak in the number of new cases since the outbreak of the pandemic was recorded in the fourth week of October. In addition, the state of alert had been extended until November 9. Therefore, new, stricter measures have been implemented. Noteworthy is the obligation to wear masks in various places, and the attendance of sports, catering and cultural facilities only by fully vaccinated or recovered persons. In addition, there is a curfew on weekends for unvaccinated people. In the meantime, teleworking is recommended whenever possible and, as of 25 October, schools are closed. Although a reduction in mobility levels is to be expected, Figure 4.53 demonstrates the opposite. The driving curve remains between 100% and 150%, as recorded in July 2021. Moreover, the trend of the curve is constant throughout the month. In the walking curve, there is a decrease of 83% in the first half of the month, and on day 1 the percentage of change in driving requests was 206%.

In Figure 4.54, it is noted that the Residential curve assumes higher values than in previous months, indicating that people did indeed spend more time at home due to the new restrictions. One can also notice a big difference in the behaviour of the Parks curve, which assumes much lower values than in July (for example on day 16 it assumes -

59%). Furthermore, in this month the curve rarely assumes positive values. A secondary cause for this phenomenon could be the less pleasant climate. The Workplaces curve also assumes lower values on weekends, in comparison with the previous months. On weekdays, although teleworking has been implemented, there is no noticeable significant change in the Workplaces curve but rather in the Transit stations curve.

Regarding gas emissions (Figure 4.55), the average CO_2 emissions (petrol vehicles) suffered a decrease of 16.8% compared to the equivalent value of July 2021. However, the average emissions of October 2021 are only 2% lower than the baseline value. Overall, although more stringent measures have been implemented over the month, this is not reflected in the emissions.

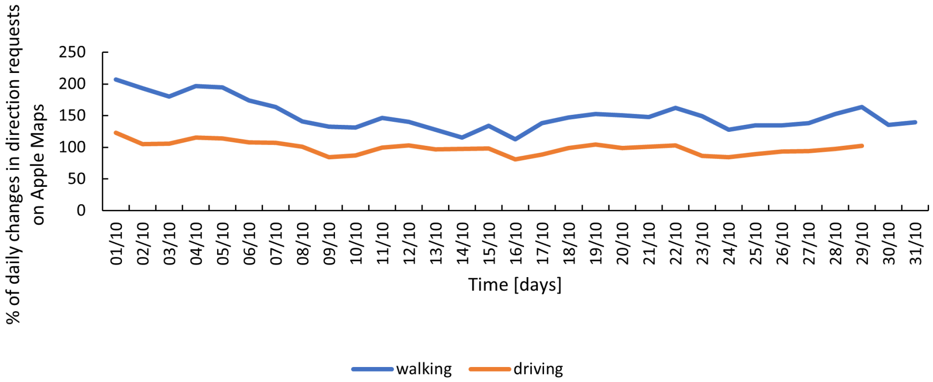


Figure 4.53: Apple mobility patterns, October 2021, Bucharest.

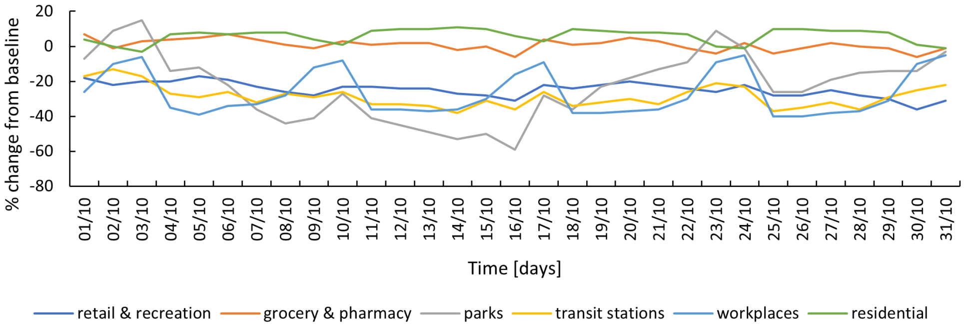


Figure 4.54: Google mobility patterns, October 2021, Bucharest.

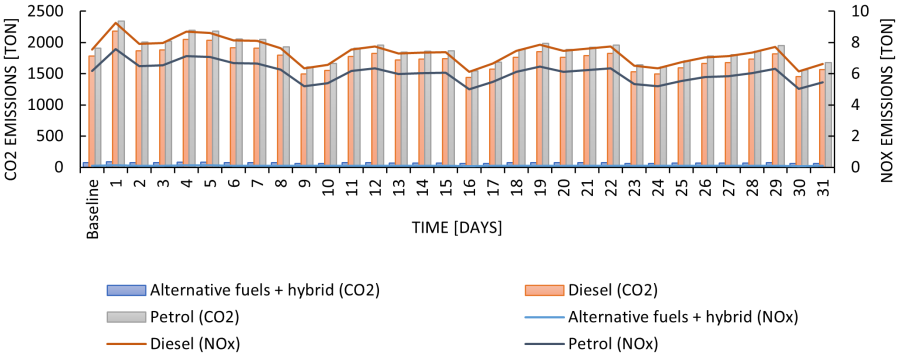


Figure 4.55: CO_2 and NO_x emissions, October 2021, Bucharest.

4.4.3 Stockholm

The data used in this study leads to the conclusion that the light vehicle fleet in the city of Stockholm consists of 64.14% petrol-powered vehicles, 34.25% diesel-powered vehicles and only 1.61% alternative fuel vehicles, as shown in Figure 4.1. Once again, as the latter class represents a very small proportion of the light vehicle fleet, its influence on emissions should be minimal. The following analysis was based on [Ludvigsson 2020], [WHO 2022], [Olofsson and Vilhelmsson 2022], [ECDC 2022], [Government Offices of Sweden 2022] and [Krisisinformation 2021].

March 2020

The first case of infection was confirmed in Sweden in early February 2020, before the WHO declared the situation a pandemic. Compared to other European countries, more stringent measures were only implemented at the end of March 2020, including limits on participants at events. In addition, a general lockdown was not implemented as in other places and the vast majority of school establishments remained open. Overall, it can be said that the country has chosen a different approach to the pandemic situation. This view is shared by [Ludvigsson 2020] who states that the Swedish authorities focused on slowing down rather than stopping the pandemic.

For example, when comparing the level of mobility on March 11, 2020 with the value on March 31, one notices a reduction of only 20.5%, in Figure 4.56 for the driving curve. In fact, the trend of the curves remains almost constant over the last two weeks. This indicates that although some containment measures have been implemented, they have had little effect on the mobility of people. Furthermore, in comparison with the countries previously analysed, the influence of weekends on the curves is not remarkable.

Figure 4.57 shows that the Residential curve has experienced an increase of about 20% since the beginning of the month, demonstrating that people have indeed spent more time at home. The Retail and Recreation, Transit stations and Workplaces curves show very similar behaviour between them, decreasing from March 9th onwards by about 40%. However, in the Workplaces curve, the influence of the weekends is noticeable.

Concerning CO_2 and NO_x emissions by the circulating fleet, it is not obvious from Figure 4.58 the influence of the measures implemented in Sweden. For example, when again comparing day 11 with day 31, there is a decrease of 20.5%. Compared to the baseline value, day 31 shows a decrease of only 23.9%.

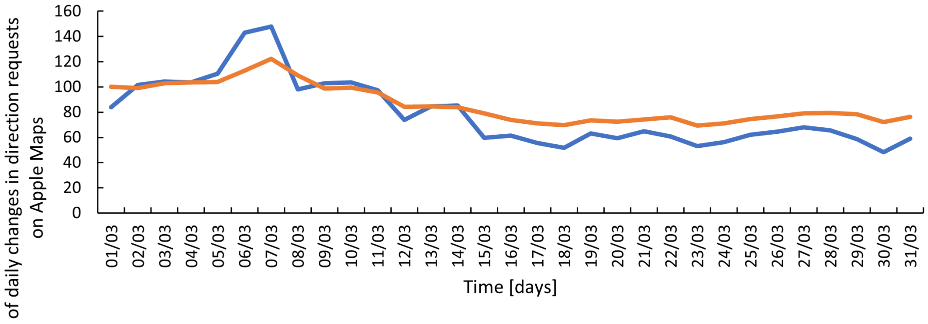


Figure 4.56: Apple mobility patterns, March 2020, Stockholm.

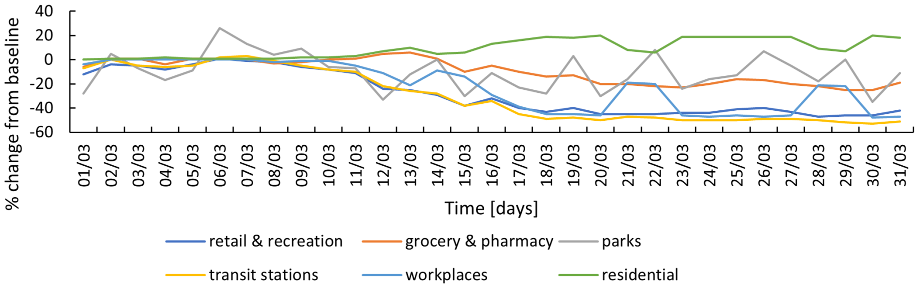


Figure 4.57: Google mobility patterns, March 2020, Stockholm.

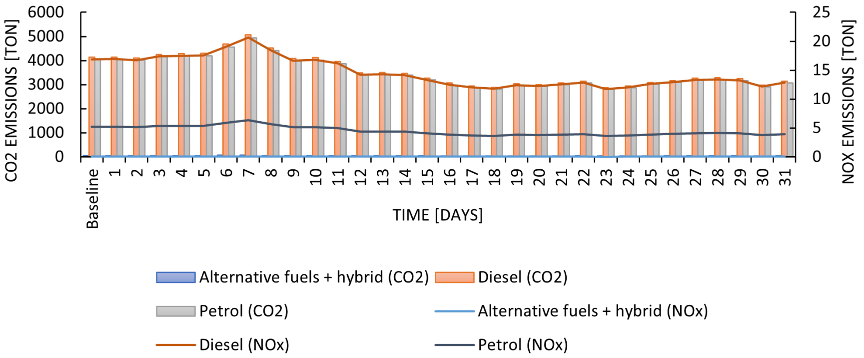


Figure 4.58: CO_2 and NO_x emissions, March 2020, Stockholm.

June 2020

Although in June the number of cases of infection is higher than in previous months, the Swedish government has decided to ease some measures. For example, people without symptoms were already allowed to move around freely and some of the restrictions on people entering Swedish territory were also lifted. However, the recommendation to telework continued. Only at the end of the month was it recommended to wear face masks, in hospital facilities or nursing homes, to care for suspected or confirmed cases of infection.

Compared to the end of March 2020, early June mobility levels were much higher. This finding is based on the curves in Figure 4.59 which show values of over 100% (walking and driving), contrasting with the values close to 70% seen at the end of March. This could mean that the population was already somewhat used to the situation and therefore moved in a normal way. Concerning the influence of weekends in the reduction of mobility levels, this is not as notorious as in the cities previously analysed. There is a 21% and 12% decrease in mobility on foot and driving, respectively, on the 6th because it is a public holiday. On the 19th a sharp decrease is also registered, 34% (driving) and 41% (walking), corresponding to a Friday eve of a bank holiday.

Figure 4.60 shows that the Parks curve reaches very high values, close to 120% and the only day that reaches negative values is June 6th. The Residential curve also indicates that the percentage of change in the time spent at home was close to 0%, compared with the baseline. The curves related with shopping and workplaces show very similar behaviour, showing a decrease on the 19th just like in Figure 4.59. Furthermore, although teleworking is recommended, the Workplaces curve assumes values of -45% on weekdays, similar to the values at the end of March. In other words, the level of commuting to workplaces did not suffer significantly from the pandemic situation.

CO_2 and NO_x emissions by the circulating fleet in June (Figure 4.61) were higher than those registered in March. The average emissions over the month are higher than the baseline value for both pollutants and for all three categories of vehicle fuel. Again, the only time in the month when there is an approximation to the baseline values is 19 March, as was the case in Figure 4.59 and 4.60.

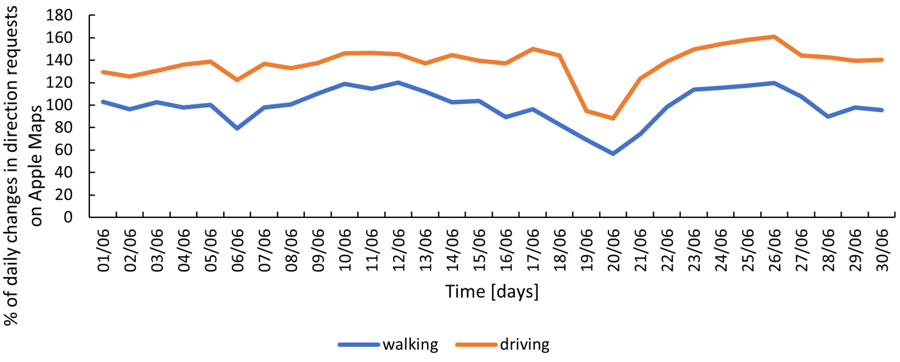


Figure 4.59: Apple mobility patterns, June 2020, Stockholm.

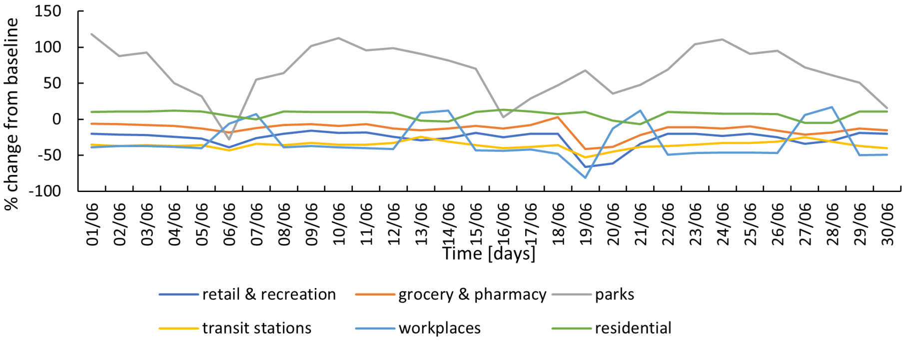


Figure 4.60: Google mobility patterns, June 2020, Stockholm.

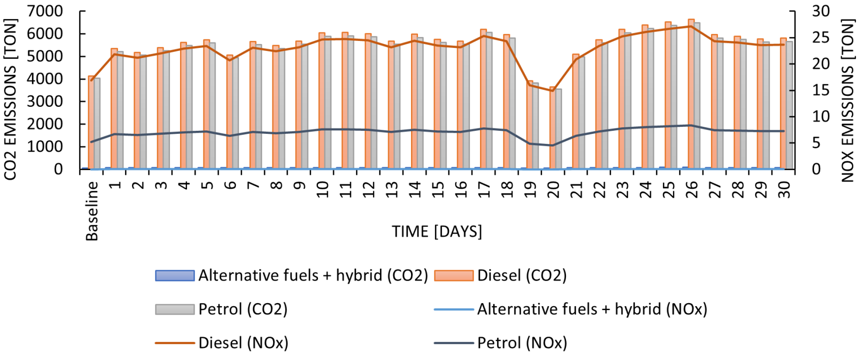


Figure 4.61: CO_2 and NO_x emissions, June 2020, Stockholm.

October 2020

In July and August, the number of new infections was lower than in June. However, at the beginning of October these figures increase. One of the measures that may have led to this increase was the beginning of face-to-face classes for all study cycles after the summer. Also, at the end of the month, measures targeting older people are lifted.

By observing Figure 4.62, we can see that the daily percentage of change in requests for direction is higher than the one registered in June. For example, when comparing the first day of both months, one notices an increase of approximately 20% for walking mobility and only 1.4% for driving. Although the curves have some oscillations, these do not correspond to the weekends.

Figure 4.63 expresses much lower mobility levels than in June, namely in the Parks curve where the maximum in October is 37% and in June it was 118%. The remaining curves maintain the same behaviour throughout the month, that is, the mobility patterns were constant throughout this period.

As far as emissions are concerned (Figure 4.64), the column and line trend remain almost constant throughout the month except on day 2, when there is a peak. On this day, CO_2 emissions reach a value 31.2% higher than the baseline, for diesel vehicles.

This disturbance coincides with the day 2 disturbances in the Figure 4.62 and 4.63.

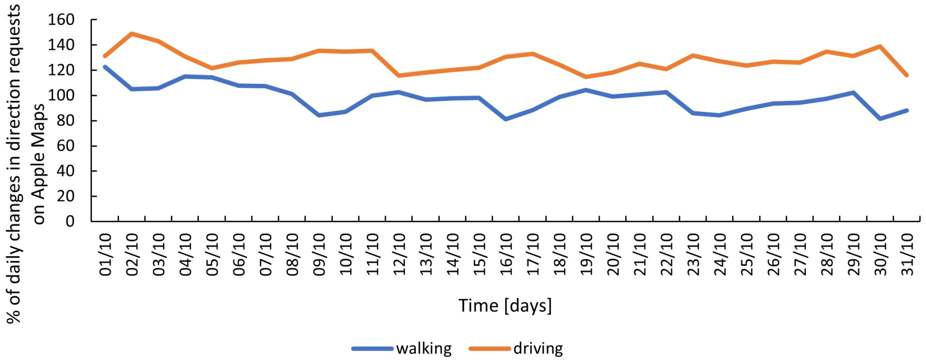


Figure 4.62: Apple mobility patterns, October 2020, Stockholm.

Figure 4.63: Google mobility patterns, October 2020, Stockholm.

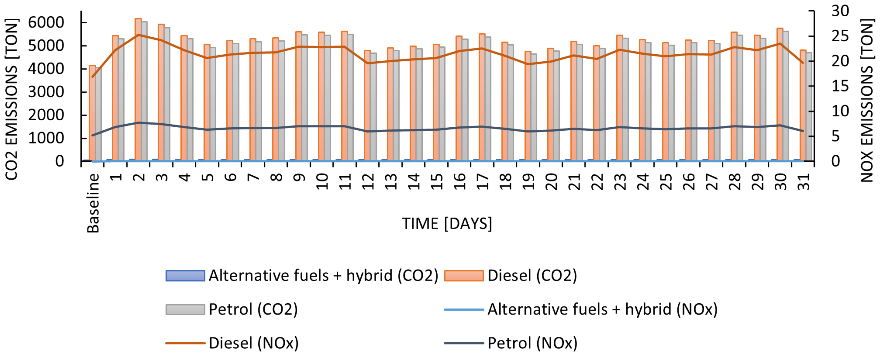


Figure 4.64: CO_2 and NO_x emissions, October 2020, Stockholm.

December 2020

In December, as the pandemic situation in the country worsened, new measures were implemented. For example, secondary schools were closed, and gatherings of people were restricted. In the third week of December, the authorities decided to close several public services and institutions until mid-January.

In fact, Figure 4.65 shows a clear decrease in mobility levels in December 2020, compared with other months previously analysed. In other words, the curves relating to journeys on foot or by car almost always assume values below 100%. Besides this, the influence of weekends is already noticeable, with minimums coinciding with Sundays. A large decrease is perceptible between 23 and 24 and an increase between 24 and 28, due to the festive season of Christmas and national holidays.

In Figure 4.66 it is evident that the behaviour of the curves differs from previous months in that it shows more oscillations. In the Residential curve, for example, although the trend is constant throughout the month, it assumes higher values compared with previous months. In other words, people spent more time at home this month. The Retail and Recreation curve is around 10% lower, compared with October. In relation to Figure 4.67, we conclude that the average CO_2 and NO_x emissions are 11% lower than the baseline, for Diesel vehicles.

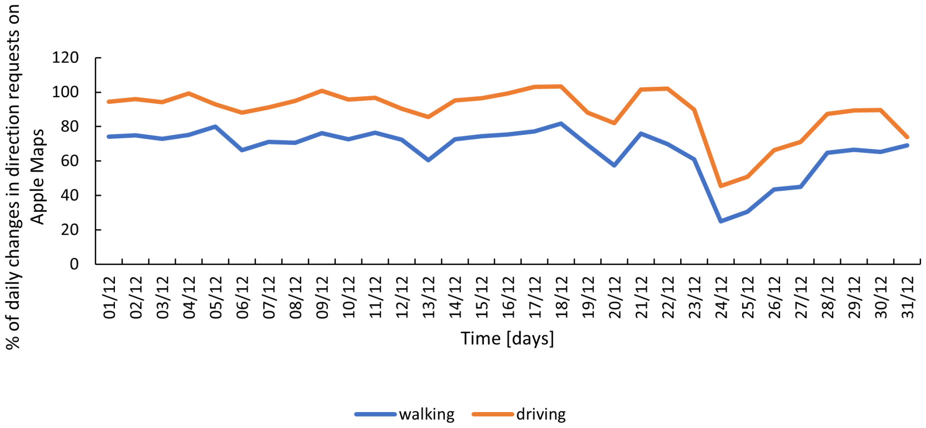


Figure 4.65: Apple mobility patterns, December 2020, Stockholm.

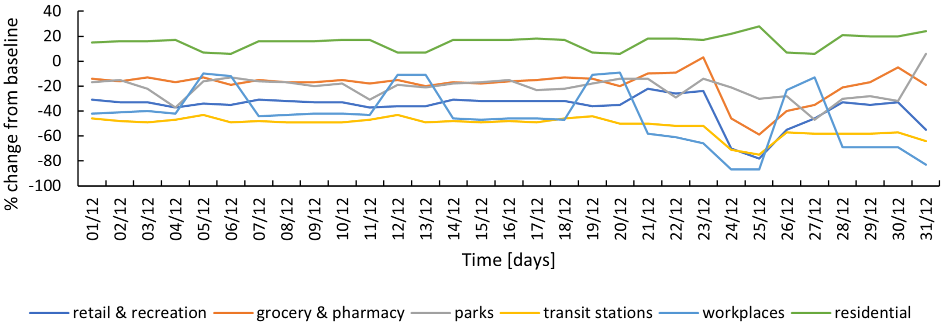


Figure 4.66: Google mobility patterns, December 2020, Stockholm.

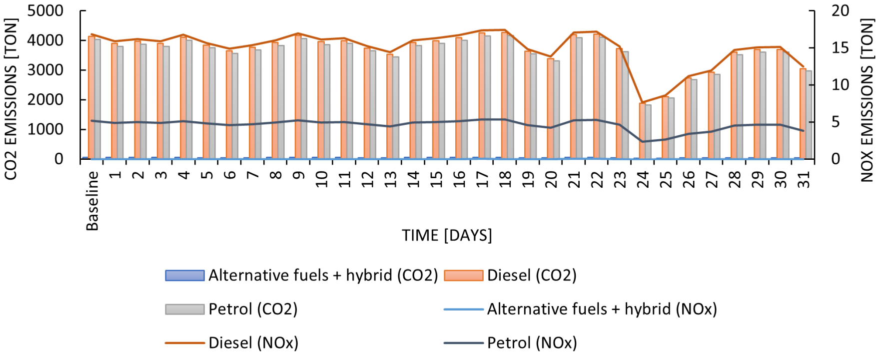


Figure 4.67: CO_2 and NO_x emissions, December 2020, Stockholm.

January 2021

As the pandemic situation developed, the Swedish authorities took a different position and implemented stronger rules. On 10 January, a temporary ”pandemic law” is enacted, giving the government more power to combat the spread of COVID-19 until 31 March 2022. Namely, lower capacity limits in shops, sports venues and gatherings. In-person secondary and higher education remains suspended and non-essential services closed until February. A reduction in mobility levels from this date would therefore be expected. However, Figure 4.68 does not reflect this as the driving and walking curves take on very similar values to previous months. Despite this more restricted phase in Sweden, the data analysed shows that this was not reflected in practice. Indeed, the average change percentages in December driving requests are 67% (walking) and 89% (driving), whereas in January they are 69% and 89%, respectively. Among the months previously analyzed, January 2021 is the one that shows more constant curves throughout the month (Figure 4.69). The only curve that seems to have decreased, compared to December for example, is Retail and recreation.

Regarding CO_2 and NO_x emissions, represented in Figure 4.70, there is a big decrease on day 1 - because it is a public holiday. After this date, the emission trend is not much disturbed. Only at the end of the month do emissions increase slightly and exceed the baseline value on day 28.

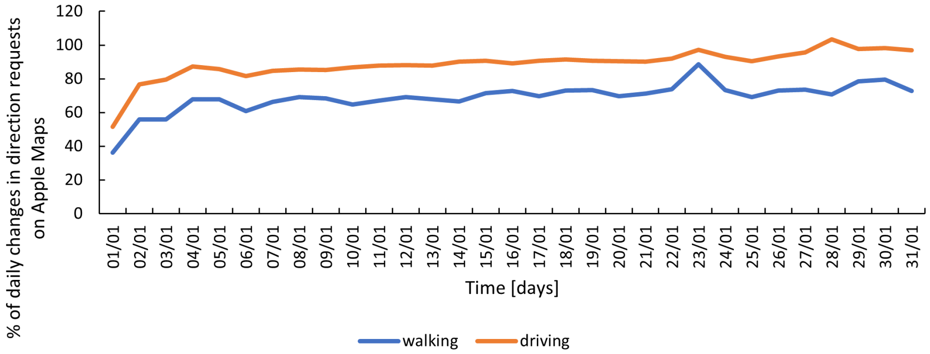


Figure 4.68: Apple mobility patterns, January 2021, Stockholm.

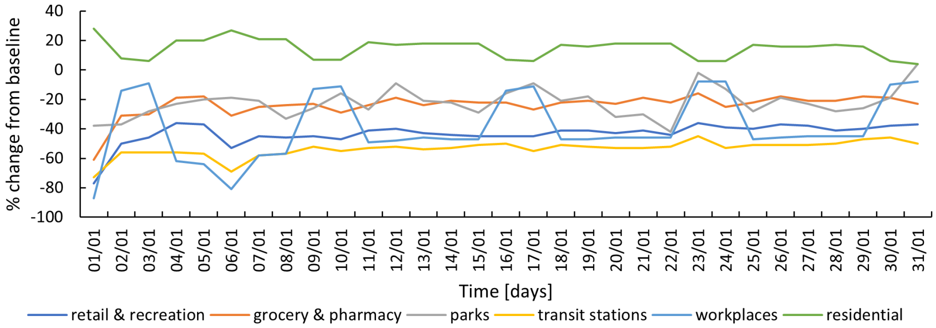


Figure 4.69: Google mobility patterns, January 2021, Stockholm.

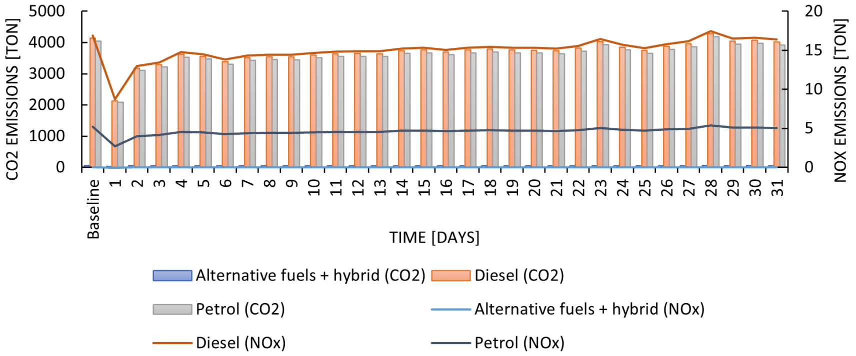


Figure 4.70: CO_2 and NO_x emissions, January 2021, Stockholm.

July 2021

By the summer of 2021 the pandemic situation had calmed down, with far fewer new cases of infection than in previous months. Phase 2 and 3 of the easing of restrictions then began in July. One of the main changes was an increase in the number of visitors allowed at events and infrastructure (including transport).

This paradigm shift is remarkable in Figure 4.71, where it is possible to observe the values of the driving and walking curves. In July, these present values close to 140% and 120%, respectively, with an increase of about 50% compared to January 2021. Although the driving curve remains very constant throughout the month, the walking curve shows some oscillations, with most of its minimums coinciding with weekends. July is also the first month where there is a significant change in mobility patterns according to the destination of the trips, Figure 4.72. For example, the Parks curve undergoes an expansion, going from values close to -20% (January 2021) to 80%. Despite the improved weather conditions and the fact that it is a summer holiday, the freer movement of people is remarkable. On the contrary, the Workplaces curve suffers a decrease, its values being about 20% lower than the equivalent values of June 2020. As far as the remaining curves are concerned, their behaviour does not differ significantly from the June 2020 season.

Concerning emissions by circulating vehicles (Figure 4.73), in this month the values already exceeded by far the emissions considered as baseline. The average CO_2 emissions (diesel vehicles) were 33% higher than the baseline value. In other words, the mobility of people - and consequent emissions - was not only equivalent to that recorded in a pre-pandemic period but exceeded it.

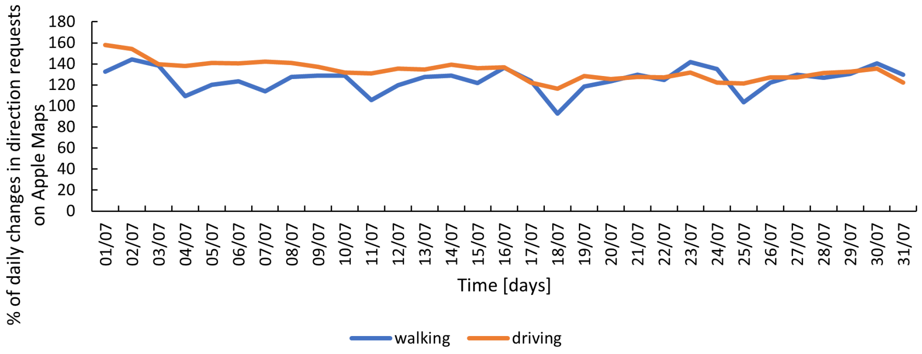


Figure 4.71: Apple mobility patterns, Julyl 2021, Stockholm.

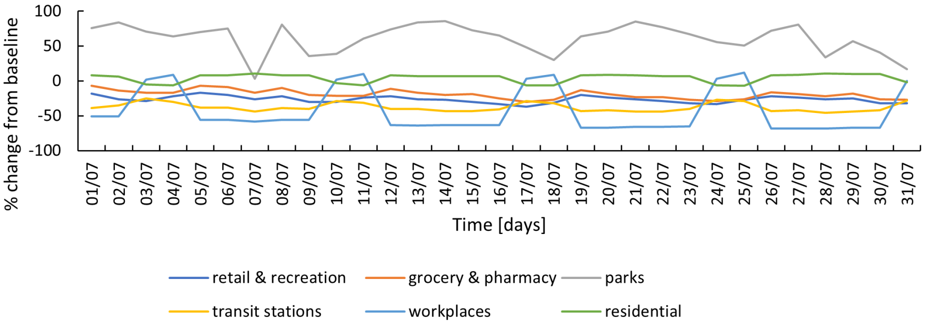


Figure 4.72: Google mobility patterns, July 2021, Stockholm.

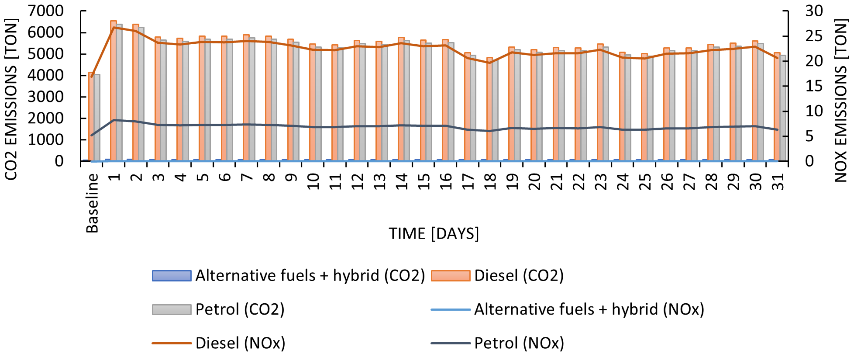


Figure 4.73: CO_2 and NO_x emissions, July 2021, Stockholm.

October 2021

In the last days of September begins phase 4 of easing restrictions, teleworking is no longer recommended and restrictions on gatherings are lifted. In fact, the curves in Figure 4.74 show a more oscillating behaviour compared to July 2021. In the curve relative to walking the influence of weekends is notable, with Sundays corresponding to the curve's minimums. On the contrary, the maximums of this curve correspond to Saturdays. In a general analysis, the average percentages of change in requests for driving directions in October 2021 are 41.5% (walking) and 7.5% (driving) higher than in October 2020. This means that in fact, people have moved more freely in a 1-year period.

The same conclusion can be drawn from the analysis of Figure 4.75. All curves suffer an increase, compared to the month previously analysed, except Residential and Parks. The Residential curve does not change since there were no new recommendations to stay at home. In the case of the Parks curve, the decrease is probably due to worse weather conditions. The greatest differences are in the Transit stations curve and in the Workplaces curve, which present higher values due to the lifting of several restrictions, namely teleworking. This increase in people mobility is also reflected in CO_2 and NO_x

emissions, Figure 4.76. In October 2021 the average of CO_2 and NO_x emissions was 37% higher than the baseline, pre-pandemic period.

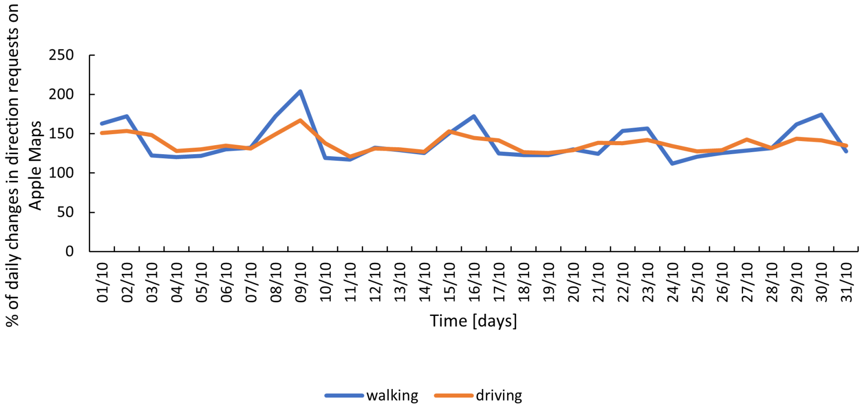


Figure 4.74: Apple mobility patterns, October 2021, Stockholm.

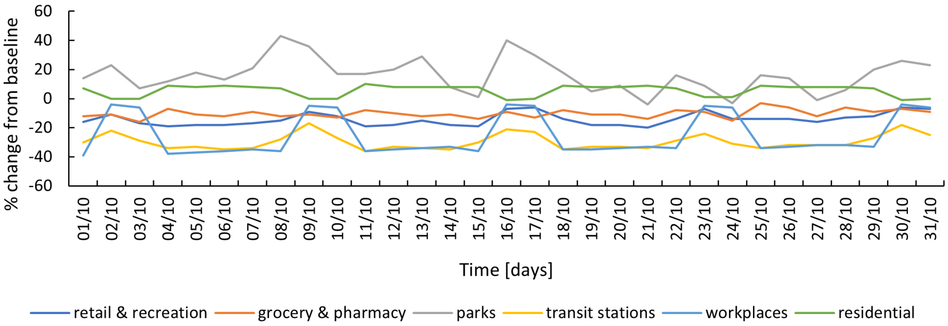


Figure 4.75: Google mobility patterns, October 2021, Stockholm.

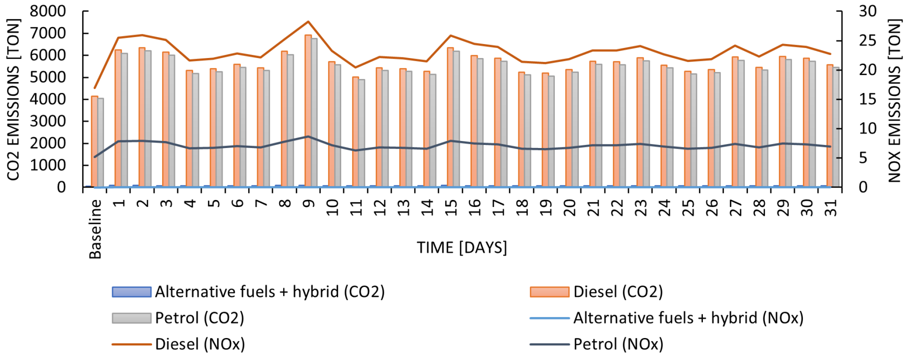


Figure 4.76: CO_2 and NO_x emissions, October 2021, Stockholm.

4.4.4 Comparison between cities

In this subsection, a more comparative evaluation analysis is performed that aims to compare mobility patterns and consequent CO_2 and NO_x emissions between cities. This comparison is made based on 6 important months in the development of the pandemic situation in the three countries. These months are March, June and December 2020, and January, July, and October 2021.

When analysing the month of March, the month in which COVID-19 was declared as a pandemic by the WHO, it is noted that the mobility patterns on foot and by car were very similar between Lisbon and Bucharest. More specifically, in the second half of the month, after a sharp decrease, the curves stabilise at values close to 20%. In the case of Stockholm, the picture is different as the curves stabilise at values close to 60% in the last two weeks. Furthermore, at the end of the month, the percentage of change from the baseline, in relation to time spent at home (Residential curve), is greater in Lisbon, followed by Bucharest and Stockholm. In other words, once again it was in Stockholm that the least influence of the pandemic situation on mobility was recorded. This hierarchy is observed in the other curves. In the case of March 2020 emissions, it is pertinent to compare their evolution between day 11 (the day the WHO declaration is made) and the last day of the month. In the case of Lisbon, there is a decrease of 82% but in Bucharest the decrease is 76% and in Stockholm only 24%.

In the case of walking and driving mobility in June 2020, a greater influence of weekends in Bucharest is noted. In addition to this, an increase in mobility levels throughout the month is noticeable, although of different dimensions for the three cities. Bucharest is the city that shows a higher increase than the other two cities. In the graphs resulting from the Google mobility data, disparate behaviours are observed. For example, Lisbon is the city in which mobility patterns remain similar throughout the month, with no curve having undergone growth relative to the baseline (except Residential). In Bucharest, the patterns show more oscillations, indicating that people's behaviour was not constant throughout the month. In Stockholm, although most of the curves assume similar values to Lisbon, it is noticeable the values above 100% assumed by the Parks curve. The CO_2 emissions (diesel vehicles) at the end of the month are 25% lower, compared to the baseline. For Bucharest it is 2% higher and for Stockholm 40% higher.

In December, the mobility curves, walking and driving, show some similarities between Lisbon and Bucharest. However, the values for Stockholm are around 20% higher than those for Lisbon. Regarding mobility taking into account the destination, the Stockholm graph stands out because most of its curves do not undergo significant oscillations outside the Christmas holiday season. Regarding emissions, once again the daily evolution of CO_2 and NO_x emissions in Stockholm stands out. For example, when comparing the 18th of December (the day with the highest emissions in the three cities) with the baseline, the following is concluded: In Lisbon the decrease is 13%, in Bucharest 18% and in Stockholm there is a 3% increase.

In the first two weeks of January 2021, driving mobility levels in Lisbon were similar to those in Bucharest. In Stockholm they were around 20% higher. However, while Bucharest and Stockholm remain at the same records for the rest of the month, in Lisbon there is a decrease of more than 20%. In relation to destinations, the percentage of change in the Transit stations curve is more negative in Lisbon than in the other cities. For example, on the last Monday of the month, the 25th, Stockholm and Bucharest show a percentage of change of -50% and Lisbon shows -71%. This difference may indicate that at the end of the month, people in Lisbon still maintained some aversion to public transport. In the case of CO_2 and NO_x emissions, when comparing again the 25th with the baseline, we see that the percentage of change in Lisbon, Bucharest and Stockholm are respectively -61%, -35% and 10%.

In July, the pandemic context in Lisbon was worse than in the other cities under study. For this reason, the levels of driving and walking mobility are the lowest. However, it is in Stockholm where there is a higher percentage of decrease in driving requests concerning Workplaces and Transit stations. Regarding CO_2 emissions (petrol vehicles), the average for the month is 8% higher than the baseline in Lisbon, 18% in Bucharest and 33% in Stockholm. These discrepancies reflect somewhat the differences between the pandemic situations in the three countries and the influence this has on the amount of emissions by the circulating fleets.

In October, Bucharest was the only city whose pandemic situation was not favourable and therefore not heading toward the relief of restrictions. For example, Apple's walking mobility change percentages in Lisbon are higher than Bucharest's, which had not happened since March 2020. The same is true for driving mobility. In the case of Stockholm, driving mobility is the lowest of all. Furthermore, a great discrepancy is noticeable between Lisbon, Bucharest and Stockholm, regarding the percentage of change in commuting to parks. These values are -1%, -22% and 16%, respectively.

The CO_2 emissions from diesel vehicles are 59% higher than the baseline in Lisbon, 2% lower than the baseline in Bucharest and 37% higher in Stockholm.

In a general analysis, Table 4.2 is presented to compare the percentage of change of the total emissions (CO_2 and NO_x) between each of the six months analysed in this section and the total value of emissions taken as baseline.

	% change from baseline					
CO_2 and NO_x total emissions	March 2020	June 2020	December 2020	January 2021	July 2021	October 2021
Lisbon	-40	-35	-37	-55	9	60
Bucharest	-46	-14	-38	-37	19	-2
Stockholm	-14	37	-11	-11	34	38

Table 4.2: CO_2 and NO_x emissions, in % percent change from baseline.

4.5 External costs analysis

From the mean activity and stock data for each studied city, we can estimate the external costs of road transport, in particular associated with passenger vehicles and light-duty commercial vehicles. In this study, we focused on exploring the evolution of the external costs under four domains: accidents, air pollution, climate change and noise. The focus is given to the six months analysed that were used for the comparative evaluation presented in the previous section. Note that for the estimation of external costs the reference values of the Handbook of external costs were taken into consideration [EC 2019]. These reference values for each of the countries under study are presented in the following tables, indicating the value in EUR-cent/vkm for the vehicle types under study. Thus, Tables 4.3, 4.4, 4.5 and 4.6 correspond to the costs of accidents, air pollution, climate change and noise, respectively.

Accidents marginal costs				
	Pass car (EUR-cent/vkm)		LCV (EUR-cent/vkm)	
	Petrol	Diesel	Petrol	Diesel
Portugal	2.80	2.80	1.37	1.37
Romania	5.62	5.62	4.82	4.82
Sweden	1.20	1.20	0.54	0.54

Table 4.3: Reference values for external accident costs, urban environment.

Air Pollution average costs				
	Pass car (EUR-cent/vkm)		LCV (EUR-cent/vkm)	
	Petrol	Diesel	Petrol	Diesel
Portugal	0.253	0.920	0.811	1.659
Romania	1.106	1.982	3.330	2.994
Sweden	0.349	0.989	0.695	1.397

Table 4.4: Reference values for external air pollution costs, urban environment.

Climate Change average costs				
	Pass car (EUR-cent/vkm)		LCV (EUR-cent/vkm)	
	Petrol	Diesel	Petrol	Diesel
Portugal	1.854	1.844	2.813	2.564
Romania	2.183	2.048	2.686	3.335
Sweden	2.188	1.804	2.371	2.777

Table 4.5: Reference values for external climate change costs, urban environment.

Noise average costs				
	Pass car (EUR-cent/vkm)		LCV (EUR-cent/vkm)	
	Petrol	Diesel	Petrol	Diesel
Portugal	0.8	0.8	1.1	1.1
Romania	2.2	2.4	2.9	2.9
Sweden	0.4	0.4	0.5	0.5

Table 4.6: Reference values for external noise costs, urban environment.

In a first approach, the daily evolution of the total external costs of each category was obtained and it was found that this evolution followed the same trend as the CO_2 and NO_x emissions observed in Section 4.4.

In the city of Lisbon, the values of external costs related to accidents and climate change are higher than those of air pollution and noise. However, in all four domains there is a significant decrease between the average costs of the first and last fortnight of March 2020. For example, for accidents, there is a cost of 47E4 EUR in the first fortnight and 9E4 EUR in the second, indicating a decrease of around 80%.

In the case of Bucharest, the external costs for accidents and noise are the highest, compared to air pollution and climate change. When comparing the first and last fortnight of March 2020, we note a 67% decrease in average external costs, from 79E4 EUR to 26E4 EUR.

In Stockholm, the categories climate change and accidents stand out with the highest external costs. However, the decrease in costs in March 2020 is not as significant as in the other cities, being only 24%, i.e., accounting for 46E6 EUR-cent in the first fortnight and 34E6 EUR-cent in the last one. The fact that there was not such a significant decrease in the external costs may be related to the fact that mobility levels in Sweden were not impacted by the pandemic in the same way as in the other locations studied.

The second approach aimed to perform a comparative evaluation of external costs estimation between cities, on a monthly basis, for the four studied categories. Tables 4.7, 4.8, 4.9, and 4.10 present this data.

From Table 4.7 it can be seen that the highest values of external accident costs are associated with the city of Bucharest. One of the reasons that can justify this phenomenon is the fact that, according to some studies, areas with a lower density of motorways - as is the case of Romania - lead to a higher number of traffic accidents. Moreover, Lisbon is the city that presents the lowest values for external costs related to accidents, except in October 2021. In this month, Lisbon presents the second highest cost value. Since the pandemic situation at this time was very free in Portugal, people were moving at normal levels or even above pre-pandemic levels, possibly causing higher external accident costs than in previous months.

In the case of external costs associated with air pollution (Table 4.8), Stockholm shows the highest values, followed by Bucharest and Lisbon. In December and January, Stockholm's costs are slightly lower than in the other months, probably due to the implementation of the pandemic law in January 2021. Once again, Lisbon presents higher values in October 2021, compared to previous months, for the reasons presented in the accident costs analysis.

In what concerns the external costs of climate change (Table 4.9), Stockholm presents values around 3 times higher than the other cities, in March 2020. Although Lisbon and Bucharest increase their values of climate change costs in 2021, they are still around half the values of Stockholm.

With regard to the external costs associated with road noise, Bucharest is the city with the highest values (Table 4.10). The fact that the vehicle fleet in Romania is older may justify that the noise emitted by cars can be higher.

		Lisbon	Bucharest	Stockholm
2020	**March**	8,6E+06	1,6E+07	1,2E+07
	June	9,0E+06	2,5E+07	1,9E+07
	December	9,0E+06	1,9E+07	1,3E+07
2021	**January**	6,5E+06	1,9E+07	1,3E+07
	July	1,6E+07	3,6E+07	1,9E+07
	October	2,3E+07	2,9E+07	2,0E+07

Table 4.7: External costs associated with Accidents, EUR.

		Lisbon	Bucharest	Stockholm
2020	**March**	3,2E+06	5,2E+06	8,8E+06
	June	3,4E+06	8,1E+6	1,4E+07
	December	3,2E+06	6,0E+06	9,1E+06
2021	**January**	2,4E+06	6,2E+06	9,1E+06
	July	5,8E+06	1,2E+07	1,4E+07
	October	8,6E+06	9,6E+06	1,4E+07

Table 4.8: External costs associated with Air Pollution, EUR.

		Lisbon	Bucharest	Stockholm
2020	**March**	7,0E+06	6,8E+06	2,4E+07
	June	7,3E+06	1,0E+07	3,7E+07
	December	7,3E+06	7,8E+06	2,5E+07
2021	**January**	5,3E+06	7,9E+06	2,5E+07
	July	1,3E+07	1,5E+07	3,8E+07
	October	1,9E+07	1,2E+07	3,9E+07

Table 4.9: External costs associated with Climate Change, EUR.

		Lisbon	Bucharest	Stockholm
2020	**March**	3,1E+06	7,0E+06	4,8E+06
	June	3,2E+06	1,1E+07	7,4E+06
	December	3,3E+06	8,1E+06	5,0E+06
2021	**January**	2,3E+06	8,3E+06	5,0E+06
	July	5,6E+06	1,6E+07	7,5E+07
	October	8,3E+06	1,3E+07	7,7E+06

Table 4.10: External costs associated with Noise, EUR.

The third approach is to look at external costs as a whole, i.e., the sum of costs relating to accidents, air pollution, climate change and noise. This is for the months mentioned above, i.e., March, June and December 2020, and January, July and October 2021. Table 4.11 shows these monthly values for the three cities and also the value corresponding to the sum of the costs for the three months of each calendar year. Once again it is possible to order Lisbon, Bucharest and Stockholm in descending order in terms of the level of impact of the pandemic. In this case, Lisbon shows an increase of about 62% between 2020 and 2021, Bucharest 38% and Stockholm 17%.

	2020				2021			
Total External Costs EUR	March	June	December	Total	January	July	October	Total
Lisbon	2,2E+07	2,3E+07	2,3E+07	6,8E+07	1,7E+07	4,0E+07	5,9E+07	1,1E+8
Bucharest	3,5E+07	5,4E+07	4,0E+07	1,3E+8	4,1E+07	7,8E+07	6,4E+07	1,8E+8
Stockholm	5,0E+07	7,8E+07	5,2E+07	1,8E+8	5,2E+07	7,8E+07	8,1E+07	2,1E+8

Table 4.11: Total external costs.

Costs for society

Although the monthly evolution of the external costs of the three cities has been presented above, it is necessary to relate this information to the economy of each of the three countries in order to be able to compare in a relative way the impact of the pandemic on the road externalities addressed in this study and, consequently, the costs for society. Thus, it is concluded that the gross domestic product (GDP) would be a good indicator for this purpose. GDP is defined by the measurement of the value added produced via the production of goods and services in a nation over a specific period [OECD 2022]. In addition, it accounts for the revenue generated by that manufacturing, or the total amount spent on finished goods and services (except imports). Table 4.12 shows how external costs can be reflected in terms of the GDP of Portugal, Romania and Sweden, i.e., the portion of GDP that corresponds to the total external costs of road mobility. GDP data for the years 2020 and 2021 were obtained from [Pordata 2022]. From the table, it is in Bucharest that total external costs take up the largest share of GDP. Although measures to fight against COVID-19 have been implemented and reflected in the mobility levels to some extent, this finding may be due to the fact that the circulating vehicle fleet in Romania is older than in the other countries, and therefore more polluting and yielding higher external costs reference values. According to the ACEA report [ACEA 2022], Romania's average age of the passenger cars fleet is 16,9 years, Sweden's is 10,2 and Portugal's is 13,2. When it comes to the light commercial vehicle fleet, Romania also presents the oldest one.

	2020				2021			
Share of costs in GDP	March	June	December	Total	January	July	October	Total
Lisbon	0,011%	0,011%	0,011%	0,034%	0,008%	0,019%	0,028%	0,054%
Bucharest	0,016%	0,025%	0,018%	0,059%	0,017%	0,032%	0,027%	0,076%
Stockholm	0,011%	0,016%	0,011%	0,038%	0,010%	0,015%	0,015%	0,040%

Table 4.12: Share of external costs in the GDP.

4.6 Limitations of the current study

It should be noted that despite the attempt to conduct a comprehensive study, it still has some limitations, mainly due to the easy access to accurate data. For example, we relied on data provided by Apple and Google mobility trends reports that were made available right from the beginning of the pandemic. These reports allowed for some insights on how restrictive policies have been impacting mobility patterns, as our study shows. Nevertheless, these data compare any change relative to baseline days that were considered to be before the pandemic outbreak was declared, and this can not ensure that between January and February 2020 the visitor numbers to specific categories of location were considered 'normal'. It may happen that some cities were already putting into practice some mobility restrictions due to active cases of infection and/or people were already reducing their travels. This, however, can not be assessed accurately. Additionally, data do not take into account seasonal variation, thus, this is not reflected in the reports. Likewise, the effect of weather conditions on walking and driving modes was not possible to be considered when analysing the mobility patterns in the cities under study, due to the lack of data. The use of such data also entails another limitation, that we are aware of, which is related to the possibility of generalisation to the population, since the data only reflects the mobility patterns of people who actually used Google and Apple mobility apps and is, therefore, limited to a group of people. Since this study's goal was to explore the impacts in terms of emissions and also estimate the external costs of road transport (passenger and light-duty vehicles), it was found reasonable to use macroscopic emission models, such as COPERT. Nevertheless, the use of this software requires a very detailed database regarding the vehicle fleet compositions. As explained previously, this was only possible by using the data provided by EMISIA at the national level and then, adjusting to the city level, by considering the same proportion of vehicle categories within each city. It may happen that this is not linear, and thus, the local fleet compositions may be affected by some bias but was an estimation.

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Chapter 5

Conclusions

The abrupt emergence of the SARS-CoV-2 virus and its classification as a pandemic prompted countries to take drastic measures. Mobility restrictions, curfew orders and lockdowns were implemented. In addition, teleworking was also recommended, and several face-to-face services were suspended. Consequently, people's mobility patterns changed.

The pandemic, besides being associated with direct health and consequences on society, indirectly generates other impacts. In other words, these types of events lead to a paradigm shift in the way people move. Since the transport sector is of great significance in the economies' maintenance of countries, it is in everyone's interest to understand how to circumvent the effects of the pandemic to keep it active but also more sustainable. Also, road mobility and its negative externalities represent an obstacle to sustainable mobility, showing it is necessary to study in depth the various externalities and also how they are impacted by major events such as pandemic contexts.

It is extremely relevant to incorporate the findings of studies of this kind in decision making about the future of transport. In the specific case of this dissertation, which studies the impact of the pandemic on road externalities, it is necessary for the authorities to understand how this context has impacted people' mobility patterns and what the cost variations are for the economies of countries and societies. Given that there has been a sharp decline in the use of public transport and a consequent shift to other modes of transport, authorities should take these inputs into account when assessing investments in the transport sector. Moreover, the pandemic and the "new normal" turn out to be an opportunity to make changes in the way people move to reach a new level of more sustainable mobility. New policies implemented can eventually contribute to a faster reduction of GHG emissions, through decarbonisation, and of the external costs of road transport. In addition to this, this effort contributes to a better quality of life in cities and urban areas through better planning.

In this case, the effects of different traffic scenarios, with different levels of daily mobility, on road externalities are studied. The mobility scenarios are created from aggregated information from Apple and result in a daily evolution of vehicle stock circulating in each city. Using the COPERT software it was possible to calculate a daily estimate of CO_2 and NO_x emissions, for the chosen period and for the three cities under study. In a next step, the external costs associated with road externalities are estimated: accidents, air pollution, climate change and noise.

The results of this dissertation indicate that more severe restrictions with a greater impact on driving mobility result in a greater decrease in CO_2 and NO_x emissions and, consequently, lower external costs associated with the circulation of passenger cars and light goods vehicles.

The comparison between cities suggests that when it comes to the impact of the restrictions implemented on mobility, there is a hierarchy, in the sense that Lisbon seems to have been most impacted, followed by Bucharest and Stockholm. For instance, comparing their emissions evolution between 11th March (the day the WHO declaration is made) and the last day of the month, there is a decrease of 82% in Lisbon but in Bucharest the decrease is 76% and in Stockholm only 24%. However, in the end of the selected period, October 2021, this order of cities is not followed. In fact, CO_2 and NO_x total emissions are 60% higher than the baseline in Lisbon, 2% lower than the baseline in Bucharest and 38% higher in Stockholm. In other words, although the results indicate that the city of Lisbon was the most cautious throughout the pandemic period, in the end it presents values of mobility and emissions much higher than those considered as baseline, i.e., before the pandemic.

Moreover, the external costs results showed the lower the levels of mobility in cities, the lower the external costs of these movements in road transportation. For example, in Lisbon, for all 4 categories of externalities, there is a significant decrease between the costs of the first and last fortnight of March 2020, around 80%. In Bucharest, this decrease was only 67% and, in Stockholm was 24%. The fact that there was not such a significant decrease in Stockholm's external costs may be due to the fact that mobility levels in Sweden were not impacted by the beginning of the pandemic in the same way as in the other locations studied. Concerning the costs for society, an association with GDP was made, to understand the share of external costs in each country's GDP. The results showed that Stockholm was the city that experienced the least variation between 2020 and 2021, in terms of share of costs in GDP.

Having found some limitations in the work, possible future work is proposed below. It would be interesting to explore and incorporate the estimation of noise emissions during the pandemic period. In addition, could be interesting to use a cluster analysis based on similarity measures to identify groups of patterns and levels of similarity, to extract meaningful information hidden on mobility data.

In conclusion, the structure of this research may be used in future work concerning other cities and even more extensive periods, in a pandemic context of COVID-19 or other diseases. It is important to reinforce that the pandemic affected mobility patterns and the whole transport sector at the most critical times but that this influence is still felt today, even though the situation is now under control in most countries. In other words, it is necessary to study the long-term impacts of the pandemic on the use of transport and users' behaviour and perception towards different transport modes.

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