Impact of COVID19 Forced Confinement for CO_2 Emission, NO_2 Concentration, and Traffic Congestion Throughout EU Nations and United Kingdom (UK)

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Abstract

The coronavirus outbreak has led several cities to come to the standstill and country lockdown within several locations to reduce coronavirus spread. Here we investigate CO_2 emission, NO_2 concentration, and mobility throughout EU nations and the United Kingdom (UK) from January 2019 until the end of August 2021. In accordance with the previous research obtained by Liu et al. and Le Quéré et al., as mentioned in the literature, our results show a reduction of CO_2 emission for an extended period of 2020 and 2021 compared to the annual emission in 2019. This work obtained abrupt reductions of 10.66% and 4.36% in 2020 and 2021, respectively. Although the ratios and relationship between CO_2 and NO_2 were considered, we found that monthly NO_2 concentration was reduced by 2–39% for ±1σ in 2020 and 13–34% for ±1σ in 2021 (until August) relative to 2019. Additionally, during confinements, the average annual mobility was substantially reduced by 36% for 2020 and 24% for 2021 (until August) relative to 2019. By discussing the role of distinct countries, the current study can contribute to comprehending the role of coronavirus as a huge disruptive factor in socio-economic activities, air quality, and city mobility.

Introduction

The outbreak of coronavirus as well as cases quickly distributed, primarily throughout China in January, however rapidly growing to Europe (mainly Spain, France, and Italy), Japan, South Korea, and the United States among late January as well as mid-February 2020, prior the reaching worldwide proportions by the time the pandemic was announced. The quick spread throughout developing and developed nations, together with the substantial pressure on the health systems, have pushed nearly all the government authorities to act several levels of social distance actions with regional or national lockdown [1,2], which had effects on human mobility (traffic congestion) and energy demand, CO_2 emissions and nitrogen dioxide (NO_2) concentrations into the atmosphere and air, all over the world. These have effects on cities and mobility and indirect implications on various sectors, i.e. society, economy, and tourism [3].

Because of the unexpected decline of socio-economic activities, which caused an extreme decrease in transport in several European cities/countries, the NO_2 concentration was strongly reduced over Europe. Hoanget al. [4], and Bauwens et al.[5] showed that NO_2 concentrations based on the Tropospheric Monitoring Instrument (TROPOMI) and Ozone Monitoring Instrument (OMI) were observed to decrease by on average 32% for some European countries. Changes in NO_2 concentrations were analyzed by Wang and Su [6] for China, Ogen [7] for Italy, Spain, France, and Germany, Zinke [8] for China, Baldasano [9] for Madrid and Barcelona, and Diffenbaugh et al. [10] for UK and China.

Le Quéré et al. [11] inferred from relations between activity data and confinement severity that day-to-day worldwide CO_2 emissions were reduced by a maximum of 17% by early April 2020 compared to the same period in 2019, while Liu et al. [12] showed from global near-real time activity data a 8.8% reduction of worldwide CO_2 emissions in the first half of 2020 in comparison with the identical period in 2019, mainly from reductions in the transportation sector. Han et al.[13] predicted emission reductions in China within the first three months of 2020 around 11.0% however it had quick recovery as described in Friedlingstein et al. [14] and Zhend et al. [15].

In the ground transportation sector, although some studies were conducted about mobility in cities (e.g. Marinello et al. [16] for northern Italy, Iacus et al. [17] for France and Italy, Bergman and Fishman [18] for the 99 countries, Sahraei et al. [19] for the 12 countries in Europe, North and South America, Han et al. [13] for the China, Zheng et al. [20] for the China, Koehl [21] a consideration for the several countries, Koren [22], Gutiérrez et al. [23] for the Spain, Liu et al. [24] for the China), while there is still a lack of complete analysis in comparing of mobility (driving, transit, and walking) throughout EU countries.

Therefore, the principal objective of this research is to examine traffic congestion, CO_2 emission, and NO_2 concentration which occurred throughout EU nations and the United Kingdom (UK) during the coronavirus crisis from the January of 2020 up to the end of August 2021 compared to the same period in 2019. This research uses up to date data on traffic congestion (driving, walking, and transit), CO_2 emission for several sectors (ground transport, industry, power generation, residential, domestic, and international aviation), and NO_2 concentration ground based measurements.

Result

We analyzed a combination of mobility data (driving, walking, and transit), the emission for several sectors (ground transport, industry, power generation, residential, domestic, and international aviation), and NO_2 concentration from the January of 2020 up to the end of August 2021 to calculate daily changes compared to the same period in 2019 in EU nations and the UK except Croatia, Cyprus, and Malta because of no data.

In the case of traffic congestion, our analysis was conducted before the confinements, and the fractional reduction afterwards was calculated for each European nation and UK. In addition, its effects on each mode (driving, walking, and transit) were evaluated, and compared with the same period in 2019.

The TomTom traffic index [25] offers traffic congestion ranges within several cities worldwide for the past ten years. The review rates cities from the maximum to the minimum congested. It is powered by actual traffic information as well as displays all the modifications on the traffic movements. In this regard, a zero-congestion degree indicates that the traffic flow is totally ‘normal’ or fluid; however, it does not indicate zero emissions as well as any automobiles. It is consequently crucial to recognize the lesser threshold of emissions whenever the congestion degree is actually zero. To accomplish this, Liu et al. [28] established a sigmoid function of day-to-day mean TomTom congestion degree (see “method”) with the mean daily vehicle through publicly accessible real-time information through an average of 60 roads in the megacity region for the city of Paris. The function developed for the city of Paris utilized for some other locations involved within the TomTom dataset.

A radar chart (Fig. 1a) presents the average monthly traffic congestion during the COVID-19 throughout EU countries and the UK during 2019, 2020, and 2021. In 2020, there was no reduction in average traffic congestion until late February. The drop was coincident with the spread of the coronavirus as well as the beginning of lockdowns with more significant reductions by -31% (March), -74% (April), -57% (May), -31% (June), -13% (July), -15% (August), -19% (September), -27% (October), -48% (November), and -40% (December) compared to the same period in 2019. In 2021, average traffic congestion in comparison with 2019 was reduced by -33% (January), -26% (February), -30% (March), -27% (April), -11% (May), -5% (June), -25% (July), and -39% (August). This was because of particular limitation guidelines (see Supplementary Tables S1 until S3) announced and by government authorities. Analysis for each EU nation & UK (see Supplementary Figs. S1 until S5) shows that traffic congestion significantly decreased in April 2020 due to the impact of COVID-19 lockdown measures, which was estimated at around -94% and -45% as the maximum and minimum decrease in Italy and Sweden, respectively. The analysis indicated that traffic congestion fluctuated during the eight months of 2021, as provided in Supplementary Figs. S1 until S5.

The distribution of traffic congestion during rush hour of morning and evening for all EU nations and UK throughout 2020 in comparison to 2019 is represented in Figure 1b. Following the lockdowns (see Supplementary Tables S1 until S3); the congestion was substantially reduced since the end of February, by -30% (for mornings) and -33% (for evenings). It reached a minimum level in April of -78% (i.e. for mornings) and -70% (i.e. for evenings). These relative reductions gradually attenuated from the first of May until July as a consequence of lifting lockdown measures from level 3 to 2 (e.g. Austria, Belgium, Malta, Portugal, Spain, UK) and from level 2 to 1 (e.g. Ireland, Romania, Slovakia, Slovenia) and those reached to the -14% (i.e. for the morning) and -11% (i.e. for the evening). Then, the ranges of mobility during morning and evening decreases to -47% and -33%, respectively, until the end of 2020.

Apple mobility changes [26], and the Le Quéré et al. [11] pointed out that more than 50% of the people worldwide decreased travel by more than 50% in April 2020, and the Google mobility [21] data point out that more than 80% of the people throughout 114 nations decreased their travel by more than 50%. Forster et al. [27] deduced that Google mobility information and emission decrease rates depending on confinement level evaluation in Le Quéré et al. agree on country-level ground transportation tendencies to around 20%.

Based on the collected data from Apple mobility trends [26], daily human mobility including three modes, i.e. driving, transit, and walking, (Fig. 2) was analyzed from the January 2020 as beginning of the spread of COVID-19 until the end of August 2021. These comparisons were carried out based on the three-level restriction order (see Supplementary Tables S1 until S3), and it was identified on levels of 0 to 3 as well as assigned the level to which standard day-to-day actions were restricted for part or entire of the people in each country. Level 0 means that no actions were in place, level 1 that policies aimed at minor categories of people suspected of carrying the virus, level 2 that policies aimed need closing (only some categories or levels, for example just public schools or just high school) [28,29], and level 3 signifies countrywide policies [11]. The gray shading in Figure 2 demonstrates the third level as the highest restriction order.

In Austria, four times lockdown announcements as the third level were imposed. On March 16th, 2020, the first lockdown caused a dramatic decrease in overall mobility, of -66% and -81% for driving and walking, respectively. In addition, there was a significant decline on November 17th (-45% and -61%), December 26th, 2020 (-53% and -73%), and April 1st, 2021 (-48% and -66%) for driving and walking during the lockdown announcements as the third level, respectively.

In Belgium, the mobility trends for all sectors were approximately close together except before the first lockdown as the third level, whereas the walking mode was larger than others. Although the mobility trends from the first of January until March 17th, 2020 increased, they substantially decreased after March 18th, 2020 to around -78%, -86%, and -80% for driving, transit, and walking, respectively. Similarly, these trends decreased to -42% (driving), -43% (transit), and -55% (walking) during the second lockdown on November 1st, 2020.

In the Czech Republic, restriction as the third level was imposed from March 15th ; until April 19th, 2020, where the overall mobility for driving, walking, and transit dramatically decreased to -76%, -91%, and -89%, respectively.

In Denmark, although there was a restriction at the third level after January 4th ; 2021, mobility trends for all sectors fell because of the second level restriction and reached -56% (driving), -80% (transit), and -63% (walking) on March 22nd ; 2020. Then, after the third level restriction, driving, transit, and walking decreased to -57%, -71%, and -60%, respectively. It clearly shows that transit usage had the highest decrease than other modes because of the government's stay-at-home order.

In Estonia, two lockdowns as the third level were announced. For the first one, after March 27th, 2020, the mobility trends for driving, transit, and walking declined rapidly to -48%, -73%, and -61%, respectively. One year after the first announcement, the second one started, and it decreased to -14% (driving), -34% (transit), and -14% (walking). In this country, mobility increased quickly between June and December 2020, simply because of the beginning to lift lockdown measures from level 3 to 1.

Finland was one of the EU nations without any restriction order as the third level. Although lockdown measures (level 2) began from March 16th, 2020, for three months, the mobility trends were decreased to nearly -42% (driving), -65% (transit), and -50% (walking). Based on survey outcomes conducted by Clausnitzer [30], from June 2020, more than fifty percent of the people living in the Finnish mentioned that they were buying less often from physical shops throughout the pandemic. There were no substantial distinctions among the kinds of shops; Finnish buyers visited throughout coronavirus; however, going to the department stores and shopping malls were relatively less popular compared to before. Similarly, in Sweden, although coronavirus appeared on 24 January, lockdown measures applied only until level 2 and the government permitted Sweden's bars, restaurants and schools for under 16-year-olds to keep open. In this regard, the mobility trends for driving were estimated to be higher than transit and walking.

The detailed dataset and graphs related to the mobility trends for all other EU nations (France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, UK, Norway) can be found in the supplementary section (see Supplementary Figs. S6 until S8).

The percentages of monthly traffic congestion during rush hour in morning (AM) and evening (PM) in 2020 in comparison to 2019 across EU countries and the UK can be seen in supplementary Figures S9 - S13. Regarding this evaluation, the percentages of congestion during PM times were estimated to be larger than AM times during most of the months of 2020.

Historical data for CO_2 emission throughout EU nations from 1965 (see Supplementary Fig. S14) shows several fluctuations until 2019. Due to the lack of data in Estonia, Lithuania, and Latvia, the CO_2 emission was provided from 1985).

The latest data (CO_2 emissions data were collected from https://carbonmonitor.org/) display (Fig. 3) that the curtailment of mobility and economic activity due to COVID-19 throughout 2020 pushed down European CO_2 emission by 10.66% in comparison with 2019, while emissions, during the first six months of 2021, increased by 11.14% from 2020 and remained lower by 4.36% relative to 2019, respectively.

In general, the transportation sector represents 31.30% of EU nations CO_2 distribution in 2019 [31]. As lockdowns began after February 2020 in EU nations and the UK, based on the online data extracted from (https://carbonmonitor.org/), monthly ground transport emissions compared to 2019 (Fig. 3a) decreased by 16.43% (March), 31.51% (April), 20.36 (May), 1.04% (June), 0.11% (July), 3.82% (August), 9.79% (November), and 2.51% (December). Generally, ground transportation emissions in 2020 reduced by 5.89% (1.71 Mt CO_2), and within the six months of 2021 increased by 11.38% (1.64 Mt CO_2) relative to 2020 and remained 1.32% lower than (0.19 Mt CO_2) 2019, respectively.

Because of stay-at-home regulation, though the alter within electricity usage by public/commercial buildings and households was measured as a component of the power emissions. Acquiring day-to-day emissions through this field is high uncertain compared to some other areas, given that day-to-day residential natural gas usage information is not accessible for whole nations [12]. Accordingly, monthly residential emissions (residential emissions data were collected from https://carbonmonitor.org/) in 2020 compared to 2019 (Fig. 3b) decreased by 12.41% (January), 7.58% (February), 7.74% (April), 13.74% (May), 3.53% (September), 4.85% (November). Generally, residential emissions in 2020 decreased by 2.46% (0.51 Mt CO_2), and within the six months of 2021, increased by 11.72% (1.50 Mt CO_2) and 6.54% (0.83 Mt CO_2) relative to 2020 and 2019, respectively.

Industry emissions from chemicals, steel, and some other manufactured items from fossil energy-burning and cement generation represent on average 29 percent of the worldwide CO_2 emissions throughout a normal year, with a greater share of nationwide emissions in developing nations. In the current research, since data collected from Liu et al. [32] and online data from (https://carbonmonitor.org/), mere emissions via direct fuel usage as well as chemical procedure emissions through the industry field were taken into consideration, electricity associated emissions regarding the industry are generally measured with the power creation field [12]. Monthly industry emissions in 2020 compared to 2019 (Fig. 3c) decreased by 1.39% (January), 4.97% (February), 12.52% (March), 29.53% (April), 20.79% (May), 11.27% (June), 7.05% (July), 6.03% (August), 5.82% (September), 3.30% (October), and 0.28% (November). Generally, industry emissions in 2020 reduced by 8.56% (1.78 Mt CO_2), and in the first six months of 2021 increased by 8.76% (0.88 Mt CO_2) and decreased by 5.02% (0.53 Mt CO_2) relative to the 2020 and 2019, respectively.

Monthly power sector emissions in 2020 compared to 2019 (Fig. 3d) decreased by 17.10% (January), 27.01% (February), 9.47% (March), 30.52% (April), 24.77 (May), 7.85% (June), 9.83% (July), 13.60% (October), 8.89% (November). Generally, power sector emissions in 2020 decreased by 11.60% (3.56 Mt CO_2), and within the eight months of 2021, increased by 15.37% (2.24 Mt CO_2) and decreased by 5.13% (0.79 Mt CO_2) relative to the 2020 and 2019, respectively.

Aviation sector emission is divided into two parts, including domestic and international. Figure 3e and Figure 3f show that international aviation had a significant decrease in 2020 and 2021 compared to 2019. Generally, domestic aviation emissions in 2020 reduced by 48.05% (0.26 Mt CO_2), and in the first six months of 2021 increased by 2.19% (0.003 Mt CO_2) and decreased by 51.91% (0.14 Mt CO_2) relative to the 2020 and 2019, respectively. The broad ranges of international flight emissions indicate two considerable reductions throughout 2020, one right after April and the other within December and November coincident with lockdown actions and travel bans globally. Generally, international aviation emissions throughout 2020 reduced by 58.82% (3.67 Mt CO_2), and in the first six months of 2021 decreased by 26.93% (0.36 Mt CO_2) and 66.67% (1.98 Mt CO_2) relative to 2020 and 2019, respectively.

Figure 4 shows the emission of NO_x associated with five different sectors from 1970 up to 2015. In EU countries and UK[33], the most significant contributions to the global increase in emissions come from transportation (increased by 36.60% from 1970 to 1990) and power industry (increased by 49.42% from 1970 to 1980). Then these trends declined to 3.56 Million (55.68%) and 1.35 Million (67.11%) until 2015, respectively. In the case of agriculture and building, NO_x emissions were begun at 0.50 Million and 1.12 Million in 1970, and they had mildly fluctuating until 2015 and reached 0.45 Million and 0.70 Million, respectively. Lastly, for other industrial combustion, although the trend started from 3.50 Million NO_x emissions, however, it dramatically decreased to 1.25 Million (64.17%) until 2015.

NO_x leads to acid deposition as well as eutrophication of water whereas it leads to more acidification for the soils. The following effects of acid deposition are often substantial, such as negative results on aquatic ecosystems inside lakes and rivers and the destruction of crops, forests, and other vegetation. Eutrophication frequently leads to extreme reductions in water quality with the following effects: reduced biodiversity, modifications in species dominance and composition, and toxicity impact. In this regard, NO_2 is related to negative impacts on individual health; at excessive concentrations, it can raise susceptibility to respiratory infection, decreased lung performance, and inflammation of the airways. It also plays a role in creating tropospheric ozone and secondary particulate aerosols in the atmosphere, which are essential air pollutants because of their harmful effects on individual health and some other climate impact [34].

Research conducted by Bauwens et al.[5] pointed out unprecedented NO_2 column reduction throughout western Europe, South Korea, the United States, and China due to public health actions enforced to contain the COVID-19 outbreak from January 2020.

The evolution of NO_2 concentration throughout EU nations and the UK, from January 2019 to eight months of 2021, is visualized in Figure 5 and Supplementary Figs. S15 and S16. The comparison of three years in Figure 5 displays reduces in surface concentrations of NO_2 during 2020 and 2021 compared to the identical time in 2019. This was because of the coronavirus outbreak, the imposed interruption in vehicle congestion and the decrease in industrial action throughout the lockdown.

In Austria and Belgium, the NO_2 concentration in February 2019 reached the highest level, which was around 17.39 (ppb) and 24.46 (ppb), respectively. In Bulgaria, although the mean level of NO_2 concentration in 2019 (except September and November) was computed to be more than 2020, however in 2021, it significantly increased with the maximum value of 17.29 ppb (February) and minimum value of 7.87 ppb (May) which was because of the progressive lifting of confinement.

In the Czech Republic, the trend of concentration during 2019 and 2021 was estimated close together where it was around 8.5 (ppb), 10 (ppb), and 6 (ppb) for January, February, and March, respectively. However, it dramatically decreased for April and May 2021 to 4.23 (ppb) and 2.97 (ppb), respectively, which was substantially lower than the same period in 2019.

In Denmark, except September 2019, the percentages of NO_2 concentration were significantly higher than in 2020 and 2021, especially for April, May, and June. The average concentration distinction in Finland as another country in the Nordic region between 2019 and the other two years (2020 and 2021) decreased around 41.21% and 33.77%, respectively.

France is actually one of the nations where the mortality case associated with the COVID-19 was abnormal. The percentages of NO_2 concentration during 2020 and 2021 significantly decreased compared to 2019, which was around 20.13% and 40.30%, respectively. The detailed dataset and graphs related to the NO_2 concentration for all other EU nations can be found in the supplementary section (see Supplementary Figs. S15 and S16).

NO_2 is generally co-emitted with CO_2 emission, so NO_2 information might be utilized to calculate CO_2 emissions. Prior research approximated local CO_2 emissions depending on NO_x concentration, as well as the NO_x concentration to CO_2 emission ratios through bottom-up emission ranges [35–37] or co-located satellite retrievals of CO_2 and NO_2[38].

In this regard, we initially determined the monthly values of CO_2 emission for several sectors (ground transport, industry, power generation, residential, domestic, and international aviation) and NO_2 concentration ground-based measurements. Figure 6, as a scatter graph, indicated a robust linear relationship between CO_2 emission and NO_2 concentration in 2019 (Fig. 6a), as well as a solid connection for the mentioned factors from the first of January 2020 until August 2021 (Fig. 6b). These powerful linear connections among NO_2 and CO_2 are evident with suitable correlation R^2=0.77 and R^2=0.78 for 2019 and 2020-2021, respectively. All graphs as the linear regression between CO_2 emissions to NO_2 concentrations in 2020, 2021 (until August), and all data from the first of January 2019 until August 2021 throughout EU nations and the UK can be found in the supplementary section (see Supplementary Fig. S17). Accordingly, a study carried out by Liu et al. [35] suggested a robust linear connection among CO_2 and NO_x from 2006 until 2016 in the United States (US).

Based on the approximate values from Figure 6 and Figure 7, the CO_2 emission and NO_2 concentration ratio (See Methods) were decreased after the first of January 2020 until August 2021 relative to the same period of 2019 simply because of human being actions produced by the coronavirus. Error bars (Figure 7) display the average ratio of 39.90, 35.06, and 33.68 with standard deviations of 2.4, 2.7, and 2.0 (±1σ) for ratios of NO_2 to CO_2.

Discussion

Our evaluation of daily mobility, NO_2 concentration, and CO_2 emissions shows the impacts of coronavirus on human beings in 2020 and 2021 with sectoral details on daily traffic congestion and emission.

The approximated reduction in day-to-day fossil CO_2 emissions via the forced and severe confinement of EU nations and the UK in 2020 decreased by 10.66% compared to the same period in 2019 and possibly unseen before. At face value, a 10.66% relative decrease of emissions appears to be small in comparison with the value of the disturbance of human being actions produced by the COVID-19. In 2021, the pandemic's impacts on worldwide emissions reduced as lockdown limitations relaxed and several financial actions restarted in various European nations; therefore, CO_2 emissions increased by 11.14% during the first six months of 2021 to the same period of 2020. However, it declined by 4.36% in comparison with the same time in 2019. Findings from the current research have mentioned that among all sectors (ground transport, industry, power generation, residential, domestic, and international aviation), the aviation industry had a drastic decrease in CO_2 emission for 2020 by 58.82% (international) and 48.05% (domestic) relative to the same period of 2019. However, the residential sector had the lowest decline in CO_2 emission, which was around 2.46%.

Le Quéré et al. [11] described that most modifications detected in 2020 are probably short-term as they do not indicate structural modifications within the energy, transportation, or economic systems. The public stress of confinement, as well as associated modifications, could change the upcoming trajectory unexpectedly; however, social reactions solely would not drive the permanent and deep reductions required to achieve net-zero emissions. Circumstances of low-energy and/or material demand explored regarding climate stabilization clearly goal to complement decreased demand with greater well-being, a purpose not achieved through compulsory confinements. Nevertheless, options can be found to arrange structural modifications in motion through applying economic stimuli aligned with low carbon pathways [39].

If the outbreak stays under control in the following several weeks, the yearly emissions reduction will be substantially fewer compared to 2020 and the eight months of 2021. We calculate that overall NO_2 concentration in EU nations and the UK for the 2020 and 2021 until August were 20.72% and 22.39% lower than 2019, respectively. Our outcomes indicate that emissions were almost restored in distinct nations when restrictions were changed from first to the second and third levels. For instance, the values of NO_2 concentrations in Austria in 2020 during July, August, and September increased than other months simply because of the progressive lifting of confinement. In France, it was increased for July and August, which was significantly more than other months. Nevertheless, in 2021, emissions decrease stays considerable and even amplified in some nations impacted by a great range of coronavirus cases. For example, the mentioned concentration in Belgium, Czech Republic, Denmark, Finland, and Germany declined during the six months of 2021 relative to the same period of 2019 even though lockdowns were simultaneously being relaxed throughout the countries (see Supplementary Figs. S15 and S16). Overall, in 2020, the percentages of NO_2 concentration relative to the same period of 2019 throughout the EU nations and the UK decreased by 20.43% (Austria), 28.13% (Belgium), 28.89% (Bulgaria), 19.83% (Czech Republic), 22.53% (Denmark), 28.21% (Estonia), 41.21% (Finland), 20.13% (France), 13.86% (Germany), 17.28% (Hungary), 40.90% (Ireland), 29.33% (Italy), 16.28% (Netherland), 19.83% (Poland), 32.63% (Portugal), 30.07% (Romania), 25.19% (Slovakia), 22.03% (Slovenia), 20.78% (Spain), 41.82% (Sweden), 36.24% (UK), and 22.79% (Norway).

It is actually worth mentioning that the coronavirus outbreak has generated Million of fatalities throughout the globe; however, it needs to be accepted that worldwide NO_2 concentrations considerably reduced during and after the lockdown. Due to the fact most NO_2 concentration is derived from transportation and industrial sources, the extreme decrease of these types of activities because of the several government limitations led to a 55% fall in NO_2 concentrations worldwide. Such a NO_2 level decrease had not been achieved, though numerous funds and policies were utilized to support the solution and attempts to decrease NO_2 concentrations [4,40]. In this regard, a move from fossil energy to green power, for example, solar and wind can reduce NO_2 concentrations.

When lockdowns stopped daily life, leisure trips and commuting for several millions of families came to a sudden stop. Urban transport utilization dramatically decreased to its minimum degree in year [41]. In this environment, biking or personal vehicles shared micro-mobility, and walking could outpace public transportation. Of these, biking and walking are generally currently one of the most desirable choices [42]. In research conducted by Nouvellet et al. [43], the average mobility throughout 52 nations achieved its lowest, with a decrease of 63 percent from baseline on 11 March 2020. Mobility after that recovered, with an approximated average decrease, achieving 14 percent from baseline on 25 October 2020. The ten countries (the list of countries can be found in the research conducted by Nouvellet et al. [43]) with the minor modifications saw mobility decrease around 37-51 percent from baseline. The ten nations with the most significant modifications saw mobility decrease around 72-83 percent from baseline [43].

Regarding our analysis, the percentages of traffic congestion throughout EU nations and the UK did not encounter a major decline during January and February 2020 relative to 2019. However, this trend decreased overall by -31% (March), -74% (April), -57% (May), -31% (June), -13% (July), -15% (August), -19% (September), -27% (October), -48% (November), -40% (December) because of several restriction announcement. In 2021, EU nations again announced unexpected situation as well as placed their nations under lockdown and stay-at-home restriction; therefore, the traffic congestion keep continue to decrease by -33% (January), -26% (February), -30% (March), -27% (April), -11% (May), -5% (June), -25% (July), and -39% (August) comparison with the same period of 2019. Therefore, one particular policy implication is a modification in communication techniques and individual's working style, recognized through operating from home as well as having teleconferences to decrease pollution and traffic congestion.

Although several policy-makers and organizations have now highlighted the chance for a green recovery that will advance environmental targets and restore economies, emissions could also come back and surpass pre-outbreak ranges if stimulus and recovery depend on carbon-intensive energy accessibility [12,44].

By taking into consideration the limited accessible data, these pioneering research offer significant contributions to comprehend the role imposed socio-economic limitations can have on the traffic congestion, NO_2 concentrations, and CO_2 emissions tendencies, as well as support the description of efficient climate strategies.

Method

CO_2 emission. The CO_2 emissions and sectoral framework from 1965 until 2019 for EU nations and the UK and sectors are collected through Emissions Database for Global Atmospheric Research (EDGAR) (https://edgar.jrc.ec.europa.eu/) [45]. Emissions of CO_2 consist of all fossil CO_2 resources like metal (ferrous and non-ferrous) manufacturing processes, non-metallic mineral processes (for example, cement manufacturing), fossil fuel combustion, agricultural liming, and solvents utilize, urea generation. Massive range biomass burning with forest fires, Savannah burning, as well as sources and sinks through land-use, land-use modification, and forestry are omitted. Liu et al.[12,32,46] described that the values of CO_2 emission calculated from Equation 1.

Emission= $\sum\sum\sum \gamma_{i,j,k} * \lambda_{i,j,k}$ (1)

For the above formula, index i addresses nations, index j addresses sectors including ground transport, industry, power generation, residential, domestic, and international aviation, k addresses three necessary fossil fuel forms: natural gas, oil, and coal. Emission elements can be more divided in the energy acquired per unit of fuel (TJ/t), the net heating values regarding every fuel "v," the oxidation level "o," and the carbon content "c" (tC/TJ) that is the portion as a percentage of fuel oxidized throughout emitted and combustion to the atmosphere [12]. Therefore, Equation 1 can be converted to Equation 2.

Emission= $\sum \sum \sum \gamma_{i,j,k} * \left(v_{i,j,k} * c_{i,j,k} * o_{i,j,k}\right)$ (2)

Liu et al. [12,32] elaborated that electricity generation information by creation forms at the resolution of 1 hour to 15 minutes for EU nations and the UK are gathered through the ENTSO-E Transparent platform (https://transparency.entsoe.eu/) [47]. Data for the EU nations and the UK are accessible via this platform. The cumulative industrial generation index was utilized for the industrial sector to calculate the growth rates of emissions gathered through Eurostat (https://ec.europa.eu/eurostat/home) [48]. For the ground transportation sector, traffic index as congestion level were collected from TomTom website (https://www.tomtom.com/tr_tr/) [25]. The congestion degree signifies the additional time used on travels, in percentage form, in comparison with uncongested circumstances.

A zero-congestion degree indicates that the traffic is generally “normal” or fluid; however it does not indicate zero emissions as well as any vehicles. It is consequently essential to recognize the lesser threshold of emissions whenever the congestion degree is actually zero. To accomplish this, Liu et al. [32] developed the time series of mean day-to-day TomTom congestion degree “called as X” with the day-to-day mean vehicle (in vehicles per day) through publicly accessible real-time “called as Q” information through an average of 60 roads within the megacity region for the city of Paris where data were collected from (https://opendata.paris.fr/pages/home/). Lastly, a sigmoid formula (Equation 3) was utilized to fit the connection among Q and X:

$$Q = a + \frac{bX^c}{d^c + X^c}$$

3

Where a, b, c, and d as the regression variables are 100.87, 671.06, 1.98 and 6.49, respectively. Liu et al. [32] presume that relative modifications for day-to-day emissions were proportional to the relative change in the function Q(X) through Equation 3. Next, the developed Q(x) for Paris was utilized for several cities involved in the TomTom database, presuming that the relative value of emission and vehicle number follows a close connection with TomTom. The emission modifications were initially computed for specific cities and then weighted through city emissions for aggregation to national modifications.

For international and domestic aviation, Liu et al. [12] described that since there is no appropriate reference for estimation of CO_2 emission, it can be calculated by presuming a constant, i.e. CO_2 emission element per km flown, throughout the entire fleet of aeroplanes. This particular prediction is sensible if the flight mix among several groups (freight operations, wide-body aircraft, narrow-body aircraft, and regional) has not altered substantially. The International Council on Clean Transportation (ICCT) released that CO_2 emissions through passenger aviation and commercial freight led to 918 Mt CO_2 in 2018 depending on the OAG flight repository [49] and emission variables through the PIANO repository [50]. The kilometres flown are generally calculated; presuming great circle range among the take-off, cruising, descent, and landing details for every flight as well as are cumulated over the entire flight. As the landing and departure airfields are recognized about flights, the km has flown (and therefore CO_2 emissions) per nation, and every nation among international or domestic traffic can be classified. Consequently, the day-to-day CO_2 emission was calculated as the product of length flown through a CO_2 emission element per km flown.

For the residential sector, Liu et al. [12] described that the computation of emissions was carried out within three measures: (1) Utilizing the EDGAR reports of 2018 residential emissions as the standard. The residential emissions were divided into two components (heating and cooking emissions) for every nation based on the EDGAR recommendations. The emissions through cooking were presumed to stay steady, although emissions through heating were presumed to rely on and fluctuate through the heating demand. (2) Computation of population-weighted heating level days for every nation as well as every day depending on the ERA5 reanalysis of 2-m air temperature. (3) According to the alter of population-weighted heating level days in every nation, the EDGAR 2018 residential emissions were scaled for other years, i.e. 2019, 2020, and 2021. They considered that the list of heating level days is generally day-to-day values and day-to-day emission updates regarding residential resources worldwide.

NO_2 concentration. NO_2 is actually a reddish-brown gas that is released through the entire combustion motors. It is one of the main substances which are released from combustion motors. At the exhaust pipe, i.e. the point of emission, the percentage of NOx is close to 10% NO_2 and 90% NO. After some hours throughout the atmosphere as well as in the existence of Volatile Organic Compounds (VOCs), the NO is generally transformed to NO_2. This particular effect can take place around a few seconds to some hours. NO_2 reacts more with other compounds throughout the air to generate elements known as Peroxyacyl Nitrates (PANs), particulate matter, and nitric acid. Due to the possibility of NO_2 to generate these types of "secondary" pollutants, it is essential to regulate and monitor NO_2 [40].

The historical data for NO_x concentration from 1970 until 2015 for several sectors such as agriculture, buildings, power industry, transportation, and other industrial combustion throughout EU countries and UK were collected from the EDGAR website (https://edgar.jrc.ec.europa.eu/country_profile/EU28) [33]. The magnitude of the global level of NO_2 concentrations was collected from the world's air pollution: real-time Air Quality Index (AQI) (https://waqi.info/) [40]. Although the AQI depends on measurement of NO_2, Ozone (O_3), particulate matter (PM_{10} and $PM_{2.5}$), Carbon Monoxide (CO), and Sulfur Dioxide (SO_2) emissions, this research utilized only NO_2 concentrations, especially during 2020 and 2021, relative to the same period of 2019. Since the collected data for NO_2 concentration were daily base, the average values for each month were calculated and then utilized for visualization (see Supplementary Figs. S15 and S16)

Traffic congestion. We gathered TomTom congestion worldwide degree information through TomTom website [25]. The congestion degree signifies the additional time taken during travel, in percentage, in comparison with uncongested situations. TomTom congestion degree information is accessible for 416 cities worldwide and 57 nations at a temporal resolution of 15 min to one hour. More remarkable than fifty percent of the cities documented by TomTom are generally throughout North America (93 cities) and Europe (228 cities from 30 nations without Russia). In addition, 23 cities are from Africa and Oceania, 13 cities are from 5 nations in South America, and 59 cities are from 13 nations in Asia and Russia. The list of 416 cities consists of the main cities throughout these nations [12].

The extracted data from the TomTom website were included congestion for 2019 and 2020 in comparison with 2018 and 2019 (in %), respectively, congestion levels weekly 2021 in comparison with 2019 (in %), the highest average daily congestion 2019 and 2020 (in %), the number of days with low traffic during the different level of restriction order. Since the traffic congestion for 2021 was collected weekly, an average level of four weeks was assumed as a month in 2021. For 2019, it was calculated in two phases. First, average values (in %) of morning and evening monthly congestion levels 2020 in comparison with 2019 were computed (called as Y). Then, based on the existing values of 2020 (called X), the congestion levels for 2019 were calculated [X-(Y*X)].

We collected the percentages of mobility trends for several modes (driving, walking, and transit) from the Apple mobility trends website except for transit mode for Austria, Bulgaria, Greece, Latvia, Lithuania, Poland, Portugal, Romania, Slovenia [26]. Apple mobility data are available for approximately all countries/regions, sub-regions, and cities throughout the EU nations and UK. Therefore, this is an appropriate database for making the comparison of urban mobility for all mentioned countries. Since the data on the Apple website is not based on the percentage, it was calculated based on the (Z-100)/100, where Z is known as mobility values. This was conducted simply because the first day as the baseline (13/January/2020) was determined as 100.

The ratio between CO_2 emission and NO_2 concentration. The method to infer the ratio between CO_2 (E_{CO2}) emissions and NO_2 concentration (C_{NO2}) utilizing the following equation:

$$Ratio_y = \frac{\sum_y C_{NO2}}{\sum_y E_{CO2}}$$

4

Where y represents the target year.

In a research carried out by Liu et al. [35], a similar methodology can be found where they suggested a robust linear connection among CO_2 emission and NO_x concentration from 2006 until 2016 in the US. In this research, E_{CO2} was calculated by summation of monthly values of CO_2 emission for several sectors, including ground transport, industry, power generation, residential, domestic, and international aviation collected from (https://carbonmonitor.org). In addition, C_{NO2} was calculated by summation of the monthly magnitude of NO_2 concentration ground-based measurements collected from (https://waqi.info/) throughout EU nations and the UK.

Declarations

Author contributions

Mohammad Ali Sahraei: Conceptualization and Supervision; Software; Data analysis, Validation, and Visualization; Methodology; Writing draft, review, and editing.

Babak Ziaei: Conceptualization and Supervision; Software; Data analysis, Validation, and Visualization; Methodology; Writing draft, review, and editing.

Competing interests

The author(s) declare no competing interests.

Data availability

Mobility data using Apple mobility trends for several modes, including driving, transit, and walking, are available at https://covid19.apple.com/mobility. Traffic congestion for 2019, 2020, and 2021 using Tomtom Traffic Index are available at https://www.tomtom.com/en_gb/traffic-index/. Global nitrogen dioxide emissions data are available at https://waqi.info/. NO_2 concentrations data from 1970 to 2015 are available at https://edgar.jrc.ec.europa.eu/country_profile/EU28. CO_2 emission data for several sectors are available at https://carbonmonitor.org/. CO_2 emission data from 1965 to 2019 are available at https://edgar.jrc.ec.europa.eu/report_2020.

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Figures

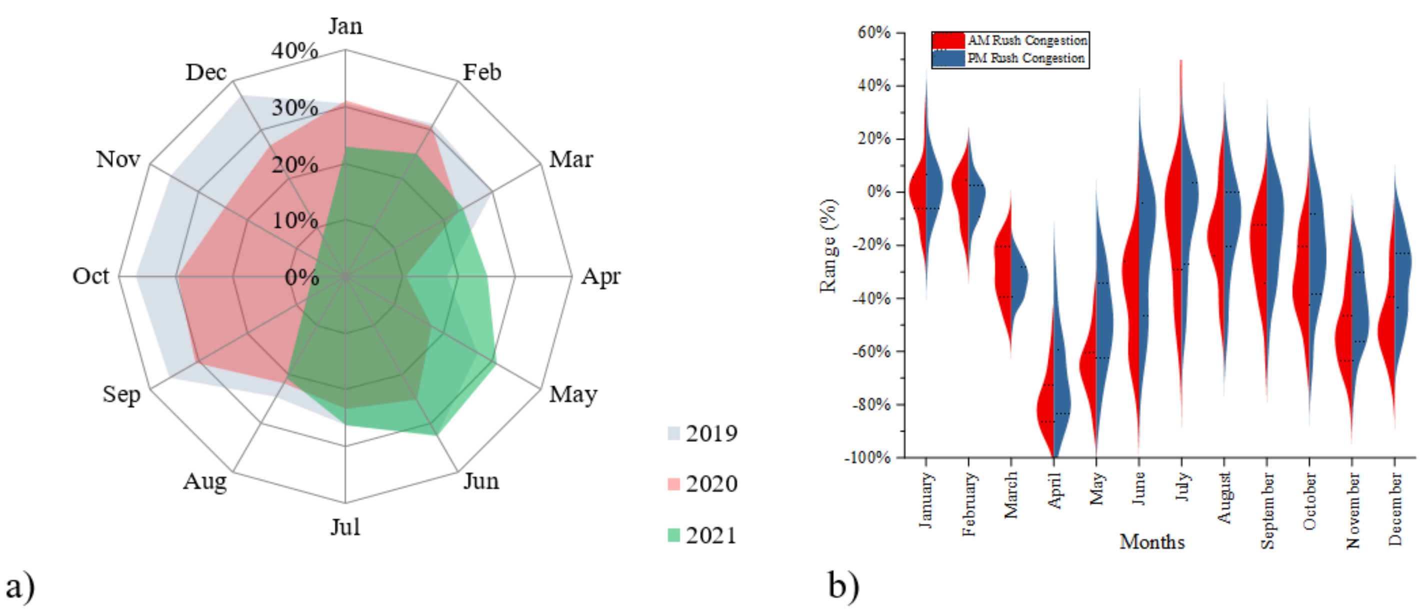

Figure 1

Monthly traffic congestion relavive change with respect to the January 2019 until end of August 2021 **throughout EU countries and the UK. a,** Average reductions of monthly traffic congestion in EU nations and the UK during 2019, 2020, and 2021, **b,** Violin plot showing the distribution of traffic congestion during rush hours, i.e. mornings (red) and evenings (blue), in 2020 compared with 2019 for EU nations and the UK. Data Source [25].

Figure 2

Mobility trends for three modes of transportation. Daily human mobility by sector (driving, transit, and walking) from January 13 2020 to the first six months of 2021. The source of data was collected from Apple mobility report [26].

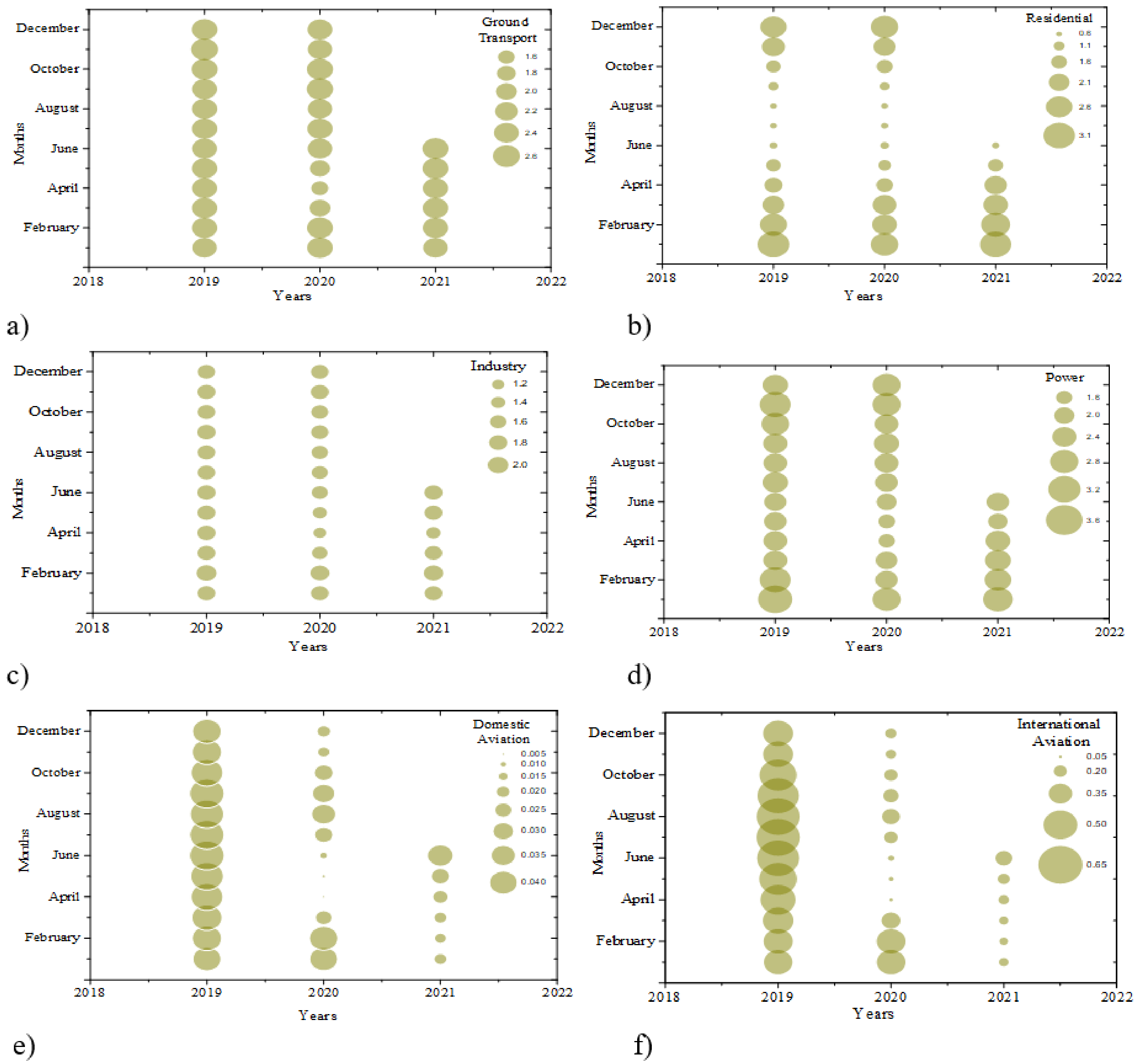

Figure 3

Comparison of CO_2 emission based on several sectors. Monthly comparison of CO_2 emission for **a,** ground transport, **b,** residential, **c,** industry, **d,** power, **e,** domestic aviation and **f,** international aviation during 2019, 2020, and the first half of 2021 all over the EU nations and the UK. Circle size represents the mass of CO_2 emission (Mt CO_2 per day). The source of data was collected from (https://carbonmonitor.org/).

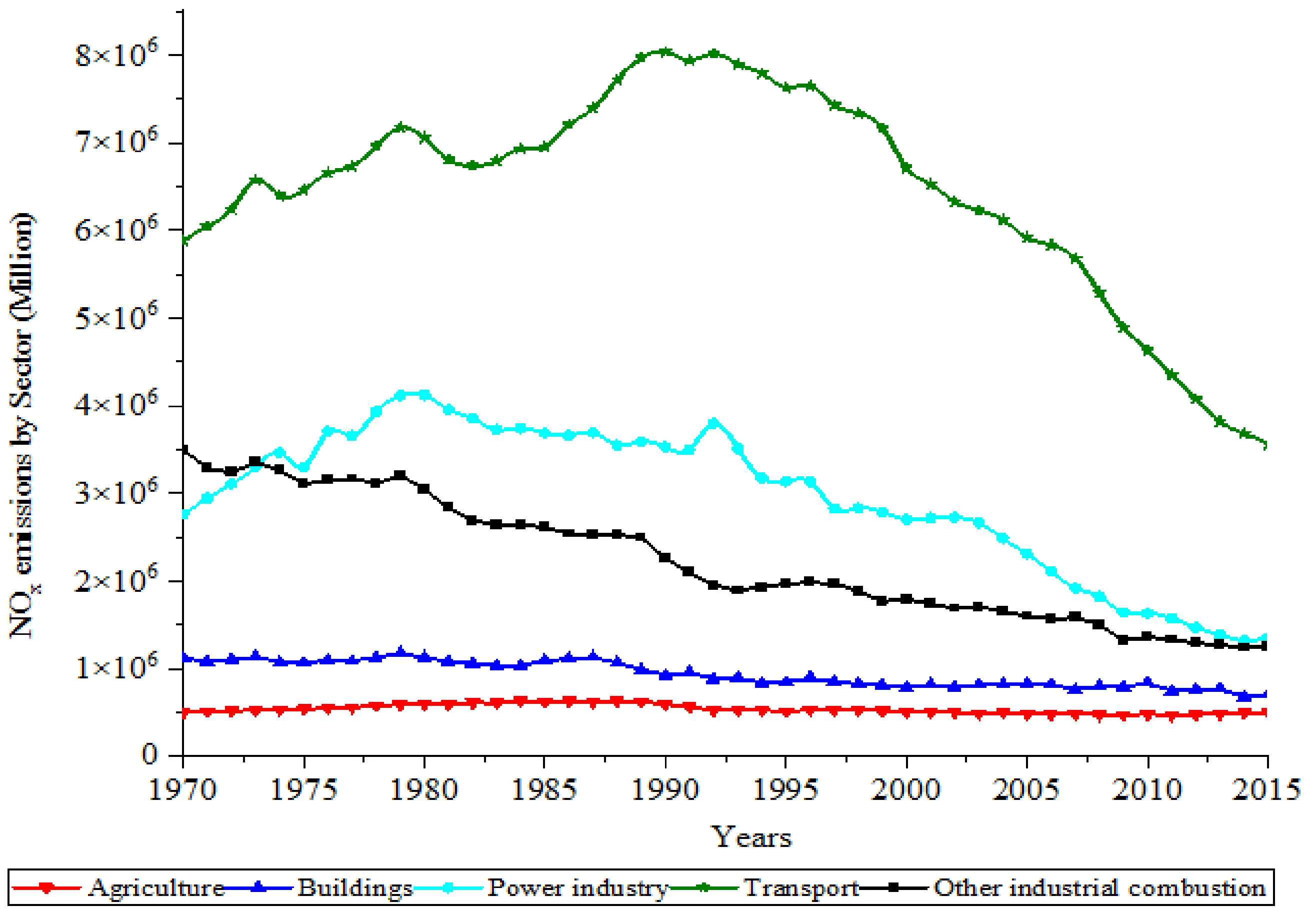

Figure 4

Historical data for NO_x emission. Sector level (agriculture, buildings, power industry, transport, other industry combustion) comparison of the NO_x emission for 45 years from 1970 until 2015 throughout EU nations and the UK. The source of historical data was collected from EDGAR [33].

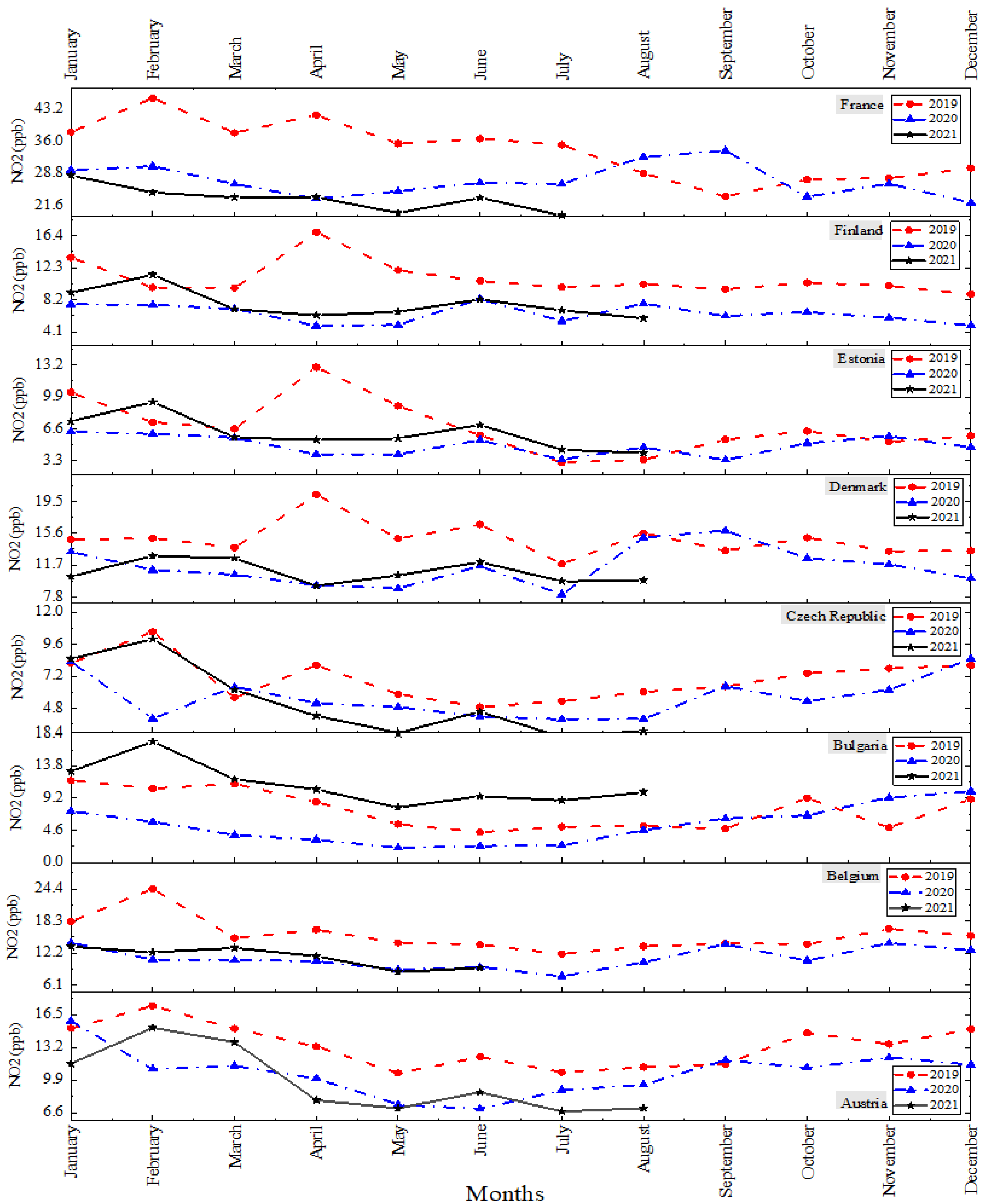

Figure 5

NO_2 concentration trends. Monthly NO_2 concentration within European Union nations and the UK during 2019, 2020, and the first half of 2021. There is a lack of data and information associated with the NO_2 concentration for countries, i.e. Belgium, Greece, and Slovakia, as seen in the above Figure and supplementary Figs. S15 and S16. The source of historical data was collected from EDGAR [33].

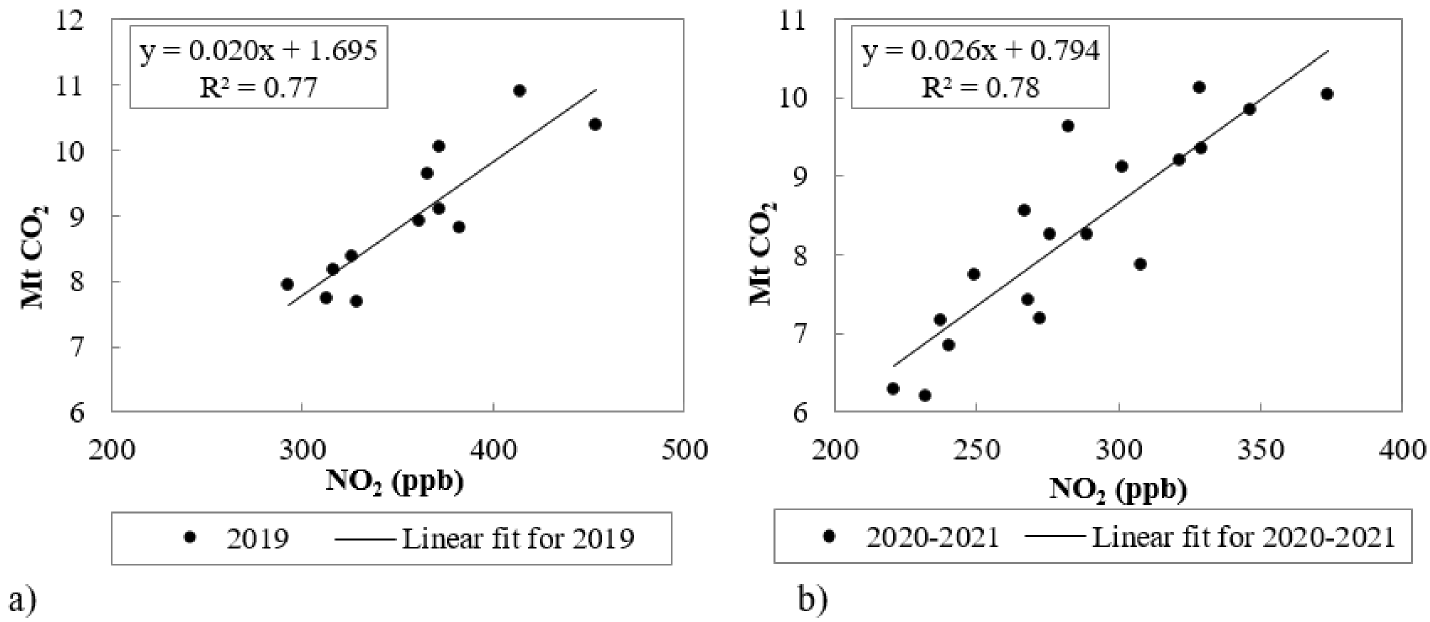

Figure 6

Scatter plots of CO_2 emissions versus NO_2 concentration. Linear relationship for monthly CO_2 emissions and NO_2 concentrations, **a,** for 2019 and **b,** from January 2020 until August 2021. The line indicates the linear regression of CO_2 emissions to NO_2 concentrations.

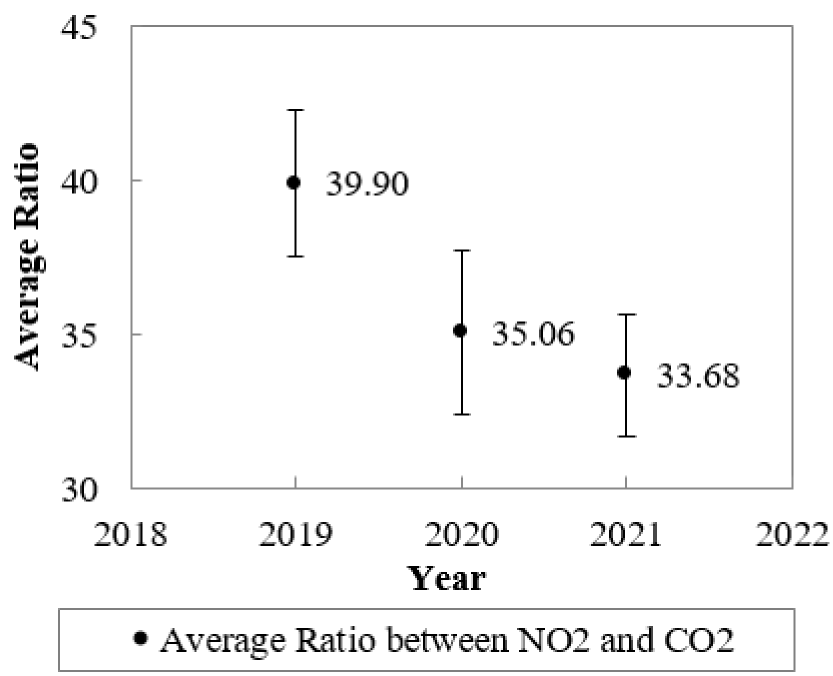

Figure 7

Average ratio between CO_2 emissions versus NO_2 concentration. The annual average ratio of emissions in the period 2019-2021 (until August 2021), updated from the (https://carbonmonitor.org/) and (https://waqi.info/) with a standard deviation of 2.4, 2.7, 2.0 (±1σ) during 2019, 2020, and 2021, respectively.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Suplementarydata.pdf