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Implications of COVID-19 lockdowns on surface passenger mobility and related CO_2 emission changes in Europe

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HIGHLIGHTS

- New and real-time carbon estimates from surface passenger transport during COVID-19.
- Emissions fell by half but almost completely recovered after strict lockdowns.
- Private and public transport trends are not aligned with EU Green Deal goals.
- The disruption of travel behaviour represents opportunities for structural changes.

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ABSTRACT

The coronavirus pandemic has severely affected our daily lives, with direct consequences on passenger transport. This in turn has strongly impacted the energy demand of the transport sector and associated CO_2 emissions. We analyse near real-time passenger mobility and related emission trends in Europe between 21 January and 21 September 2020. We compiled a dataset of country-, sector- and lockdown- specific values, representing daily activity changes in private, public, and active passenger transport. In the aggregate, surface passenger transport emissions fell by 11.2% corresponding to 40.3 $MtCO_2$ in Europe. This decline was predominantly due to the reduction of private passenger transport in five European countries (France, Germany, Italy, Spain, and the UK). During the first lockdown in April 2020, CO_2 emissions from surface passenger transport declined by 50% in Europe, resulting in a 7.1% reduction in total CO_2 emissions. After April 2020, private passenger travel recovered rapidly, while public passenger flows remained low. Solely prompted by the private sector, a rebound in total emissions and surface passenger transport emissions of 1.5% and 10.7%, respectively, was estimated at the end of the study period. The resulting situation of increased private and decreased public passenger transport is in contradiction to major climate goals, and without reversing these trends, emission reductions, as stated in the European Green Deal are unlikely to be achieved. Our study provides an analysis based on a detailed and timely set of data of surface passenger transport and points to options to grasp the momentum for innovative changes in passenger mobility.

1. Introduction

The recent and on-going coronavirus COVID-19 pandemic has strongly affected our daily lives and economic activities. To contain the spreading of the disease, governments have imposed lockdown measures, including the closing of workplaces, educational institutes, restaurants, and other social interaction points. In Europe, and as of 18 March 2020, more than one third of European citizens (250 million people) lived under strong lockdown [1] and all member states of the European Union had implemented some form of restriction of movement [2].

The COVID-19 pandemic has altered all outlooks on future mobility. During COVID-19 lockdowns a reduced necessity to travel and an increased risk perception while travelling significantly impacted passenger transport demand [3,4]. Forster et al. (2020) found out that more than half of the world's population reduced mobility by more than 50% during the climax of the first pandemic wave [5], with public transport being most affected [6]. For example, some European cities have

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reported a decline of public transport usage of more than 80% during the peak phase of the pandemic in spring [7]. Recent literature has repeatedly analysed a modal shift from public to individual transport modes [8] such as to the private car [9–12] as well as to active transport modes [9–11]. In an online survey collected from people around the world, Abdullah et al. (2020) investigated a significant shift from public to both motorized and non-motorized transport modes. Bucsky et al., (2020) showed an increase in the modal share of the car of 22% and a decrease in the use of public transport of 25% in Budapest. Similar results are shown for studies in the Netherlands [10] and Italy [9,11]. An increased importance of travel characteristics related to the risk of infection [13,14] seem to strongly define this shift in travel behaviour. At the same time, a modal shift towards the car will most likely lead to an increased dependence on the car [12] and an increase in car sales in the coming years [14]. As a response to less customers, major European public transport operators have reduced the frequency of their services [15–17]. In London, for example, up to 40 underground stations were closed by the end of March 2020 and several bus lines were suspended [18]. In Naples, Rome and Valencia, night service was completely stopped and in Valencia, line suspensions and service cuts led to an overall 35% service reduction on working days [15]. According to the OECD's report on cities COVID-19 policy responses (2020) '*During France's lockdown, 30% of Paris' RATP [public] transport network was operational, and only […] 4% of the 12 million typical daily trips pre-COVID- 19*' were being made [19]. As a reaction to the pandemic, mobility options that comply with social distancing were in the epicentre of political discussions. Many cities have substantially incentivized cycling and walking by implementing pop-up lanes, car-free sections and wider sidewalks. Kraus and Koch [20] reported that European cities have implemented, on average, 11.5 km of provisional pop-up lanes. Paris, for example, turned 50 km of car lanes into bicycle paths and announced 274 million € investments into the bicycle network. Brussels converted 40 km of car lanes to cycle streets and Milan has launched a plan that includes the transition of 35 km of car lanes into walking and cycling lanes after lockdown eases [21]. The literature on previous crises highlights that a crisis can trigger a modal shift in surface passenger transport. For example, in response to the terrorist attacks in London in July 2005, targeted at public transport, Londoners avoided commuting by public transport and the government reported an upsurge in bike use of 13% within the first month after the terrorist attack [22]. The IEA believes that COVID-19 responses will be comparable to those seen related to the Severe Acute Respiratory Syndrome (SARS) crisis. During SARS, the city of Taipei (Taiwan) reported that public transport ridership dropped by 50% during the peak of the crisis, but returned to pre-crisis levels after four months [23].

Since most of COVID-19 related interruptions entail consequences for all modes of transport, including private cars, public transport, cycling and walking, a momentum to rethink mobility options has been created. The decrease of passenger transport activity is of particular interest because not only does the transport sector account for a large share of global energy-related CO_2 emissions and remains the main pollution factor in cities, but it is also extremely difficult to decarbonize [24]. A closer look at European's energy sectors and associated emission patterns reveals that almost one-quarter of total CO_2 emissions are attributable to the transport sector [24] and between 1990 and 2016, energy consumption by the transport sector (freight and passenger) grew by as much as 34% [25,26]. Within the transport sector, road transportation represents the heaviest emitter in Europe, accounting for roughly 70% of all transport emissions [27]. Most of all road transport emissions can be attributable to passenger transport [28]. As Europeans have become more mobile than ever, passenger road transport activities have steadily increased and are projected to continue to do so for decades to come. Estimates of the European Commission in 2019 estimated an increase of 42% for passenger transport in 2050 [29]. If mobility behaviour will not change, rising demand for mobility will most likely further create a situation characterized by poorer air quality, growing CO_2 emissions, high noise levels, severe congestion, and space problems [30]. National governments have been pushing for transport emission cuts already for decades, but without success [29]. However, the severe socio-economic disruption of COVID-19 has modified energy demand within the transport sector and the associated anthropogenic emissions enormously. Studies of ground-based and satellite observations [31,32] and mobility data [5,33] indicate that pollution levels have decreased during COVID-19. According to IEA's Global Energy Review of July 2020, global energy demand had dropped by 3.8% during the first quarter of 2020 compared to the first quarter of 2019 [34]. Subsequently, global carbon emissions fell by as much as 5.8% in 2020. Le Quèrè et al. (2020) computed emission reduction in 2020 as a function of the duration of confinement and found a year-on-year emission reduction of 4.2% if pre-pandemic conditions had returned back to normality by mid-June and 7.5%, assuming that restrictions remained until the end of 2020 [33]. For Europe in particular, both emission scenarios indicate a decline of 5.1% and 8.5%, respectively. In absolute terms, emissions from surface transport were most significantly affected, showing a 36% decline by 7 April 2020 while contributing 43% of the total emission change. The analysis by Liu et al. (2020) estimated a 12.7% emission decline for EU27 & UK during the first six months of 2020, largely due to changes in ground transportation (40% of the total decrease) and with France, Spain and Italy exposing the largest reductions [35]. A similar observation was made by Guevara et al. (2020), where CO_2 emission reductions for Europe were as high as 10.3% between 1 January and 31 July 2020, with most of the reductions coming from road transport and aviation [36]. However, previous crises, such as the economic crisis in 2008, have taught us that without rethinking our daily habits, long-lasting impacts are unlikely to come. Even though a green recovery was at the heart of the EU stimulus packages of the economic crisis, year-on-year emissions witnessed an upswing of 2.4% in the EU27 between 2009 and 2010, representing the highest emission increase over the course of the previous 20 years [37].

The literature specifically targeting COVID-19 induced emission trends in surface passenger transport is scarce. For example, what happened to passenger traffic after the severe closures in April and what is the impact of resulting surface passenger transport trends, such as increased private commuting on CO_2 emissions in Europe? Caused by the ongoing pandemic, mobility behaviour of passengers and thus transport emissions have been disrupted for several months, which might contribute to the momentum to pursue a smarter and greener transport system. New developments and needs of passenger transport must be addressed with innovative research while ensuring the fulfilment of the European Green Deal targets. Therefore, more information on today's trends is necessary. Here, we examine specifically passenger mobility and near-real time emission trends during the first COVID-19 pandemic wave between 21 January and 21 September 2020 in all EU27 + UK countries. By capturing not only strict lockdowns but also a period of extended or lifted lockdowns, we provide a picture of road and rail surface passenger emission trends in Europe, with a special focus placed on present-day developments within private, public, and active passenger transport. To discover and compare the impact of different lockdown policy approaches on activity and associated emission changes, we selected six countries with different lockdown policies for a detailed analysis. We furthermore explore if passenger trends comply with mobility and transport targets of the European Green Deal. Analysing mobility fluctuations during COVID-19 times will further open opportunities to discuss mobility policies needed for a green recovery and low-emission pathways.

2. Methods and data sources

2.1. CO_2 emission estimates

Our analysis includes all EU27 countries + the UK (abbreviated as EU27 + UK), and focuses on six European countries that represent different lockdown strategies during the COVID-19 pandemic, namely Spain, France, Italy, Germany, the UK, and Sweden. For example, Italy was the first country that imposed severe and forced lockdown measures while Sweden's lockdown policies were built upon the 'freedom under responsibility' approach and national recommendations (Supplementary COVID-19 lockdowns in Europe). The focus countries represent 61% of Europe's total and 78% of Europe's passenger CO_2 emissions. We estimate daily surface passenger transport emissions during COVID-19 lockdowns indirectly from statistical analysis of daily activity data and country-specific emission factors, with a special focus placed on differences between the private, public, and active passenger transport sector. Additionally, we analyse how the activity and associated CO_2 emissions of countries with different policy approaches differ over time. Mobility data of Google, Apple, TomTom traffic, Waze and other mobility platforms released in response to the COVID-19 pandemic served as a unique opportunity to derive emission trends for EU27 + UK (see Data Availability and Supplementary Mobility data, Table S1). Most datasets cover many EU countries which is beneficial over previous methods, as emission trends can be analysed more consistently across EU countries. In addition, we collected non-disclosed data from individual cities' municipal governments, national governments, and mobility-related institutions. Due to the long atmospheric lifetime of carbon dioxide, any COVID-19 related perturbation only triggers small changes in the direct CO_2 signal which is why annual emission reports of energy and fuel consumption are traditionally used to assess CO_2 emissions changes. However, since inventory assessments lag reality by roughly one year, there are currently no such inventories to assess the impact of COVID-19 on CO_2 emissions. Compared to annual emission reports, new-real time carbon estimates provide much faster insights about present-day CO_2 trends [35].

The analysis will cover eight months, starting one month prior to the first lockdown in Europe on 21 January 2020 until 21 September 2020. Daily emission changes ($\Delta CO_2^{c,m,t}$) per country (c), transport mode (m) and day (t) will be computed indirectly through quantifying activity indicators per lockdown level (l) and phase of lockdown level (p) ($\Delta AI^{c,m,l,p}$) in Eq. (1).

$$\Delta CO_2^{c,m,t} = CO_2^c \times \delta S^{c,m} \times \Delta AI^{c,m,l,p} \quad (1)$$

Mean daily CO_2 emissions per country (CO_2^c) in $MtCO2d^{-1}$ were derived from the *Global Carbon Project* for the latest available year [38]. The parameter $\delta S^{c,m}$ is the fraction of emissions from a given transport mode in a country, derived from various sources (Supplementary Sectoral allocation, Table S2). Different phases of the same lockdown level (p) are distinguished to account for changing mobility responses over the frequency of lockdown implementation. A country that had faced L1 two times, for example, was defined as having two phases of L1 (L1 P1 and L1 P2). Total surface transport emissions are composed of both, road, and rail transport emissions. Thus, aviation and shipping transport emissions were excluded from the analysis. Final emissions changes in surface passenger transport (excluding ferry transfer) are influenced by private and public passenger transport modes that exhaust emissions. It is assumed, that private cars (priv. car), motorcycles (priv. moped), and public transport modes, including railway (pub. rail), buses (pub. bus), trams (pub. tram) and rapid transit (pub. rapid) influence the total emissions from surface passenger transport.

2.2. Activity data

Surface passenger mobility changes for the private, public, and active transport sectors were analysed by using data of mobile phone users and data of vision-based technologies for each European country. Open access phone data provided access to large and representative sample sizes. For example, according to a US study, roughly 90% of smartphone users (not only Google) keep the location service open [39]. Considering Google's current search engine market share of 93% in Europe [40], our study would already cover 4% of the population, even if only 0.5% of google users activate their google maps application. This is more than any survey or poll can reach. The same holds for other phone data. Apple, for example, held a share of 31.77% of the European smartphone market in October 2020 [41]. Activity changes for most data sources are reported as percentage changes relative to the same period in 2019 or a fixed baseline of 'normal' activity levels prior to the confinement in 2020 (Supplementary Table S1). A detailed explanation of the baseline of all datasets can be found in Supplementary Mobility data. In general, mobility data for public and private transport agreed very well, showing correlations of 0.6–0.9 (Supplementary Fig. S1 and Supplementary Data processing). Due to the different nature of activity data (e.g., different baseline, regional dissimilarities and differently biased), it was impossible to identify one representative dataset that determines the overall implication on CO_2 emissions. Thus, we used activity indicators ($\Delta AI^{c,m,l,p}$) that average each countries' activity changes for all data sources per mode of transport, level of lockdown and phase of lockdown. In addition, we used the standard deviation of the mobility data to derive high and low estimates of the activity indicators. The Oxford COVID-19 Government Response Tracker (OxCGRT) was used to capture and compare policy responses consistently between countries [2]. The OxCGRT tool aggregates 17 standardized indicators into four indices. The single indicators record common policies on closure and containment (C1-C8), the economy (E1-E4), and health (H1-H5). We used the 'stringency index' (SI), which assesses the severity of lockdowns using nine indicators (C1-C8 + H1) that affect the mobility of people, on a scale of 1–100. SI was calculated for each day and country as the average of the individual indicators and served as an indicator for assessing the final lockdown level on a scale of 1–5. The health indicator H1 was included because information campaigns were supposed to have a significant impact on people's risk perception and subsequently their travel behaviour [42].

3. Results

The outbreak of COVID-19 triggered a broad spectrum of governmental responses in the European Union, and lockdown measurements differed in terms of starting dates, scale, type, and level of restrictions (Fig. 1, Supplementary COVID-19 lockdowns in Europe). The final

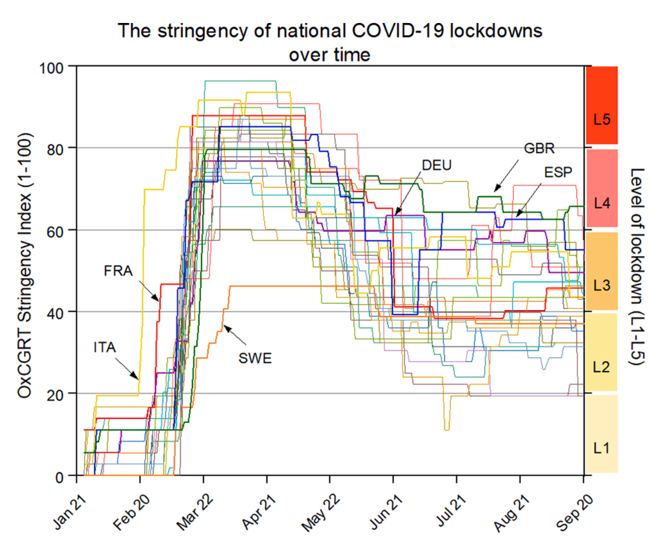

Fig. 1. The stringency of lockdowns for EU27 and UK over time. Included policy indicators from the Oxford COVID-19 Governmental Response Tracker (OxCGRT) formed the stringency index on a scale of 0–100 [2]. This index was then used to distinguish between different levels on a scale of 1–5. The six selected countries representing different lockdown policies, France (FRA), Germany (DEU), the United Kingdom (GRC), Italy (ITA), Spain (ESP) and Sweden (SWE) are highlighted.

lockdown level index assesses the lockdown stringency based on included policy indicators such as school or workplace closure over the course of the pandemic on a scale of 5 levels (L1-L5), with L1 representing the weakest and L5 representing the strictest lockdown measures. To distinguish activity responses with respect to the frequency of lockdown implementation, different phases of the same lockdown level were identified. The phase of lockdown (p) was defined as the number of times a country had implemented a certain lockdown level. A country that had faced lockdown level 3 (L3) twice, for example, had been defined as having two phases of L3. With a localised lockdown on 21 February 2020 in the region of Lombardy, Italy was the first country to impose a severe and enforced lockdown. This is reflected in an abrupt increase in the stringency index on 21 February (Fig. 1). Spain and France followed with national lockdowns on 14 and 17 March, respectively. Germany and the United Kingdom imposed national lockdowns on 20 and 23 March, respectively. By the end of April, the stringency index recorded for Germany and the UK were lower than those recorded for Spain, France and Italy. Compared to other EU countries, the UK implemented strict lockdowns relatively late. Unlike all other countries, no national lockdowns were enforced in Sweden and lockdown policies were based on the 'freedom under responsibility' approach and national recommendations. As a result, Sweden's stringency index remains low throughout the lockdown chronology. Since the beginning of May, most EU countries lifted lockdown restrictions. Policy responses after May varied not only between but also within countries more than in previous phases. However, since early October, a second wave characterised by an increasing number of daily COVID-19 cases and deaths pushed policymakers to again minimise activity.

3.1. Public and private passenger transport

Activity declines, represented by negative percentage changes from the baseline value occurred to a larger extent within higher lockdown levels, such as L4 and L5 (Table 1). This holds for both the private and the public sector. On average, focus countries exhibited greater activity declines than the EU within both sectors. The transport option that is linked to a higher risk of contagion, namely public transport, experiences stronger activity declines than private transport. Discrepancies between public and private passengers emerged strongest when countries faced lockdown levels 2 and 3, indicating that especially the beginning and the end of the analysed period triggered different mobility responses with respect to both transport sectors.

Over the entire period of study, private and public transport experienced a 2% and 29% decline compared to pre-pandemic values, respectively. In general, private transport declined the most in April, showing activities of 56% below the baseline (for the EU). However, public traffic received an even harder blow than private passenger transport in April and activities decreased by 61% compared to pre-pandemic levels. During the last three weeks of study (September), private transport resumed to activity levels of 23% above the baseline, whilst public transport flows declined by as much as 7% compared to the pre-pandemic baseline. In the aggregate, 10 out of 26 analysed countries exhibited an upsurge in private passenger travel over the entire period while no country experienced increased public passenger travel. Fig. 2 explores changes in daily private and public passenger transport for individual focus countries and the EU over time (for all countries see Supplementary Fig. S2). Individual focus countries represent the trend in the EU to a large extent. During the climax of the first pandemic wave in April, daily activity dropped by 80% and 90% for the private and public sector, respectively. Italy, as the first country to implement lockdown level 4 reduced activities in both sectors earlier than other countries. Countries that were especially hit by the pandemic in April, namely Italy and Spain, cut down activity in both sectors most markedly. In contrast, Sweden, the country with the weakest lockdown policies, showed higher activity levels than most other countries. Sweden's private transport sector experienced the smallest reduction within the EU, showing a 25% decline, compared to a 56% decline for the EU (April). After the depression in April, activities progressively resumed in both sectors. Even though most countries (except for Sweden and Finland) were still in strict lockdown at the end of April (L4 and L5), activity levels in both sectors already started to recover. This suggests that the effectiveness of strict lockdown levels weakened over time (Supplementary Fig. S3). The private sector responded with a fast and continuous recovery, often characterized by activity volumes above pre-pandemic levels and at the end of September, 23 out of 26 European countries showed higher private passenger travel. Compared to the private sector, public transport resumed to a lesser extent and at a slower pace, often not being back to pre-pandemic levels. At the end of the study period, 19 out of 26 European countries showed reduced public passenger travel compared to pre-pandemic times.

3.2. Implications for CO_2 emissions

During COVID-19 lockdowns, substantial decline in CO_2 emissions from surface passenger transport emerged compared to the baseline (country specific 2018 or 2019 values) (Fig. 3). Estimates of daily CO_2 emissions from surface passenger transport reflect mobility changes over time. In April, where most EU countries faced the strictest lockdown policies, emissions from surface passenger transport encountered their deepest downturn, showing an overall decline of 49.9% (±8%) and 44.4% (±5%) for the EU and focus countries, respectively (Fig. 3, Graph c). During that month, daily EU emissions drastically dropped by 730.8 (±112) ktCO_2/day (Fig. 3, Graph a). This contributed to a 7.1% (±1%) decline in total EU emissions (public = 0.32 ± 0.1%, private = 6.68 ± 1%). After April, stay-at-home orders began to ease, and emissions declined with decreasing rates over time. Within less than three months, total surface passenger emissions bounced back to emission levels that were 10.6% (±10%) higher than the baseline value in September. Due to higher activity in surface passenger transport in September, total EU emissions increased by 1.5% (±1.4%) or 156.8 (±142.8) ktCO_2/day, compared to 2019. This points to a rebound in total emissions in the aftermath of the first COVID-19 wave. Emission trends for the focus countries predominantly resemble those illustrated for the EU (Fig. 3, graph b and d).

Considering the entire study period, the EU saved 40.3MtCO_2 (±35.3MtCO_2) and total emissions declined by 1.6% (±1.4%) due to changes in surface passenger activities (Table 2). In comparison, focus countries cut their emissions by 2.1% (±1.2%). The six selected countries accounted for 33.0MtCO_2 (±18.9MtCO_2) of the total emissions savings, which is 81.7% (±13%) of EU's total emission savings (their

Table 1
Parameter values, showing average activity changes for all datasets and each level of lockdown (L1-L5), compared to the baseline for the EU and focus countries (for baseline values see Supplementary Mobility data).

Sector	Country Code	Country Name	Level of Lockdown					n
			1	2	3	4	5	
Private	EU + UK	EU and UK	7%	17%	3%	−32%	−63%	26
	F-EU	Focus Countries	5%	3%	−5%	−28%	−75%	6
Public	EU + UK	EU and UK	5%	−15%	−28%	−50%	−70%	26
	F-EU	Focus Countries	5%	−21%	−35%	−54%	−87%	6

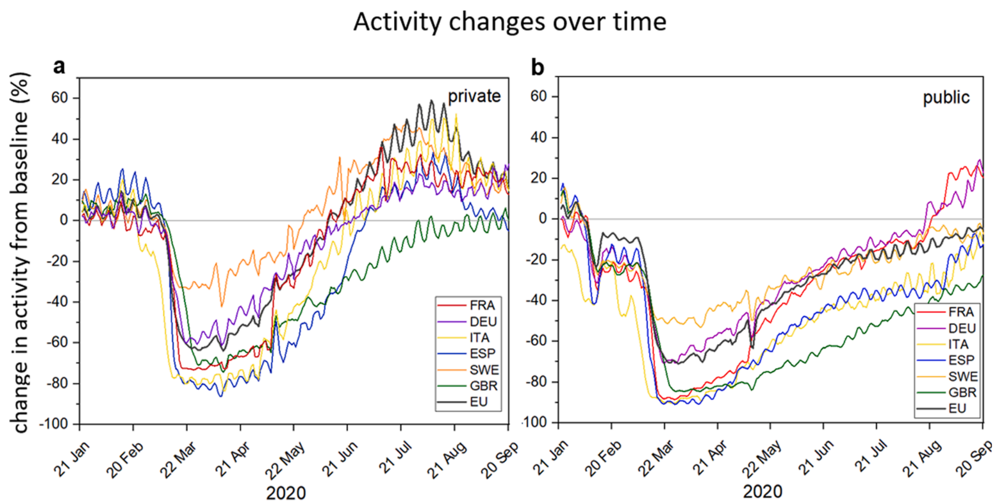

Fig. 2. Daily activity changes reported as percentage changes from a baseline for private (a) and public (b) passenger transport over time for individual focus countries and the EU, based on aggregated mobility data.

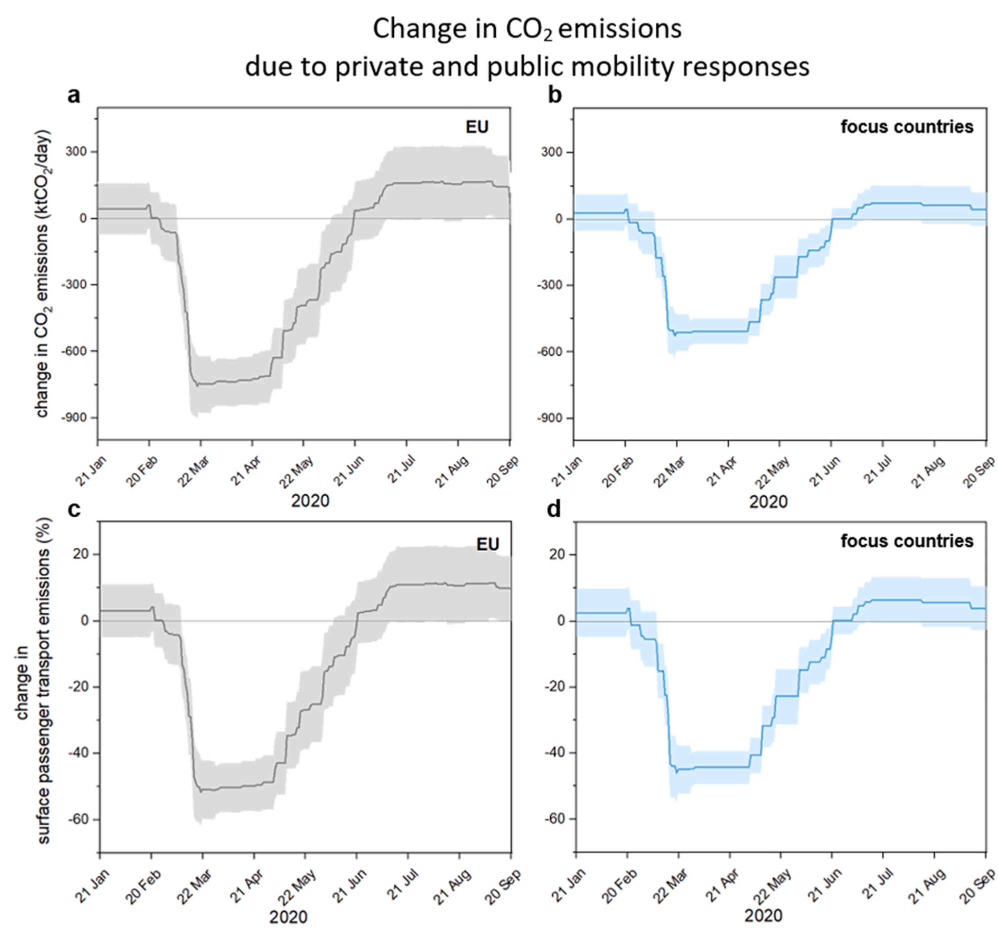

Fig. 3. CO_2 emission changes for the EU and selected countries over the study period in 2020. High and low estimates, derived by the standard deviation of the activity data are represented by trend bands. Graphs a and b represent total CO_2 emissions in $ktCO_2$/day for all European and focus countries. Graph c and d show emission fluctuation as percentage changes compared to the baseline (country specific 2018 or 2019).

'normal' emission contribution represents 61% of Europe's total and 78% of Europe's passenger CO_2 emissions). Comparing focus countries with the EU reveals that focus countries cut their total emissions to a greater extent, showing a 0.5% (±1.4%) stronger emission reduction than the EU. The same holds for April, where emissions of the focus countries plummeted to −8.0% (±0.9%) compared to −7.1% (±1.1%) for the EU. However, the downturn of emissions within the public sector is slightly smaller for focus countries than for the EU.

All focus countries combined were responsible for 81.7% (±13%) of the EU's emission savings over the entire study period. Fig. 4 (Graph a)

Table 2

CO_2 emission changes for European countries and focus countries over the entire analysed period (a) and for April (b). The table summarizes results for CO_2 emission changes as a function of activity fluctuations in private and public surface passenger transportation. A distinction is made between total emission savings ($MtCO_2$), daily average emission change ($ktCO_2$/day) and the average percentage change in total emissions and surface passenger transport emissions. Final estimates for individual countries can be found in Supplementary Table S3. High and low estimates for the entire period and April can be found in Supplementary Table S4 and Table S5.

Transport sector	European countries (EU27 + UK)				Focus countries (F-EU)			
	Total emission savings (MtCO2)	Average emission change (ktCO2/day)	Average emission change (%)	Average change surface passenger transport emissions (%)	Total emission savings (MtCO2)	Average emission change (ktCO2/day)	Average emission change (%)	Average change surface passenger transport emissions (%)
Private (a)	−35.8	−146.3	−1.4	−10.0	−30.1	−122.8	−2.0	−10.8
Public (a)	−4.5	−18.3	−0.2	−1.3	−2.9	−11.7	−0.2	−1.0
Total (a)	−40.3	−164.6	−1.6	−11.2	-32.9	−134.4	−2.1	−11.8
Private (b)	−20.9	−697.7	−6.8	−47.6	−14.6	−486.1	−7.7	−42.6
Public (b)	−1.0	-33.2	−0.3	−2.3	−0.6	−20.0	−0.3	−1.8
Total (b)	−21.9	−730.8	−7.1	−49.9	−15.2	−506.1	−8.0	−44.4

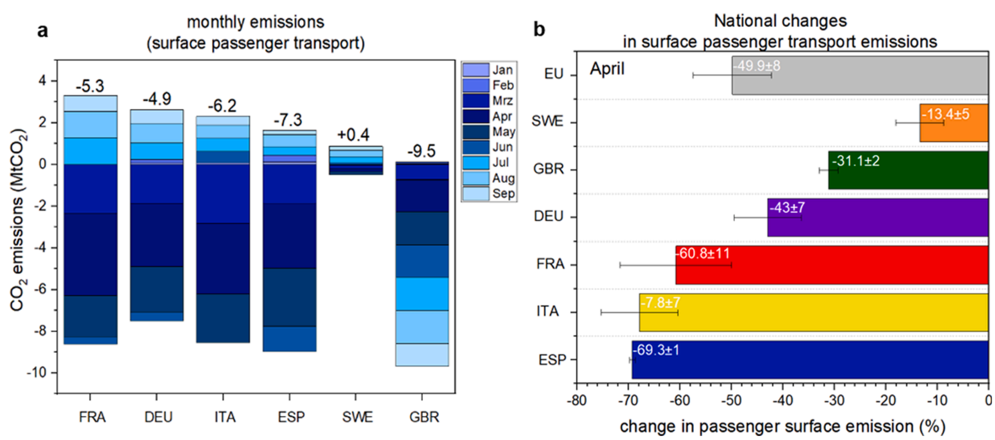

Fig. 4. Illustrates monthly changes in surface passenger transport emissions in $MtCO_2$ from January to September (a) and percentage change of total emissions for surface passenger transport in April for individual focus countries (b). High and low estimates, calculated as the standard deviation from the different mobility datasets, are represented by arrow bars.

illustrates monthly emission changes for individual focus countries. Italy, as the country with the first lockdown, experienced an earlier and stronger decline in emissions than other countries. Furthermore, a rebound in emissions was detected for Italy one month prior to other countries. In all countries but the UK, emissions snapped back in May to levels above business-as-usual. The UK was one of only four countries that did not implement different phases of the same lockdown level, and compared to other countries, the UK's lockdown policies were characterized by a strict persistence of high but not the highest lockdown level (L4). The UK stands out as having the most gradual and profound emission decline from surface passenger transport. In general, countries with tighter stay-at-home orders and stronger activity declines, such as France, Spain, and Italy, reached higher emission cuts than countries with less strict lockdowns, such as Sweden (Fig. 4, Graph b).

Over the entire study period, surface passenger emissions in the EU drastically declined by 11.2% (±10%). Only a small fraction of the total emission savings accounted for public transport (4.5 ± 2.2 $MtCO_2$ out of 40.3 ± 35.3 $MtCO_2$ total savings), while the remainder was attributable to private transport. Thus, emission savings due to the public sector are small compared to savings achieved within the private sector, which is highlighted in Fig. 5. During the climax of COVID-19 lockdowns in April, surface passenger emissions were cut by 49.9% (±7.6%), with 95.5% (±0.5%) of emission reduction coming from the private and 4.5% (±0.5%) from the public sector. During that time, the private sector cut its own emissions by 54.8% (±8%) while the private sector achieved emission declines of 17.2% (±5%). Comparing sectoral emissions at the end of September shows that emissions within the private sector were increased by 13.7% (±11%), whereas public transport emissions remained 9.1% (±5%) below the baseline. Thus, all emission increases can be allocated to private transport in September.

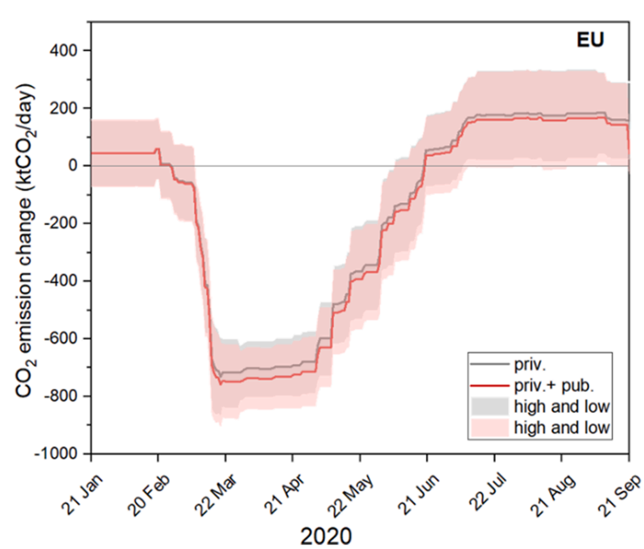

Fig. 5. Daily CO_2 emission changes in $ktCO_2$ for private transport (grey) and including public transport (red). The trend line represents high and low estimates.

3.3. Active passenger transport

Pedestrian and cycling traffic declined in lock step with stricter lockdown measures (Table 3). During weaker lockdown levels 1 and 2 (L1 and L2), European countries experienced increased walking traffic, while the more stringent lockdown levels L3, L4 and L5 resulted in lower pedestrian activity compared to the baseline in 2020. Estimates of Table 3 rest on different baseline values, namely a 2019 baseline for cycling and a 2020 pre-pandemic baseline for walking (Supplementary Table S1). From previously discussed literature (Supplementary Seasonality), it can be assumed that the 2020 baseline (of Q1: Jan) for walking generally captured lower participation than expected for other months of the year. Thus, activity reductions for walking are most likely underestimated. With this recognition in mind, there is high evidence that walking declined more markedly than cycling during lockdowns in Europe. Only lockdown level 5 (L5) triggered a cutback in cycling activity. In fact, all other lockdown levels recorded higher cycling activity compared to 2019. Focus countries followed the trend seen for the EU to a large extent. In general, focus countries cut walking activity and cycling in the highest lockdown level more noticeably than the EU (the same pattern was seen for passenger and public transport). Biking in all other lockdown levels (L1-L4) was more popular in focus countries than in the rest of the EU.

In April, when most countries faced the strictest lockdown policies, cycling and walking showed the largest declines. Compared to 2019, daily cycling activities plummeted by 43% and 44% for the EU and focus countries, respectively. Compared to the pre-pandemic baseline in 2020, daily walking activities dropped by 70% for European and by 74% for focus countries. Biking resumed fast, which was characterized by a radical upsurge after 3 May to levels 33% (EU) and 40% (focus countries) above the baseline at the end of May. In the wake of the pandemic, biking and walking progressively picked up as the preferred form of transportation. Fig. 6 accentuates this notion by showing increased activity levels over time. Between June and September, the upsurge in participation was stronger for walking than for cycling. Despite the still ongoing pandemic, mobility flows increased compared to the baseline value. Local and national policies that engaged in enhancing cycling and walking infrastructure during the pandemic might have contributed to setting of this trend (Supplementary COVID-19 cycling infrastructure and biking). According to the collection of cycling measures of the European Cyclists' Federation (ECF), during COVID-19 lockdown in Europe a total of 72 cycling infrastructures had already been implemented by the time that cycling increased (5 May 2020) (Supplementary Mobility data). However, most measurements had been implemented afterwards. In total, the ECF's documents 1164 implemented cycling and 17 implemented walking infrastructure measures during 15 March and 21 September 2020 with most of them built in May. In some cases, it was not clear when and if measurements were implemented (1639 more measures were recorded without implementation date). Focus countries showed a stronger and faster upsurge in biking than the EU. This could be related to a greater propensity of focus countries' policies to promote cycling. In total, 95% of ECF's documented cycling infrastructures are recorded for the focus countries.

4. Discussion

Due to mobility changes within surface passenger transport, we estimated emission reductions of 5.1% within the transport sector between 21 January and 21 September 2020. This decline is sharper than after the economic recession in 2008, where emissions from the transport sector declined by 2.2% in the same and 3.4% in the following year [43]. In fact, this decline is the strongest breakdown of transport CO_2 emissions since 1991. Results from other studies indicate that other transport sectors, namely marine, air, and surface freight, have undergone similar reductions during COVID-19 lockdowns [33,35]. Keeping overall yearly transport emission drops as high as 5%, the EU could meet its transport target of 60% emission reduction as stated in the 2011 Transport White Paper already in 2045 (versus 2050), and the European Green Deal target of 90% transport emission reductions in 2069 (versus 2050).

For achieving goals of the European Green Deal, the European Commission (EC) seeks to reduce total transport emissions by 90% in 2050 compared to 1990 [44]. Targeted for the greening of passenger mobility, the EC wishes to modify public transport, cycling and walking, and subsequently reduce congestion and emission levels [45]. However, recent trends in passenger transport bring into question the sustainability of mobility. We identify two main concerns regarding Europe's transport emission pathway. First and foremost, a present where lockdown-like restrictions and conditions are considered the normality is not sustainable nor desirable for any society. Secondly, current mobility trends support the notion that without sudden changes, such as triggered by policy interventions, Europe will most likely not maintain the lower carbon pathway as detected during peak months of the pandemic. The potential threat of an emission rebound after the pandemic was forecast by a number of studies [46,47] and analysed by others [48,49]. For example, according to the International Monetary Fund, total emissions are forecast to rebound by 4.2% and 3.6% in 2021 and 2022, respectively [47]. Although the future trajectory of public, private, and active passenger transport remains highly uncertain, it must be borne in mind that neither the Paris Agreement nor the Green Deal targets leave time for such carbon rebounds.

To begin with the first concern, carbon emission declines during the pandemic came at huge social costs and burden. Additionally, even during the most severe lockdown period, where most European citizens were forced to stay home, 'only' 50% of surface passenger emissions were cut. This emphasizes the issue at stake: How to maintain a low-emission pathway in the future without compromising our social well-being, while reducing the high and quite resistant baseline of Europe's surface passenger emissions (50%). The importance of setting into motion structural changes in passenger transport [19] as well as exploiting opportunities to reduce overall CO_2 emissions becomes clear [50]. Efforts must be made, and fiscal incentives provided to create comprehensive green recovery plans [51]. For a low-carbon pathway that has the potential to be socially accepted in the aftermath of the pandemic, it is essential to create a smart and safe public transport system [4], improved opportunities for shared ridership [51,52] and an innovative urban infrastructure (e.g., convenient cycling and walking routes, 15-minute cities) [19]. At the same time, socially acceptable travel options that comply with social distancing measures while reducing CO_2 emissions must be scaled up. In this respect, improving the safety and

Table 3
Showing average activity changes in percentage changes for all datasets and each level of lockdown, compared to the baseline for the EU and focus countries.

Transport mean	Country code	Country name	Level of Lockdown (L)					n
			1	2	3	4	5	
Walking	F-EU	Focus countries	16%	−2%	−11%	−33%	−84%	6
	EU27 + UK	European Union	28%	17%	−2%	−31%	−62%	26
Cycling	F-EU	Focus countries	36%	9%	9%	9%	−61%	6
	EU27 + UK	European Union	29%	8%	5%	6%	−39%	11

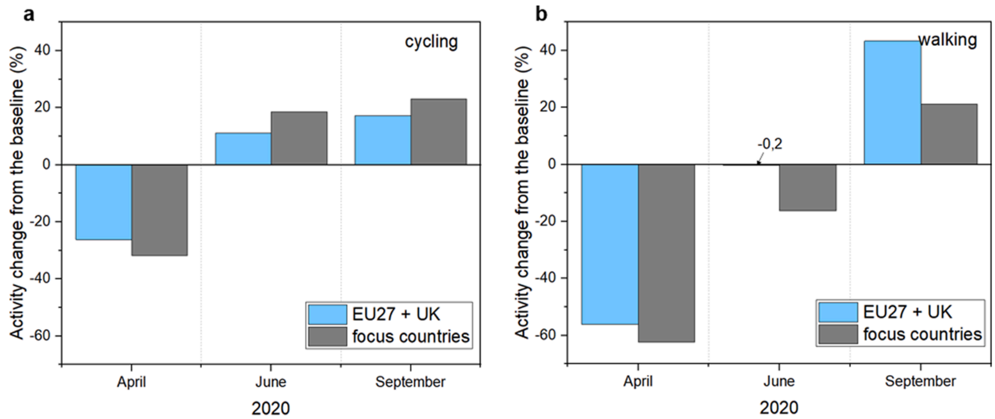

Fig. 6. Transition of people's participation in active transport, cycling (a) and walking (b) for April, June, and September for European countries (EU) and focus countries. Activity changes are shown as percentage changes compared to the baseline value.

infrastructure of active transport modes could help turn the pandemic into an opportunity [19,53]. We highlight that in the focus countries 95% of all COVID-19 cycling infrastructures had been implemented. Therefore, a well-connected and smart walking and cycling infrastructure should ensure that active transport is the most favourable transport option. Meanwhile, benefits associated with shared micromobility options should outcompete those of private transportation. This could be realized by cheaper shared micromobility, stricter rules for the use of private cars in cities, the creation of low-speed zones and the reduction of car parking spaces in cities. Given the urgency of the current climate crisis, priorities for structural changes and emission reductions must be set. Attention should focus on the massive share of emissions caused by the private sector compared to the public sector, as well as the immense role that focus countries play in overall emissions. As shown by our study, the six focus countries were responsible for 83% of total EU emission savings in surface passenger transport. This is more than their normal contribution to surface passenger transport emissions. We conclude that the policies of only six countries have a major impact on reducing overall passenger transport emissions in the EU. Thus, major efforts should be directed at preventing deep entrenchment of booming private traffic, and focus countries should play a leading role in tightening their policies on private transport.

The second concern is related to the evolution of private and public passenger transport. While public passenger transport has suffered a dramatic loss in ridership, the dynamic recovery of private passenger transport has already caused a repercussion in CO_2 emissions. Studies on mobility during the COVID-19 pandemic have pointed out similar trends. COVID-19 related risk factors seem to lure passengers from public transport [9,14] towards individual transport options and a modal shift from public to not only private car commuting but also active transport has repeatedly been analysed [8,11]. It is critical that 'sustainable mobility' agendas adapt to and address people's tendency to shift from high-density public to more private transport options. Transit systems might need to be re-designed so that they meet social-distancing requirements while becoming safer, cheaper, faster, and more convenient than ever before [54]. To maintain social distancing, McKinsey believes that public transport systems can only operate at 15% to 35% of their pre-pandemic capacity [55]. This will put an immense financial burden on public system operators [4,55]. Meanwhile, strict care must be given to ensure that COVID-19 related safety measurements do not transform public transport into an even more cumbersome way of travel. This was seen, for example, after the 9/11 terrorist attack in 2001, after which global air traffic was substantially affected for roughly half a year [56]. While strengthened security precaution after the attack seemed to rapidly enhance the feeling of safety, air travel was considered less convenient due to complicated security procedures for a longer period [57]. Smart and efficient innovation of mass and public transit systems is needed [54,58]. It is expected that the improvement and dissemination of Mobility as a Service will help with this development [54]. It was shown that the focus countries were able to reduce private, public, and walking activities to a higher extent during the peak of the pandemic. One explanation could be that from March until early April, the pandemic resulted in the most fatal outcomes in the focus countries Italy and Spain. Additionally, income is expected to play a major role in the capacity of countries to curtail activities [59,60]. The underlying assumption is that in wealthier countries a larger share of GDP is associated with service work (suitable for home office) and that wealthier countries are better equipped digitally. Our data shows that the ability of a country to curtail passenger activity during COVID-19 lockdowns decreased moderately with lower net salary. According to the New York Times'*That push is likely to exacerbate longstanding inequalities, with workers who are college educated, relatively affluent and primarily white, [more notably] able to continue working from home and minimizing outdoor excursions to reduce the risk of contracting the virus*' [61]. Additionally, Goldbaum and Cook (2020) believe that low-income groups are less capable to afford a private car and thus, may rely more heavily on public transport [59]. The necessity to avoid cuts in public transport services is highlighted, as this would further exacerbate social inequality [60] by exposing poorer and less educated people in particular to greater risk of contagion.

Mobility responses during the same strictness of lockdown shifted over time. Travel reductions within a certain lockdown level became smaller with each time of implementation. Thus, countries may still be in a transition phase towards a 'new normality', which is of particular interest for pushing forward a sustainable development paradigm. European citizens might now be more willing to change their behaviour and it might now be the momentum needed to push in a certain, more sustainable direction [19]. On an unprecedented scale, the pandemic crisis has taught us that private passenger emissions can indeed be drastically and rapidly reduced. This achievement should be the starting point for a new basal mobility where public, active, and shared transport modes outcompete individual transportation. We propose that follow-up research focuses on how to strengthen public transport, making it safer, cheaper, faster, and more convenient than ever before. Additionally, special attention should be paid to reducing emissions within private transport. Research could be carried out, for example, on intelligent applications for traffic management in automated cars, on mitigating the risk of infection in public transport systems and on modelling the impact of new transport policies. Particular attention should be paid to factors that influence transport choice and help with the so-called last mile problem. For example, demand for public transport could be influenced by the available infrastructure and enhanced connectivity (e.g., bicycle transport on trains and buses or bicycle rental at the destination).

4.1. Uncertainty and limitations

In general, satellite and ground-based emission data of the short-lived NO_x provide an opportunity to test the veracity of our analysis. CO_2 estimates of our work agree well with observed changes in NO_x of the Copernicus Atmosphere Monitoring Service [62] and the research of Guevara et al. (2020) (Supplementary NO_2 observations). However, there are significant limitations associated with the approach of our study, such as the loss of a direct estimation of surface passenger transport emissions, different baselines of the datasets and a lack of knowledge about the nature of the data. Most importantly, emission estimates were not the product of measured data but were inferred indirectly from activity data. The use of general emission indicators for countries' private and public passenger sector may lead to disregarding assumptions associated with the information source. In addition, it became apparent that using activity values as percentage changes from a baseline leads to limitations. For instance, seasonal fluctuations in private and public passenger traffic could not be captured and the datasets compared activity levels to different baselines. Despite the fact that datasets were intensively examined regarding their baseline, correlation and the direction of the error, it must be highlighted that the baselines of the data could be corrupted by abnormal changes due to, for example, holidays or seasonality. Another disadvantage of using activity data arises from the lack of access to the nature of the data. Due to the anonymization of the data, it was not possible to access the fit between sample size and overall population distribution. The younger and older generations are most likely underrepresented. Even though no information on the average income was found for either Apple or Google users, there may be reason for concern that especially Apple users predominantly represent higher income groups [63].

5. Conclusions

Our study examined mobility trends of passengers during COVID-19 lockdowns in Europe (EU27 + UK) and investigated associated CO_2 emission changes. A special focus was put on six European countries, representing different lockdown strategies during the COVID-19 pandemic, namely Spain, France, Italy, Germany, the UK, and Sweden. Analysing the first seven months of the pandemic and starting one month prior to the first case in the region of Lombardy (Italy), we present a comprehensive picture of surface passenger transport emissions during the first COVID-19 pandemic wave in Europe. For analysing passenger mobility and emission trends, we introduced a dataset of country-, sector- and lockdown- dependent parameter values, representing activity changes within private-, public- and active passenger transport. Compiled parameter values subsequently served as a proxy for quantifying daily emission changes. Our final estimates are the product of a comprehensive collection of information sources, including openly and not-openly accessible near-real time activity data from mobile phones and counting stations. Our results highlight that the upheaval of passenger transportation during the pandemic has given rise to several overlapping trends. Substantial dissimilarities between the private-, public- and active surface passenger transport sector persisted.

In general, mobility within the public sector was most negatively affected by social-distancing measures, followed by the private and active transport sector. In the aggregate, total emissions fell by 1.6% in the European Union (40.3 $MtCO_2$) due to changes in surface passenger transport. This decline was predominantly the product of focus countries, declining their private passenger transport emissions. Over the entire study period, surface passenger emissions significantly declined by 11.2%. More than 90% of this decline was coming from the private and the rest from the public sector. Especially during the first months of the pandemic , mobility decreased in lock step with lockdowns in all sectors (private, public, and active sector). Countries with weaker lockdown policies, such as Sweden, reduced surface passenger transport less than countries with strict lockdown measures such as Italy and Spain. However, European countries consistently showed that the effectiveness of strict lockdown levels (L4 and L5) weakened with the frequency of implementation. It was shown that in April, CO_2 emissions from surface passenger transport encountered a decline of 50% which contributed to a 7.1% reduction in total CO_2 emissions. After the climax of countries' lockdowns in April, private passenger travel recovered rapidly, while public passenger flows remained below pre-pandemic activity levels. Furthermore, a higher share of people participated in active transportation, raising cycling, and walking traffic intensively. Finally, changes in mobility behaviour over time entailed a rebound in emissions in the aftermath of the initial peak lockdown phase. Solely prompted by private transportation, a rebound in total emissions and surface passenger emissions of 1.5% and 10.7% was estimated at the end of the study period, respectively. Emissions snapped back to a larger extent in countries where lockdown policies showed larger fluctuations.

Our study highlights that surface passenger transport trends are complex in terms of their impact on Europe's CO_2 emissions. Overall, the effect of the COVID-19 crisis led to a decline in emissions between 21 January and 21 September 2020. However, the current development of increased private and decreased public passenger transport is not well aligned with major climate goals, and without reversing these trends, emission reductions as stated in the European Green Deal are unlikely to be achieved. Long-term mobility and emission trends remain highly uncertain and depend upon economic recovery, policy agendas, and societal pathways, which will ultimately be determined by the impetus given now. At present, mobility changes are most likely temporary reactions rather than deeply anchored behaviour changes. Together with the fact that travel behaviour has already been interrupted for several months, this constitutes a great potential for structural changes to be more accepted compared to pre-pandemic times. The timeliness and detail of near-real-time carbon estimates, such as analysed in our study, provide important insights into current emission trends of passenger transport, and offer the basis to build policy adjustments and innovative research more quickly in response to current trends.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Mobility data was requested by contacting national statistical offices, cities, companies, mobility and mobile phone platforms and intelligent transport systems (ITS). Google mobility data can be accessed via https://www.google.com/covid19/mobility/ [64]. Mobility Trends reported by Apple are available at https://covid19.apple.com/mobility [65].The Citymapper Mobility Index can be found at https://citymapper.com/cmi.Congestion [66]. The TomTom Traffic index is reported on the following webpage https://www.tomtom.com/en_gb/traffic-index/ [67]. Data of the Waze navigation app is released at https://www.waze.com/covid19 [68]. UK mobility data is accessible through https://www.gov.uk/government/publications/transport-use

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.117396.

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