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E-mail: y.shan@rug.nl and k.hubacek@rug.nl**Keywords:** public and private passenger transport, CO₂ emission trends, 1st and 2nd covid-19 waves, global analysisSupplementary material for this article is available [online](#)**Abstract**

The coronavirus pandemic has severely impacted our day-to-day activities and brought about significant change in all major sectors, especially surface passenger transport. Lockdowns and stay-at-home restrictions have significantly reduced energy demand and consequently CO₂ emissions of surface passenger transport. The change in CO₂ emissions is calculated from near-real-time activity change data as a function of 3 confinement levels. The activity change and related emission trends reflect changes in the mode of transport during different waves, this can be used to understand mobility trends and patterns when stringent measures are imposed. Consequently, constructive use of this data can help prepare and develop the transport sector in case of another epidemic outbreak or other unprecedented calamities and to build a resilient transport infrastructure post-COVID-19. This study estimates and analyzes the changes in CO₂ emissions associated with the public (bus and rail) and private surface passenger transport from March 1st, 2020 to Jan 31st, 2021 in 21 countries. The research period covers the 1st and the 2nd waves of COVID-19 in these countries. A higher activity reduction and consequently CO₂ emission reduction is displayed during the 1st wave compared to the 2nd for most countries despite implementing stringent measures during both waves. This is in line with countries adapting to the ‘new normal’ and restarting socio-economic activities. Similarly, public transport recovery is slower than private transport recovery, making it essential to focus on reinforcement and adaptation of public transport infrastructure for the future. The results show that a cumulative 510 Mt CO₂ has been reduced over 11 months in 21 countries, compared to pre-pandemic levels. This reduction brings about a 6% drop in transport CO₂ emissions and a 1.5% drop in global CO₂ emissions. This analysis sheds light on mobility trends and travel behavior of surface passenger transport modes and related CO₂ emissions in different countries which can be used to exemplify the path to recovery based on near-real-time data.

1. Introduction

The coronavirus disease (COVID-19) has considerably impacted our lives and daily human activities since early 2020. The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was declared as a global pandemic by the World Health Organization on March 11th, 2020 after an alarming surge in positive COVID-19 cases (Director General WHO, 2020). The SARS-CoV-2 is highly infectious and contagious, transmission takes place through close contact between humans and is highly likely in closed environments (World Health Organization, 2020). Gathering in closed spaces like malls, groceries, and public transport, such as buses, trains, trams, and airplanes, have been deemed as highly contagious environments and have been recommended to be avoided based on past experiences dating back to the 1900s which dealt with epidemics like influenza (Bell *et al* 2004). Affected countries took necessary measures to curb the spread of the virus by implementing home

confinement, travel restrictions, border shutdowns, social distancing measures, and wearing masks. The unprecedented change in our life brought many daily activities to a standstill. Home confinement and border shutdowns resulted in the primary, secondary, and tertiary sectors reducing operations and were forced to introduce teleworking where applicable. As a consequence of reduced activity in all major sectors, there has been a significant decline in global CO₂ emissions. In the 21st century, early April of 2020 is estimated to have the highest drop in daily global CO₂ emissions of 17% compared to 2019 (Le Quéré *et al* 2020). For almost all countries globally, the health crisis transformed into a major socio-economic crisis (Nicola *et al* 2020). This led to a total emission drop of 5.8% in 2020, compared to 2019 and such a drop might last for a couple of years depending on the spread of the virus (IEA, 2021, Shan *et al* 2021). Subsequently, based on estimates, if lockdown measures implemented during April were sustained until June the CO₂ emissions would have declined by 4.2% and by 7% if they had lasted for the whole year. Similarly, the international research initiative Carbon Monitor calculated an 8.8% (−1551 MtCO₂) reduction in global CO₂ emissions for the first half of 2020 compared to 2019 (Liu *et al* 2020)

Out of all the major sectors affected by the pandemic, road transport saw the biggest decline in activity compared to others. By the end of March, global road transport activity declined by more than 50% compared to 2019 (IEA, 2020b). According to (Le Quéré *et al* 2020), the aviation sector and the surface transportation sector had respectively the highest and second-highest activity reduction estimated for 69 countries. In Europe, passenger transport demand was severely affected during when the first lockdown measures, countries like Spain (12%), France (22%), and Italy (24%) had an all-time low of weekly vehicle miles traveled (VMT) compared to pre-covid levels nationwide (INRIX, 2020). Similarly, (Forster *et al* 2020) found that by the end of the 1st pandemic wave, transport demand declined by 50% for half of the world's population. Surveys conducted for various countries worldwide by McKinsey & Company (Chechulin *et al* 2020) and (Abdullah *et al* 2020) show that the factors which influence the choice of transport mode pre-COVID-19 such as, time, comfort, and money have taken a backseat to safety and risk of being infected. Studies show that risk perception of traveling is the most influential factor to choose a transport mode during COVID-19. Case studies in different cities such as Gdansk, Poland (Dumbliauskas and Grigonis, 2020), Vilnius city, Lithuania (Przybyłowski *et al* 2021), and various cities in the US (Liu *et al* 2020) on travel behavior and mode choice also yields similar results. As a result, public transport use has declined rapidly, leaving authorities to operate at a very low capacity to adhere to social distancing measures (UITP, 2020a). Public transport usage compared to pre-covid levels also saw a massive decline of 90% in Italy and France, 85% in Spain, 75% in the UK, and 70% in Germany (Falchetta and Noussan, 2020). This left people with no choice but to adapt to private modes of transportation steering away from public transport and sustainable mobility (UITP, 2020a). As public transportation demand has declined significantly, public means of transport are operating at very low levels of capacity. Hence, most governments have implemented public transit services reduction and reduced service frequencies to cope with the reduction in ridership (UITP, 2020a). Countries like the US, Italy, the UK, Spain, and Germany have implemented service reduction, and some suspended their service altogether in cities with reduced ridership. Other countries have reduced capacity by 50% to observe social distancing measures (UITP, 2020a, Schulte-Fischedick *et al* 2021).

Reduced transport activities have had a significant impact on CO₂ emissions. During pre-COVID-19 times, 21% of global emissions (Climate Watch, 2018) and 24% of energy-related emissions (IEA, 2020c) were produced by the transport sector. Considering the transport sector activity reduction that has transpired it is imperative to know the related CO₂ emission reduction. By the end of 2020, oil-related CO₂ emissions dropped by 1100 Mt compared to the previous year and around 50% was accounted for by the curtailment of road transport (IEA, 2021). Similarly, (Le Quéré *et al* 2020) estimated surface transport emissions reduction of 36% with an absolute reduction of −7.5MtCO₂/day to be the second-highest reduction behind the aviation sector. Ground transport was the largest contributor to the global emission reduction with −613.3 MtCO₂ (Liu *et al* 2020). Most research focused primarily on the 1st half of 2020 which only includes the 1st wave of COVID-19 in most countries. Moreover, differentiation within the road transport sector between freight and passenger transport is missing. Since freight and passenger transport's operational purpose and circumstances are different, it is important to disaggregate the CO₂ reduction through changes in activities.

Aiming at the research gap above, this study estimates the environmental impacts of surface passenger transportation during the 1st and 2nd wave of COVID-19 from March 1st, 2020 to January 31st, 2021 for 21 major economies representing 44% of transport-related CO₂ emissions in 2018 (IEA, 2020a). The 21 countries are Argentina, Australia, Belgium, Brazil, Canada, Czechia, France, Germany, Indonesia, Italy, Mexico, the Netherlands, Philippines, Russia, Singapore, South Africa, Spain, Sweden, Switzerland, the United Kingdom, and the United States of America. The selected countries include developed and developing economies from each continent, achieving latitudinal and longitudinal coverage. These countries are also major contributors to the transport CO₂ emission of their respective continents, except for Africa and Asia. An in-depth analysis of private and public (bus and rail) transport activity change in these countries is carried out to indirectly estimate the related CO₂ emissions. Initially, the activity change and related indirect CO₂ emissions of surface passenger

transport modes are analyzed in relation to the different confinement levels defined based on the Oxford stringency index (Hale *et al* 2021), as well as to the 1st and 2nd waves across different countries. This is implemented by data processing and compilation of near-real-time activity change data, stringency index, and 1st and 2nd wave periods for 21 different countries. This study then runs a fixed effects regression model, where the output predicts the activity change of surface passenger transport in relation to the stringency index during different waves. By doing so, the similarities and discrepancies between the mobility trends and travel behavior of different countries are acknowledged. This study then adopts the indirect CO₂ change estimation method used in recent research (Forster *et al* 2020, Le Quéré *et al* 2020, Liu *et al* 2020) to calculate the CO₂ emissions related to surface passenger transport change. A significant increase in activity change and related CO₂ emission is expected during the 2nd wave compared to the 1st for most countries in the study. Moreover, public transport is likely to make a slower recovery compared to private transport. Countries with a better developed public transport infrastructure are expected to recover at a quicker rate than other countries. The variation in activity change and related CO₂ emissions during the waves and different confinement levels can be instrumental in gaining insight into mobility trends and travel behavior. It can be used constructively to implement adaptation strategies to make traveling safe and transition into sustainable mobility, especially focusing on the public transport infrastructure in the future and in response to potential future pandemics.

2. Material and methodology

To estimate the environmental impacts of surface passenger transportation during the 1st and the 2nd wave across 21 countries, a conceptual research framework is implemented in the study. The private and public transport activity change data is used to indirectly estimate the related CO₂ emissions. Through different data sources, relevant activity change data for public and private transport is explored. The transport activity change and related CO₂ emissions will be analyzed to interpret their relation to the different confinement levels during the 1st and 2nd waves across different countries. Therefore, based on the stringency index of the different measures implemented in countries, 3 different confinement levels are classified. Similarly, to evaluate the variation of activity change and CO₂ emissions during the different waves, it is necessary to set an equivalent method to determine the start and end of a wave for each country. In terms of mobility demand, activity change of private and public transport mode is directly related to strictness of confinement measures as well as risk perception (Ahangari *et al* 2020, Ceder, 2020, INRIX, 2020). Hence, a fixed effect regression model is used to predict the relationship between activity change of transport mode during the 1st and 2nd wave as a result of the stringency index. The output statistics of private and public transport regression models are compared to gain insight on the relation of stringency index during the waves to the activity change. Furthermore, the surface passenger transport CO₂ emission change is estimated using a formula adapted from previous research papers (Forster *et al* 2020, Le Quéré *et al* 2020, Liu *et al* 2020). The later sections will focus on and explain in detail the individual aspects of the research framework.

2.1. Surface passenger transport activity change

Several mobile GPS navigation systems including Apple (Apple Maps, 2020) and Waze (Waze, 2020) provide daily transport activity data for different countries across the world. The nature of Apple's mobility data was more suited to achieve the aims of this research since it represents the change in mobility of private transport, public transit which includes buses, rail, tams, etc., and walking for different countries. The data shows the daily percentage change in search route requests received per country/region relative to a baseline volume of January 13th, 2020 (Apple Maps, 2020). The Waze navigation database represents the daily percentage change in km/miles driven in 45 countries for private transportation compared to the baseline, which is the average value of the corresponding day of the week, during 2 weeks from February 11th to February 25th, 2020 (Waze, 2020). This dataset represents real-life travel since it shows the change in activity in km/miles driven, which translates to CO₂ emissions from March 1st, 2020, and is essential in our work. These datasets are used synthetically to achieve close to real-time and immediate CO₂ change estimates rather than the conventional CO₂ estimation methods such as fuel consumption and atmospheric CO₂ level which suffer from time delays. Out of the 21 countries selected, Argentina, Indonesia, Russia, and South Africa only have data on private transport activity change available and lack data regarding public transport from Apple. The remaining 17 countries have data regarding activity change in both the public and private transport sector for Apple. (Refer to supplementary appendix A for more information on the datasets (available online at stacks.iop.org/ERC/4/045010/mmedia).

2.2. Classification of confinement levels and waves

Mobility reduction varies across waves for different countries and is dependent on the severity of the measures implemented in each country. The degree of measures implemented varies according to the number of

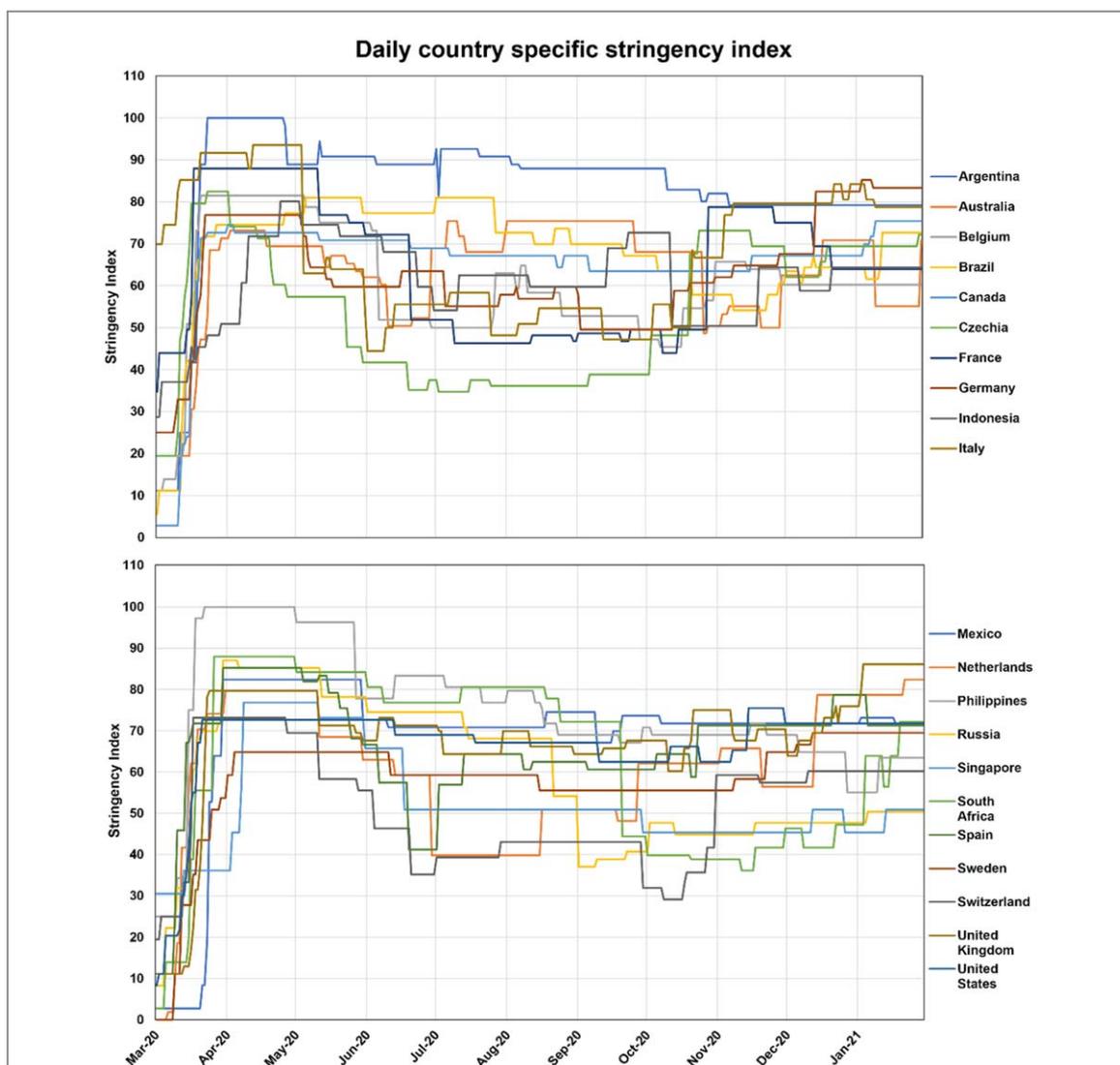


Figure 1. Stringency Index of measures implemented by the governments of all the 21 countries during the entire period of this study. (Author’s creation).

Table 1. Confinement level classification and range (Author’s creation).

Restriction levels	Classifications	Range
Low restrictions	Policies implemented are only recommended and are for a targeted region in a country.	0–35
Partial restrictions	Ranges from policies recommended for the whole country to being mandatory for a targeted region.	35–65
Strict restrictions	Ranges from policies mandatory for specific regions to mandatory for the whole country with increasing levels of restrictions	>65

COVID-19 cases in a region. Since this study compares mobility activity and emission change on a country level, we use the country level stringency index published by the University of Oxford (Hale et al 2021). The Oxford stringency index retrieves government website data and news articles regarding policy measures implemented for all the countries available. Since these policies are implemented on various scales in different countries, Oxford normalizes them by converting them into a daily index rating ranging from 0–100 (100 being the strictest), as shown in table 1. The calculation of the stringency index can be referred to in supplementary appendix B.

Figure 1 shows that once measures were implemented to curb the spread of the virus, the stringency index of the countries never dropped below the partial restriction level, i.e., SI = 35 to 65, (except Switzerland) even though the cases dropped concluding the 1st wave. It is interesting to acknowledge that despite countries experiencing much higher and more deadly cases as well as prolonged duration during the 2nd wave (John Hopkins University, 2020), which started around late August or early September for most countries the

Table 2. 1st and 2nd wave dates and duration for 21 countries (Author's creation).

Countries	1 st wave		2 nd wave	
	Start and end dates	Duration	Start and end dates	Duration
Argentina	24.03–28.11.2020	249 days	04.12.2020–31.01.2021	58 days
Australia	13.03–23.04.2020	42 days	03.07–24.09.2020	83 days
Belgium	19.03–08.06.2020	81 days	11.09–12.12.2020	92 days
Brazil	22.03–31.10.2020	223 days	01.11.2020–31.01.2021	223 days
Canada	17.03–04.07.2020	109 days	9.9.2020–31.01.2021	109 days
Czechia	19.03–30.04.2020	42 days	03.09.2020–31.01.2021	150 days
France	07.03–10.05.2020	64 days	01.08.2020–31.01.2021	183 days
Germany	13.03–18.05.2020	308 days	28.09.2020–31.01.2021	125 days
Indonesia	19.03.2020–31.01.2021	318 days	N/A	N/A
Italy	01.03–31.05.2020	91 days	04.09.2020–31.01.2021	149 days
Mexico	28.03.2020–31.01.2021	309 days	N/A	N/A
Netherlands	13.03–22.05.2020	70 days	08.09.2020–31.01.2021	145 days
Philippines	29.03.2020–31.01.2021	308 days	N/A	N/A
Russia	27.03–04.08.2020	130 days	15.09.2020–31.01.2021	138 days
Singapore	09.04–29.08.2020	142 days	N/A	N/A
South Africa	17.04–30.09.2020	166 days	15.11.2020–31.01.2021	77 days
Spain	11.03–05.06.2020	86 days	13.07–31.01.2021	202 days
Sweden	13.03–27.07.2020	136 days	29.09–31.01.2021	124 days
Switzerland	13.03–11.05.2020	59 days	07.10.2020–31.01.2021	116 days
United Kingdom	11.03–08.06.2020	89 days	13.09.2020–31.01.2021	140 days
United States	10.03–11.09.2020	185 days	18.09.2020–31.01.2021	135 days

stringency index is generally lower than the first wave, except for Argentina, Mexico, and Indonesia, who have a consistent index throughout.

An epidemic outbreak is defined as the sudden rise in the number of cases of a disease (CDC, 2012). Epidemiologists characterize an ‘epidemic wave’ as a surge in infection cases, which leads to a peak and then gradually a decline (Wagner, 2020). For this study, the 1st and 2nd waves for countries have been determined according to the definition of ‘epidemic wave’. The start of the wave is defined if there is a 100% increase in the rate of change of COVID-19 positive cases. The end of the wave is declared if the number of positive cases gradually declines below the initial value at which the wave started, or if the number of cases is low and remains at a near-constant value for 2 weeks. Countries that have a surge followed by a small dip in cases leading to a higher surge in cases are considered as a single wave since a proper decline in daily cases is lacking. The daily cases per day data are sourced from the COVID-19 dashboard by the Center of System Sciences and Engineering at John Hopkins University (John Hopkins University, 2020). The data used in this dashboard to identify the waves of different countries is the aggregate of the data collected from major health organizations like WHO, ECDC, US CDC, and other government health organizations of respective countries (John Hopkins University, 2020). The 1st and 2nd wave periods are for each country and their duration is represented in table 2.

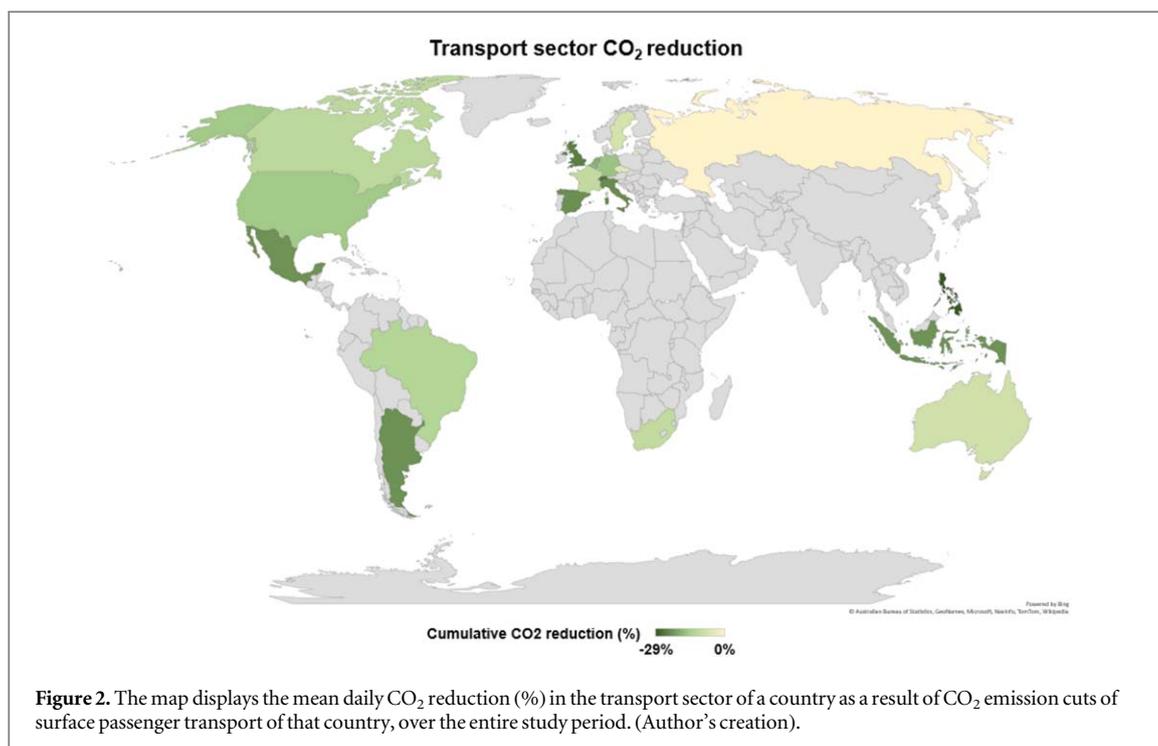
2.3. CO₂ change estimation

This paper estimates the changes in CO₂ emissions based on the change in activity data (Forster *et al* 2020, Le Quéré *et al* 2020, Liu *et al* 2020). The daily change in CO₂ emissions of each countries public & private transport sector, $\Delta CO_2^{c,ppt,d}$ (MtCO₂/day), is calculated as shown in equation (1).

$$\Delta CO_2^{c,ppt,d} = CO_2^{c,t} * \delta ppt^c * \Delta A^{ppt,d,c} \quad (1)$$

Where, $CO_2^{c,t}$ is each country's mean daily CO₂ emissions of the total transport sector (MtCO₂/day), δppt^c is the fraction of emissions of private and public transport sector of each country, and $\Delta A^{ppt,d,c}$ is the daily change in the activity of public and private transport sector of each country.

$CO_2^{c,t}$ for each country is obtained from the IEA's annual transport sector CO₂ emissions for the latest year available—i.e. 2018 (IEA, 2020a) divided by the number of days to get mean daily CO₂ emissions. δppt^c for most countries are obtained from respective government websites for the year 2018. For the remaining countries, it is assumed that the share of transport emissions of the private or public sector has not changed from the respective year of data availability to 2018 (refer to supplementary appendix C). $\Delta A^{ppt,d,c}$ is the percentage change of daily activity from a given baseline which is a date before the pandemic and acts as a function of the stringency index. The percentage change data used for private transport is the daily change in km/miles driven from the Waze mobility app, the baseline the average value of the corresponding day of the week, of the 2 weeks from 11th February—25th February 2020 (Waze, 2020). For public transport, we use the Apple mobility data for each



country, which is the percentage change of search route requests received by Apple maps compared to the baseline of January 13th, 2020 (Apple Maps, 2020). Since activity change data of the private and public transport sector is for the year 2020, we assume that there has been a no significant change in the CO₂ emissions from the year 2020.

2.4. Regression analysis

To understand the effect of stringency index on change in transport activity for the 1st and 2nd wave for different countries, we carry out a panel data fixed effect regression for public and private transport separately using R studio. Fixed effects regression is a statistical tool used to predict the dependent variable as a time-varying function of the independent variable (Hanck *et al* 2020). This model is best suited for this analysis as our interest is in predicting the activity change (dependent variable) varying over the 1st and the 2nd wave (time-varying functions) as a result of stringency index (independent variable) for different countries (individual functions). In the fixed-effects model, we assign an individual fixed-effect (Fi) and time-varying fixed effect (Ti) to the independent variable (X) for predicting the dependent variable (Y). This regression model helps us by measuring the changes in a group over time (Glen, 2020). The individual fixed effect and the time-varying fixed effect have different intercepts, one for each entity (Hanck *et al* 2020).

In the fixed-effects model, an individual-specific fixed-effect dummy variable is created for the countries in our analysis. So in this case, how the stringency index affects the change in transport activity for specific countries can be determined. In the fixed-effects model, an individual-specific fixed effect dummy variable is added for each country in our analysis, to allow showing the effects of the stringency index on the change in transport activities in different countries. Similarly, the time-varying fixed effect is added to understand how the stringency index affects the change in transport activity for a country-specific effect over a certain period. In this study, the time variable is the 1st and the 2nd waves. The impact of the stringency index on activity change for different countries during the 1st and 2nd wave is predicted by the following regression model:

$$AC'_{it} = \beta_0 + \beta_1 SI_i + C_i + T_t + \varepsilon_{it}$$

where, AC'_{it} is the predicted percentage change of activity of country i at time t , SI_i is the stringency index of country i , C_i is the fixed effects dummy variable for country i , $i = 1, \dots, 21$, T_t is the time-varying fixed effects for the 1st and 2nd wave, $t = 1$ and 2 , and ε is the standard error term.

3. Results

3.1. Cumulative CO₂ implications of activity change

During the observed 11 months, an estimated total of 510 MtCO₂ has been saved by the surface passenger transport sector of the countries included in this study. As a result, there is a 6% reduction in global transport

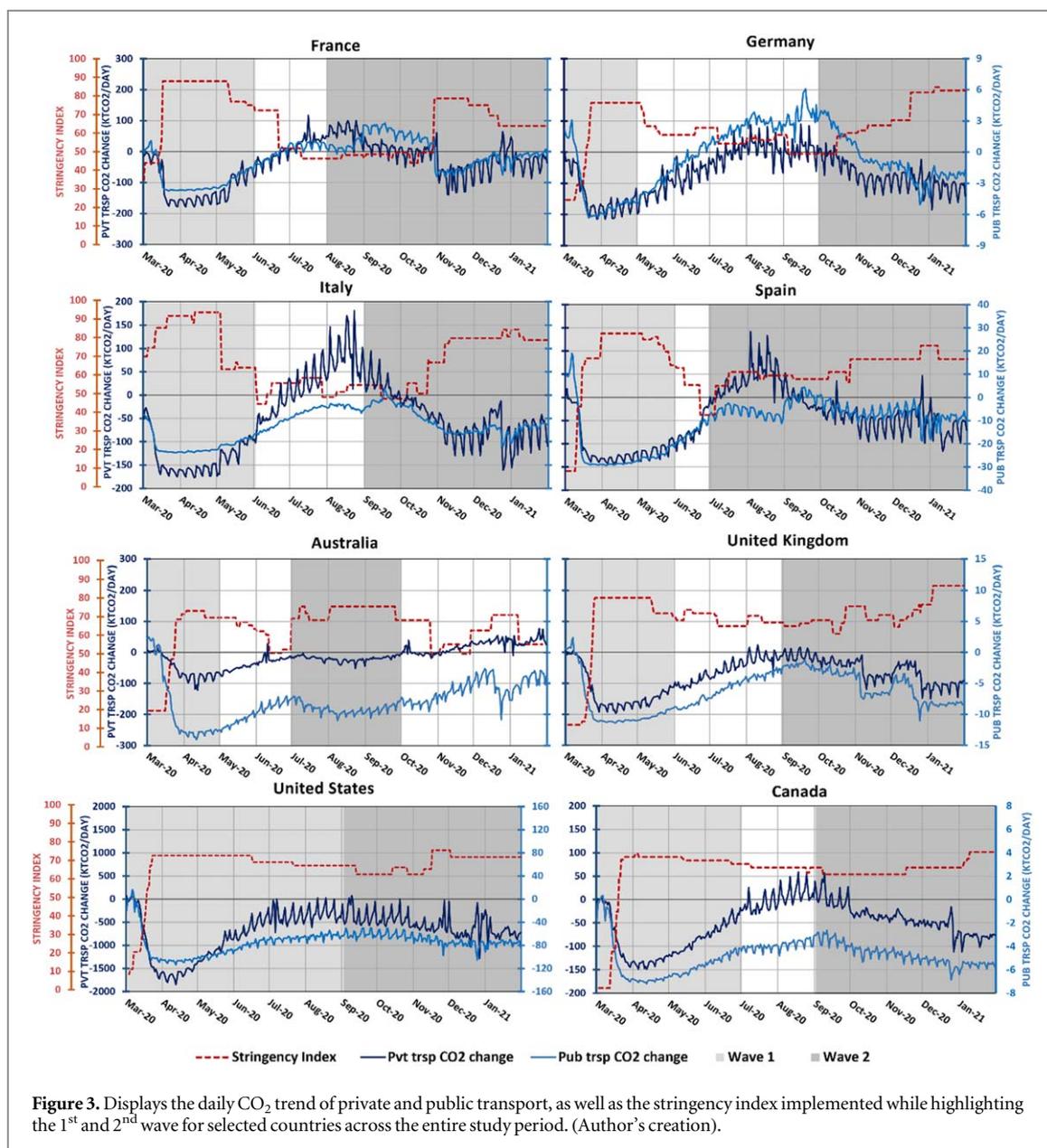


Figure 3. Displays the daily CO₂ trend of private and public transport, as well as the stringency index implemented while highlighting the 1st and 2nd wave for selected countries across the entire study period. (Author’s creation).

sector CO₂ emissions and a 1.5% reduction of the total global CO₂ emissions compared to 2018. Private transport was responsible for a high 89% (454 MtCO₂) and public transport was responsible for the remaining 11% (55 MtCO₂) of the surface passenger transport CO₂ reduction. Compared to private transport, public transport CO₂ emission reduction is on a much smaller scale as it was not a major contributor to CO₂ emissions in the transport sector pre-covid. Figure 2 displays the percentage of mean daily CO₂ reduction of each country’s transport sector influenced by surface passenger transport emissions cuts. Philippines transport sector has the highest reduction of –29%, followed by Switzerland (–26%), the UK (–24%), Italy (–23%), Argentina (–22%), Spain (–22%), Indonesia (–22%), Mexico (–22%), Netherlands (–19%), Belgium (–18%), Germany (–16%), US (–15%), Brazil (–13%), Canada (–11%), South Africa (–10%), France (–10%), Australia (–8%), Sweden (–7%), Singapore (–7%), Czechia (–5%) and Russia (0%). Refer to supplementary appendix G for detailed percentage change in CO₂ for all countries.

3.2. CO₂ emissions trends for countries

By focusing on the trends of different countries, a similarity is identified in the initial drop of CO₂ emissions change during the 1st wave of COVID-19. From March-mid to May-mid, in some cases till June, the CO₂ change drops and remains below –100 ktCO₂/day for private transport in countries with high traffic density, i.e., Germany, France, Spain, Italy, UK, Mexico, Brazil, Canada, Russia, and Indonesia (Refer to supplementary appendix F). Even though the activity change of private and public transport during this period is comparable, the CO₂ emission change of the public transport sector is on a much lower scale. The initial reduction in CO₂

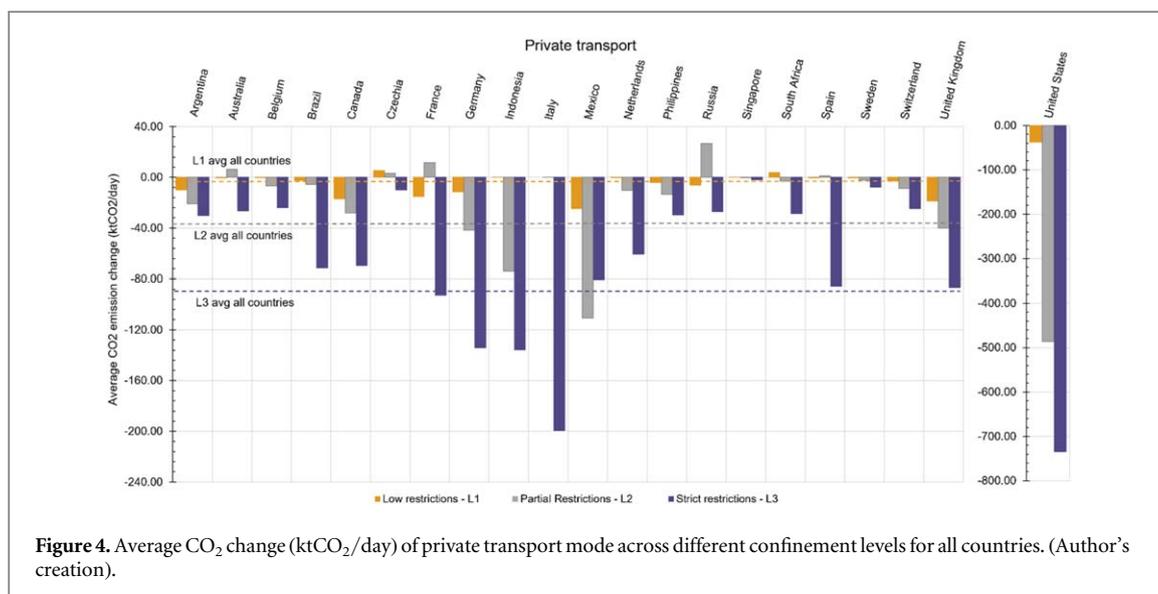


Figure 4. Average CO₂ change (ktCO₂/day) of private transport mode across different confinement levels for all countries. (Author's creation).

emissions for both transport modes is inversely proportional to the stringency index. Since a virus such as COVID-19 was unfamiliar to humans at the time, the government responses implemented were of high stringency index. As the 1st wave was coming to an end in the EU9 & UK, Russia, and Australia, the stringency index dropped as measures were relaxed. Consequently, activities were resumed, resulting in an increase in transport activity, which led to a rebound in CO₂ emissions above the baseline. The EU-9 and Russia experienced the highest rebound, along with the relaxation of measures, the seasonal variations associated with the months June, July, August are also responsible for the increased transport activity. A different trend interpreted based on the results is for the US and Canada, the stringency index remains almost constant, at times dropping by an index value of 5. These countries also experience a rebound effect but are not as prominent as other countries. Figure 3 displays the private and public transport emissions trends for selected countries. Refer to supplementary appendix F for CO₂ emissions trends of remaining countries.

The public transport sector of the countries addressed above also follows the same trend, i.e., an initial drop in the CO₂ emissions followed by a rebound effect. It can be deduced from the graphs that the CO₂ emissions increase in the months leading up to September, and the highest CO₂ increase occurs during September. There is a slow but steady increase in the activity of public transport which results in CO₂ emissions as the first wave concludes and economic activities slowly resume. This is the impact of EU9 & UK, the US, and Canadian public transport authorities adopting and implementing the necessary health and safety measures to reduce the risk perception of contracting the virus and making travel safe (UITP, 2020b).

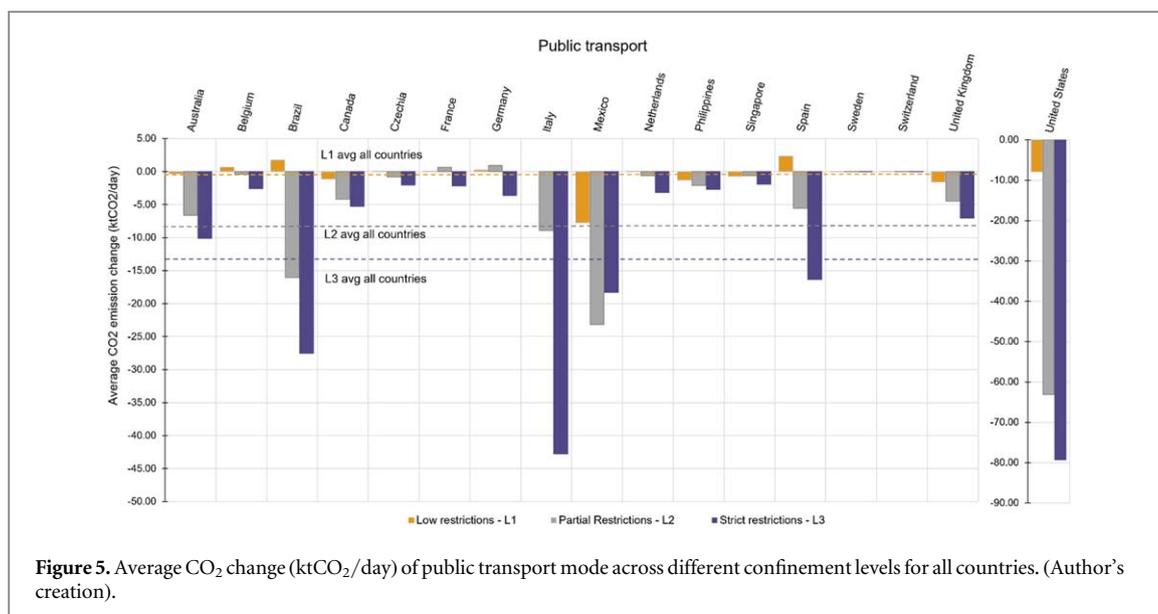
After the first wave, as a result of increased activity and countries not enforcing necessary precautions to maintain a low incidence rate, the COVID-19 cases started resurging, leading to the second wave. As the stringency index increases to tackle the second wave, CO₂ emissions decrease. But it is noticed that the CO₂ emissions decline is smaller compared to the first wave for both private and public transport since the stringency index during the second wave is lower in comparison to the first. For EU9 & UK, the private and public transport cumulative CO₂ emissions have increased by 41% (−73.1 MtCO₂ to −43. MtCO₂) and 44% (−6.9 MtCO₂ to −3.8 MtCO₂) during the peak of the second wave (Oct'20- Jan'21) compared to the first wave (March'20- Jun'20). The US and Canada together show an increase of 41% (−130 MtCO₂ to −76.4 MtCO₂) and 14% (−10.7 MtCO₂ to −9.2 MtCO₂) for private and public transport, respectively. This increase in CO₂ emissions during the second wave can be credited to the adaptation of governments and their citizens to the 'new normal'. During the second wave more economic activities including non-essentials are operating at limited capacity, prior booking, and by adhering to social distancing measures, creating a safe environment to operate.

3.3. Impact of confinement levels on CO₂ emissions

3.3.1. Private transport

Figure 4 shows the CO₂ change for private transport as a result of confinement levels. Most countries show a typical trend where the average CO₂ emissions are reduced as the confinement levels increase. This can also be noticed from the average of all countries in each level of confinement, represented by dotted lines in the figure.

Few countries like Australia, France, Russia, and Mexico differ from the trend of the other countries such as Australia and France, with an average increase in CO₂ emissions of 6.3 ktCO₂/day and 11.6 ktCO₂/day respectively in L2- partial restrictions (Stringency index = 35 to 65),. Based on the government response in



Australia, it is clear that they were hopping from L2 to L3 restrictions (Stringency index = >65) and back, depending on the severity of the COVID-19 situation. L2 restrictions were enforced during June and for most of the last 3 months of the study period. During the L2 restriction period, a measure implemented throughout was the travel ban in and out of Australia, allowing them to keep the COVID-19 number low. This allowed the non-essential business to operate at a limited capacity, with prior booking, in specific regions, which increased the transport activity (Australian Prime Minister, 2020). As a result, the average CO₂ emissions deficit declined during the partial confinement level. In the case of France, the daily average increase is due to the typical rebound effect experienced in the European countries. The stringency index was in L2 confinement for about 3 months, during this time, the CO₂ emission was above the baseline due to the reopening of socioeconomic activities. Russia displays a similar trend with a higher increase in CO₂ emissions in L2 restrictions, the reasoning of this finding will be addressed in section 3.4.1. Mexico on the other hand displayed a larger CO₂ reduction in the L2 compared to L3. This unusual trend is caused by the sudden increase in stringency index from 0 to 80 due to the surge in COVID-19 cases and consequently private transport emissions decreasing rapidly in 2 weeks. During the period of L2 restrictions, the CO₂ emissions dropped exponentially due to reduced private transport mobility. Mexico experienced L2 restrictions for only around a week, leading to a higher average CO₂ reduction, and L3 restrictions were implemented for the remaining 11 months. Hence, it can be deduced that our findings regarding the direct influence of stringency index on the CO₂ emissions can be validated.

3.3.2. Public transport

Now, the effect of the stringency index on public transport CO₂ emissions also yields some interesting results as shown in figure 5. The CO₂ increase shown in the L1 - low restriction level (stringency index = 0–35) is only the average of approximately the first two weeks of March. L1 confinement is not implemented after that in the study period, hence the data is not substantial enough to make a conclusive decision about the public transport sector during this level. From the graph, it is clear that Italy and Brazil show the largest reduction in average daily CO₂ emissions in L3 of -42.79 ktCO₂/day and -27.5 ktCO₂/day respectively, except for the US. Both the countries have a large number of public transport users and account for 9% and 10% (refer to supplementary appendix C) of their respective transport sector CO₂ emissions pre COVID-19. Due to COVID-19, there was a considerable reduction in the transport activity in these countries resulting in the high reduction of CO₂ emissions. Italy was one of the hardest-hit European countries (Pietromarchi, 2020). and naturally the public transport usage took a toll resulting in a major reduction in CO₂ based on our estimations. Whereas Brazil shows a typical reduction in CO₂ emissions during the L2 confinement. The L2 confinement period was during the last 3 months of the study period, indicating that the demand for public transport is slowly but steadily increasing during this period. This reflects the necessity of the people to get to their desired location once socio-economic activities resume, as they do not have another viable option to travel long distances. In developing countries especially, this is one of the main reasons for the gradual increase in CO₂ emissions of public transport.

In the case of France and Germany, the L1 and L2 confinement show a very small average increase in CO₂ emissions of < 1 ktCO₂/day. This is an increase above the baseline, nonetheless, showing some ray of hope in the recovery of the public transport sector. The average CO₂ emission increase is the result of the rebound effect that occurred over 4–5 months when the stringency index was in L2 confinement. This should be credited to the

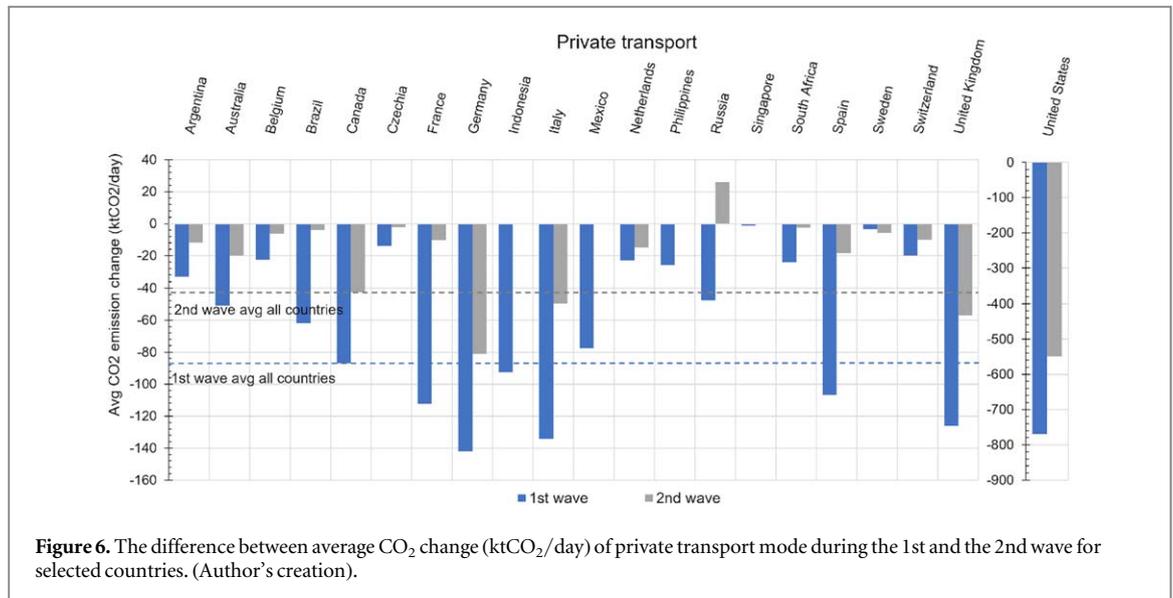


Figure 6. The difference between average CO₂ change (ktCO₂/day) of private transport mode during the 1st and the 2nd wave for selected countries. (Author's creation).

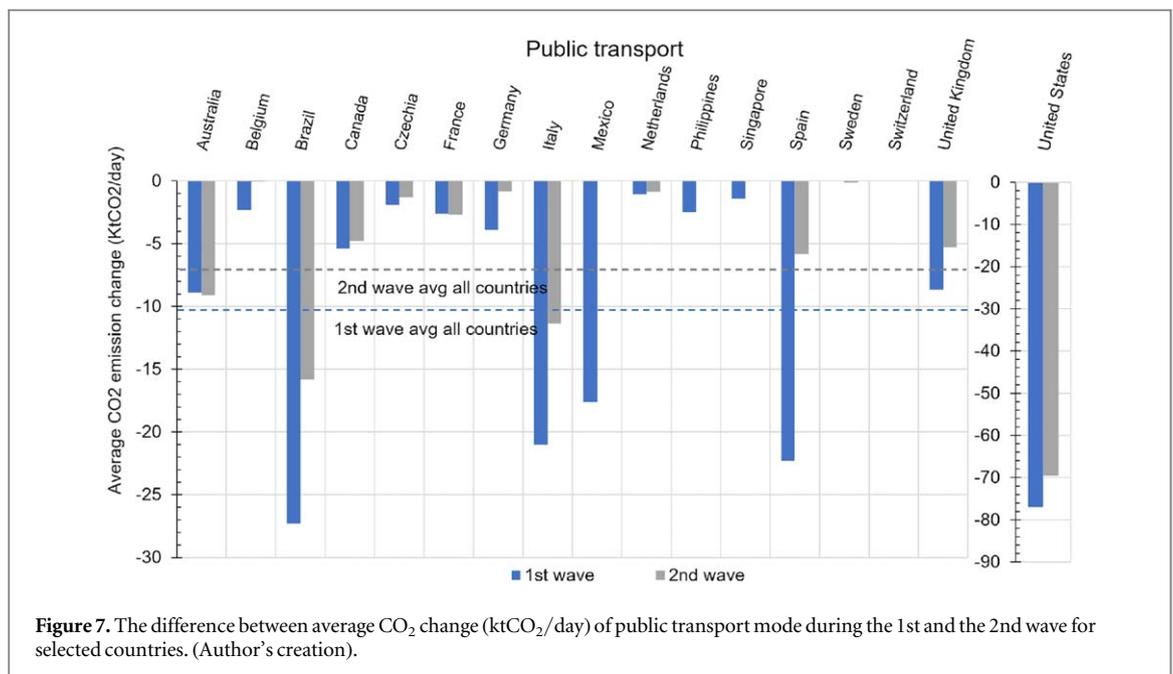


Figure 7. The difference between average CO₂ change (ktCO₂/day) of public transport mode during the 1st and the 2nd wave for selected countries. (Author's creation).

public transport authorities in both these countries, as they are more developed and have a solid infrastructure that can cope with the financial demands of adapting to the new norms to make the public transport environment safe to travel.

3.4. Change in CO₂ emissions during the 1st and 2nd wave

3.4.1. Private transport

Most of the countries took drastic measures to tackle the virus during the first wave, which led to the largest decline in 2020, during April and May. Figure 6 shows the daily average CO₂ emissions of all countries during both the waves. The second wave was tackled quite differently for different countries, as a result, the dotted lines show a 50% rebound of the average CO₂ emissions during the 2nd wave (−45.2 ktCO₂/day) compared to the 1st (−94 ktCO₂/day). The UK also followed a similar strategy, keeping their non-essentials like pubs, gyms, and restaurants open at limited capacity, and implemented a 10 pm curfew despite having a new severe second wave (Gary, 2020). On November 5th, the UK went into another lockdown until December, as a result of cases increasing rapidly (Gary, 2020). The late response in the stringency measures was to keep the economy running but adversely affected the COVID-19 cases as well as increased the CO₂ emissions. In the case of Spain, their 2nd wave started in early July, while they were still experiencing their rebound effect and the stringency index was low, resulting in a high reduction of average CO₂ emissions deficit in the 2nd wave. Once the stringency index

increased, the emissions gradually decreased, remaining higher than the first wave. In the case of Russia, L3 confinement was completely avoided during the 2nd wave. The whole country was in the middle and low range of L2 restrictions since mid-August. The main reason for this was the aim to recover their economy during the 3rd and 4th quarter of 2020, giving hope to individuals and families that face financial distress and making up for the loss attained during the 1st wave (Cordell 2020). The Doctors and health officials were frustrated with the Government's decision not to implement a lockdown or stringent measures (Sauer 2020). The 2nd wave CO₂ emission change ended up rebounding the 1st wave reduction and the CO₂ change in the latter half of 2020 completely offset the CO₂ emission reduction during the 1st half.

3.4.2. Public transport

Figure 7 shows the daily average public transport CO₂ during the 1st and 2nd wave. From the average public transport CO₂ emission change of all countries included in the study, it can be deduced that the change between the 1st and 2nd wave was quite lower compared to private transport. The 1st wave & 2nd wave average CO₂ emissions are -12 ktCO₂/day and -8 ktCO₂/day, respectively. Focusing on Spain, South Africa, and Brazil, they show the highest average CO₂ reduction during the 1st wave for developed and developing countries. These three countries have a large population using public transport as the main transport mode and contribute significantly to the transport emissions in their respective countries (Refer to supplementary appendix C). They both show a significant reduction in CO₂ deficit during the 2nd wave, Spain was more prominent with more than a 50% rebound. Adaptation and the necessity to travel play an evident role in the increase in emissions in both countries. As explained earlier, the developed infrastructure in European countries allows countries like Spain to make the necessary changes required. Adapting to the 'new normal' means making the necessary changes and taking precautions by implementing health and safety policies and financially supporting the public transport sector. Brazil and other developing countries are certainly doing everything in their capacity to make public transport safe to travel for its citizens. The road to recovery of public transport is found to be slower for them, in terms of the population that were using public transport pre-covid and the number of people using it now.

3.5. Stringency index effect on activity change during waves

The statistics of the private and public transport regression model show which transport mode is more affected as the stringency index varies across the different waves.

In the case of private transport,

$$\begin{aligned} \text{Predicted activity change} = & 37.06 - 0.88 * (\text{Stringency index}) \\ & -26.89 * (\text{Wave 1}) - 3.01 * (\text{Wave 2}) + \beta_4 * (\text{Country}) \end{aligned} \quad (2)$$

Similarly, in the case of public transport,

$$\begin{aligned} \text{Predicted activity change} = & -7.72 - 0.51 * (\text{Stringency index}) \\ & -34.36 * (\text{Wave 1}) - 9.10 * (\text{Wave 2}) + \beta_4 * (\text{Country}) \end{aligned} \quad (3)$$

Where, wave 1 is coded as, 1 = wave 1; 0 = remaining waves. Wave 2 is coded as 1 = wave 2; 0 = remaining waves. Subsequently, the country is coded as 1 = specific predictor country, 0 = remaining countries, and β_4 is the coefficient that describes the relationship between a country's activity change to stringency index.

From the constants and intercept of private and public transport fixed effects regression model can be interpreted that the public transport activity change will have a higher reduction compared to private transport at a similar stringency index validating the CO₂ emission results. The public transport intercept has a negative value (-7.7205), and the coefficients of the waves show a higher decrease in activity change compared to private transport, which has a positive intercept (37.06), and the coefficients of the waves are negative but lower than public transport. Refer to supplementary appendix H for detailed information on the fixed effects regression model variables and their estimates for public and private transport during the different waves for 21 countries.

The results of the regression model indicate that the predicted percentage change of activity during the 1st wave shows higher reduction for private transport compared to public transport, except for Belgium, France, Germany, and Sweden. (Refer to supplementary information appendix I for regression results). These 3 countries show a higher reduction in private transport. This is due to the good public transport infrastructure in these countries, allowing them to disinfect trains, buses, and stations adhering to covid-19 protocols. It should be noted that there is still a significant reduction in the public transport percentage change, but the measures taken by these countries help to maintain customer confidence and trust in public transport. The 2nd wave also shows a similar trend between public and private transport. However, it is interesting to note that in comparison to the 1st wave the private and public transport activity change has increased despite the stringency index being similar during the waves. This attests to society adapting to the 'new normal' during the 2nd wave.

4. Discussion

As a result of activity changes in the surface passenger transport sector, this study estimates a reduction of 510 MtCO₂ in total by the 21 countries included in this study. The CO₂ reduction of private and public passenger transport brings about a 6% drop in the global transport sector emissions and a 1.5% drop in the total global emissions of 2018. The last prominent drop in global transportation was 1.6% in 2009, as a consequence of the 2008 economic crisis (IEA, 2020c). The carbon monitor research initiative estimates a global ground transportation emission reduction of 992MtCO₂ from March '20 to Jan'21 (Liu *et al* 2020). There is no disaggregation between passenger and freight neither in carbon monitor nor in the IEA, which estimates a reduction of 1100MtCO₂ within the global road transport sector in 2020 (IEA, 2021). Hence, any speculations made regarding comparing the findings of this study to either carbon monitor or IEA could be flawed. The disaggregation between passenger and freight transport indeed is a great prospect for future research topics to come.

4.1. Road to recovery

In line with the Paris Climate Agreement goal, to limit the global temperature to 1.5 °C, the International Council of Clean Transport (ICCT) estimates that global transport emissions must be reduced to 2.6GtCO₂eq (1.8 to 3.3 GtCO₂eq) by 2050 (ICCT, 2020). The emission range was estimated by analyzing the scenarios and emissions mitigation pathways created by the International Panel of Climate Change (IPCC) (ICCT, 2020). The 4 key GHG mitigation strategies of the transport sector are, avoidance (avoiding unnecessary travel to reduce transport activity), modal shift (from private to more efficient mode like public, cycling, walking), reducing energy intensity (Improving efficiency of transport modes), and improving fuel carbon intensity (using sustainable low-carbon fuels for transport) (IPCC, 2014). The avoidance and modal shift GHG mitigation strategies lie within the scope and are of interest in this study. Though scenarios and strategies created to reduce emissions could not have possibly foreseen a pandemic such as COVID-19, the emissions reduction in the transport sector was a temporary silver lining. Due to COVID-19 confinement measures, a lot of necessary and unnecessary travel was avoided, this was indeed one of the mitigation strategies by IPCC. If the 5.9% reduction of the transport sector emission estimated during the 11 months of this study were continued for the years to come, the 2050 transport sector emissions goals would be achieved in less than 15 years. But unfortunately, this is just a theoretical computation and far from reality, as confinement measures would have to be in place for years to follow, which will burden the wellbeing of the society. In reality, the findings in this study show that the CO₂ emission reduction is temporary as private transport modes exhibit a quicker recovery during the later months of the pandemic. As a consequence of social distancing measures and risk perception, people are reluctant to use public transit services and are more reliant on private transport modes leading to a significant modal shift away from public transport. This is a major blow to the transport sector's sustainable transition from private to public, which is consistent with the Paris Climate Agreement. With countries experiencing less public transit ridership and more private vehicles on the roads, congestion is highly likely to increase, offsetting the reductions during COVID-19.

The main question to be asked here is will the modal switch from public to private transport 'stick' post-COVID-19? The results of global surveys conducted on travel behavior post-COVID-19 cite that more than 50% of the public transport users in The United States, travel less frequently or not at all on public transport (Fleming, 2021). Over 60% of respondents in Europe feel unsafe using public transit services during COVID-19, whereas the post-COVID-19 number of transit users will be reduced by 17%, and private car and active transport modes will increase by 21% and 23% respectively (BEUC, 2020). In a survey conducted during October for 9 countries, out of which 8 are included in our study, more than 45% of respondents are uncomfortable using public transport modes post COVID-19 (Stansbury and Alport, 2020). For the transport sector to do its part in achieving the Paris Climate Agreement, public transport has to make a quick recovery post-COVID-19. The key to improving public transport demand and recovering from the sector's downfall lies in the hands of policymakers and the public transport authorities of each country. The road to recovery of the transport sector should completely be focused on adapting and redesigning public transport infrastructure to cater to the needs of the public. To attract and build back the trust of transport users, the vehicle must be disinfected after every trip, traveling should be contactless, with convenient board and drop off points, wearing a mask should remain a compulsory rule and regular checks must be made to ensure these rules are followed (D'Inca and Cresci, 2020). For example, data regarding how crowded the public transit mode is should be provided to the transit users that are yet to board, this feature would assure safety and will increase the comfort and confidence of people (Fleming, 2021). Increased public transit services to deal with the limited capacity issue and breaks to disinfect either buses or trains, will also help in boosting the modal shift back to public transport. The current rebuilding of the public transit sector is an adequate opportunity to transition into zero-emission

buses (ZEB) and trains, across different countries. Australia is making use of the opportunity presented by COVID-19 and following the footsteps of other countries like the Netherlands, Singapore, UK, France, US, and Canada (UITP, 2021). Other emerging economies such as the Philippines, Indonesia, South Africa, Brazil, Mexico, and Argentina are trying to work towards climate mitigation targets and a covid-safe infrastructure, which is expensive. Raising the prices for public transport to meet the financial expenses of maintaining and executing COVID-19 protocols and measures (Susilo *et al* 2021), would be unfair to low-income groups that are frequent users and more reliant on public transportation. Immediate intervention and financial support from the governments to public transit authorities and operators will be critical to uphold public transport and bring it back to pre-pandemic levels. The restructuring of public transport infrastructure can be used as an opportunity by starting services in low-income areas and gaining back the confidence and trust of customers who are more dependent on public transport (Susilo *et al* 2021). Amekudzi-Kennedy *et al* (2020) highlight that multimodal transportation is key in the long run. Since a large population worldwide is currently dependent on public transport, they either cannot travel or have to adjust to the risks that come with it. Amekudzi-Kennedy *et al* (2020) rather suggests that to build a resilient transport system and successfully adapt to unprecedented events multiple sustainable transport modes such as effective combinations of private and public transport, using environmentally friendly fuels, active transportation, and other non-traditional methods. These strategies are key to reverse the COVID-19 modal switch into the sustainable transport focused modal shift and to build a resilient transport system.

4.2. Transit service reduction

As public ridership declined significantly in most countries as a result of teleworking, confinement measures, and risk perception, buses, subways, and trains were running almost empty across all the countries included in this study. Using Apple's public transport mobility data, CO₂ emissions were indirectly calculated based on the volume of search route requests. This represents the trend in activity change of transit riders in a country. Despite ridership activity reducing, if transit modes are still operating as per schedule at scaled-down or no capacity, the CO₂ emission per passenger-kilometer increases. To cope with the peak reduction of ridership during COVID-19, all governments worldwide imposed service reductions to save energy, time, and money. As revenue was limited, the public transport authorities were unable to maintain their services. To avoid overcrowding of transit modes with service reductions, only essential travel was recommended. In Paris, access to public transport was restricted to only essential and necessary users who had to produce a certificate of necessity during peak hour travel (D'Inca and Cresci, 2020). As London experienced a major reduction in the number of passengers, 40 public transport stations were shut down, followed by cutting down of routes and frequencies of bus, train, and tram services. Similarly, Washington D.C saw a 40%–50% reduction in the frequency of train services during the early periods of this study (UITP, 2020a). Baltimore, Seattle, and Detroit also reduced their transit services by almost 65%, among other states with lower service reductions in February 2020 (Ahangari *et al* 2020). Barcelona's government reduced metropolitan services by 50%, whereas urban and intercity transport saw a reduction in frequency between 33% and 67% (AMB, 2020). In the case of Brazil, 180 municipalities shut down their services to cope with the financial stress experienced, resulting in an average reduction of 25% (NTU, 2020). Even though countries worldwide implemented transit service and frequency reduction as mentioned in The International Association of Public Transport (UITP) and the International Labor Organization (ILO, 2020), the lack of sufficient information on service reduction numbers for all countries included this study. The service reduction percentages of countries available were also relative to different baselines which makes it difficult to estimate the CO₂ reduction from transit modes at a normalized level for comparison. It can be gathered that transit services have reduced around 30%–50% worldwide, which directly translates to a CO₂ reduction of 30%–50%. On average, this would be a close overestimate based on the CO₂ reduction estimated from activity change.

The fixed effects regression results of this study also shows that public ridership has significantly declined during the 1st and 2nd wave. (Refer to supplementary information appendix I). Activities in public transport took a bigger hit compared to private transport. The change in public transport activities is almost 1.5 times larger compared to private transport during the 1st wave. This is due to the stringent measures imposed during this period and when travel was necessary people opted for their private vehicles and avoided public transit. During the 2nd wave, as part of adapting to the 'new normal' private and public transit activity change improved as a whole. However, the reduction in public transport activities is almost twice than in private transport. This is the result of lack of confidence in the public transport infrastructure and system. Most countries would find it difficult to sanitize trains, buses and stations regularly and adhere to COVID-19 measures as due to lack of ticket fare revenue during the 1st wave and cleanliness factor affects public ridership (Susilo *et al* 2021).

4.3. Limitations and Assumptions

During the study, multiple limitations have been encountered, in terms of data availability, heterogeneity of data sources, age of data, the sample size of the study, etc., which will all be addressed in this section. One of the main limitations encountered is that private and public passenger transport CO₂ emissions are estimated indirectly based on the activity changes from mobility data sources. Near real-time activity change data was a key factor to answer the research question sufficiently, and this was provided by the Waze and Apple database. The indirect CO₂ estimation using activity change gave rise to multiple uncertainties. Firstly, the direct CO₂ emissions from the transport sector are unable to be accounted for, due to insufficient real-time data. Secondly, both the mobility data sources provided have a different baseline in early 2020. The comparison of activity change values of public and private transport to 2019 is impractical since it is compared to a baseline date in 2020, this affects the seasonality of the dataset and holidays (Schulte-Fischedick *et al* 2021). Additionally, 2018 mean transport sector emissions were used as this was the latest data available (IEA, 2020a). It was assumed that there would be no change in emission levels in 2019. Regarding emission shares of different modes of transport, most emerging economies had data only available for the year 2014 or earlier. The emission shares of those countries was scaled up to 2018 for countries with information regarding growth rate, otherwise, it was assumed transport mode emission share levels of 2014 or earlier remain the same in 2018 (Refer to supplementary appendix C). These uncertainties hinder the possible capacity of CO₂ emissions during COVID-19. As mentioned in the above section, the lack of data regarding service reduction in different countries also limits the scope of CO₂ estimation in this study. As Waze and Apple database's activity change is limited to their respective users, it does not give a complete representation of the entire country per se. It does represent the common mobility trend and behavior of the entire country. It is also uncertain what share of age group or income group is represented by the activity change data as per privacy policies of the mobility data sources (Apple Maps, 2020, Waze, 2020). Any knowledge on the possible representation of an age or income group would be useful in paving a specific path to recovery for certain demographics. Apple database also lacks public transport activity change for the 4 countries included in this study. Moreover, the percentage change in the volume of search route requests provided by Apple also leads to a discrepancy of CO₂ estimation within the study.

5. Conclusions

Within the scope of this study, CO₂ emissions trends and activity change as a result of COVID-19 confinement measures were estimated and analyzed for public and private passenger transport during the 1st and the 2nd wave across 21 countries. Private transport CO₂ emissions were estimated for 21 countries and public transport for 17 countries. As per the estimates, a total of 510 MtCO₂ were saved during the 11-month period, which signifies a 6% reduction in the global transport sector and a 1.5% reduction in the total global CO₂ emissions. It was determined that the EU9 countries & UK had a similar trend throughout the study period, in terms of CO₂ emissions dropping during the 1st wave, followed by a rebound effect and a drop during the 2nd wave. North American countries also have a similar trend in terms of CO₂, with a less pronounced rebound effect in comparison to EU9 & UK. The stringency index of North American countries was close to constant throughout the study period. Latin American, Asian countries and South Africa were lacking a rebound effect but instead saw a gradual increase in CO₂ emissions through the second half of the study period. Private transport showed a much more pronounced recovery relative to public transport. Public transport CO₂ emissions are estimated to be well below the baseline value despite a drop in stringency index. For Russia however, a rebound effect similar to EU9 & UK was identified after the 1st wave. The CO₂ emissions of the private transport sector remained above baseline value throughout the 2nd half of the study period, as economic activities resumed despite the 2nd wave, to restart and recover the economy. This led to offsetting the CO₂ emission reduction during the 1st wave of COVID-19 in Russia.

In general, all countries exhibited an increase in CO₂ emissions during the 2nd wave as they adapted to the 'new normal' by restarting economies and non-essential activities with the help of social distancing, limited capacity, prior bookings, etc., to ensure a safe environment to function. The increase in CO₂ emission was more pronounced in private transportation of emerging economies as it was critical to recovering their economy to keep afloat, despite the 2nd wave. Except for Sweden and Czechia that showed a higher reduction during the 2nd wave. Sweden tried to attain herd immunity by implementing low measures during the 1st wave, which did not go according to plan. By the 2nd wave, cases and deaths started increasing, forcing them to implement more stringent measures (Beswik, 2020). In the case of Czechia, the rebound effect offset the CO₂ reduction during the 1st wave, and hence a pronounced CO₂ reduction during the 2nd wave was exhibited. By highlighting the CO₂ difference between the waves, despite a significant stringency index, the research question formulated is acknowledged. The CO₂ reduction as an effect of confinement levels followed a similar theme across countries with reduction increasing significantly as confinement levels increase. Few countries like Brazil, Mexico, and

Spain had a more pronounced CO₂ reduction in public transport as they are more dependent on public transit mode. The fixed effects regression results highlight that the road to recovery is quicker in private transport showing an increase in activities during the 2nd wave compared to the 1st. Public transport activity indicates a slower recovery compared to private transport, but EU9 & UK showed a quicker recovery compared to other public transport regions in the study. This is credited to the adaptation and implementation of necessary measures to make travel safe and comfortable again. This is credited to the adaptation and implementation of necessary measures to make travel safe and comfortable again.

Post COVID-19, the road to recovery should primarily be focused on redesigning public transport infrastructure by implementing extra measures to create a safe, comfortable, and convenient environment to regain the confidence of transit users. It is of extreme importance to attract the public transport users who have shifted toward private modes of transport. The estimations of the study give us an idea of the public transport activity trend during COVID-19 and when the stringency index, consequently risk perception is low. Post-COVID-19, short- and medium-term demand for public transport could gradually increase, provided necessary measures are implemented. This will boost the sustainable transport system transition from private to public, being consistent with the transport sector's role to achieve the Paris Climate agreement by 2050.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Declaration of competing interest

The authors declare that there is no known financial interest or personal relationship that could be seen to influence the work reported in this paper.

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