An analysis of passenger transport trends and related CO_2 emissions during the waves of the covid-19 pandemic across different countries.

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Abstract

The coronavirus SARS-CoV-2 (COVID-19) pandemic has unprecedentedly impacted our lives and daily human activities since early 2020. Countries implemented measures to curb the spread of the virus by enforcing stay at home orders and travel restrictions. With major sectors being affected by the pandemic, there has been a decline in CO_2 emissions globally. As a consequence of the confinement measures, the transport sector contributes the most to the decline in CO_2emissions. This study estimates and analyzes the CO_2 emission change trends of public (bus and rail) and private surface passenger transport modes. The study is conducted across 21 countries, from March 1st, 2020, to Jan 31st, 2021, covering the 1st and the 2nd wave of covid-19. The CO_2 change is indirectly estimated using activity data and emission factor of both the transport modes of each country. The CO_2 emission change and activity change of public and private passenger transport is compared in relation to 3 levels of confinement measures as well as the different waves. Comparing the CO_2 change during the waves and confinement levels of different countries as well as zooming into the trends of individual countries is the main focus of this study.

The cumulative surface passenger transport CO_2 change over the 11 months of 21 countries totals to a reduction of 510 $MtCO_2$. This reduction brings about a 6% drop in global transport CO_2 emissions and 1.5% drop in total global CO_2 emissions. Private transport has a more pronounced contribution of 89% to public transports 11%. Philippines (-29%), Switzerland (-26%), UK (-24%), Italy (-23%) and Argentina (-22%) have the highest reduction, whereas Russia has the lowest reduction of 0%. Another key finding from the analysis is that there is a higher activity reduction and consequently CO_2 emission reduction during the 1st wave compared to the 2nd for most countries despite implementing stringent measures during both waves. This is mainly due to countries adapting to the "new normal" and restarting socio-economic activities. The second half of the study period displays a gradual increase in surface passenger transport activity and consequently a CO_2 deficit reduction, where a more pronounced increase is found in private transportation in all countries. As public transport depicts a slower road to recovery, private vehicle use has been on the rise leading to a switch from public to private. The current switch amidst the covid-19 era is steering away from the sustainable transport sector goals of net zero emissions and a major switch to public transit. Hence, to get back into achieving the sustainable transport goals it is essential to focus on improving the public transport infrastructure of all countries, especially developing economies, namely, Mexico, Brazil, Philippines, etc. This study provides insights and sheds light on the mobility behavior trends of private and public transport which will be critical in rebuilding and adjusting the infrastructure of the transportation sector in order to build back the trust of public transport users.

1. Introduction

Since the pre-industrial era, there has been a 1.1° C increase in average global temperature and is the highest it has been since over 30,000 years (Ritchie & Roser, 2017). The increase in temperature is driven by the growing energy demand and anthropogenic emissions produced over the past decades and has affected climate change drastically (IPCC, 2014). Rightfully so, new climate policies have paved the path to transition into renewables and low-carbon emitting alternatives to keep climate change under control. Amidst all this, we saw the most unexpected drop in daily CO_2 emissions in early April of 2020 compared to 2019. The 17% reduction in daily CO_2 emissions occurred as a result of countries going into home confinement and restrictions to reduce the spread of the novel coronavirus (Le Quéré et al., 2020). The virus was first identified in China on 30th of December 2019 and later on was declared as a global pandemic by the World Health Organization on March 11th, 2020 (Director General WHO, 2020). As per June 16th 2021, there has been a total of 176.7 million confirmed positive cases and 3.8 million confirmed deaths around the world (John Hopkins University, 2020). The highly transmittable nature of the virus, the fact that you are unable to see traces of the virus up to 2-4 days after being infected and the danger of transmitting the virus even if you do not have any symptoms while being unaware that you are infected (World Health Organization, 2020) are reasons responsible for the massive global spread of the virus.

Looking back at the history of mankind, we have had to face various hazards to human health and deal with epidemics like Spanish flu in the 1918's, Ebola outbreak in 2014, SARS outbreak in 2002-2004, 2009 H1N1 (swine flu) and many more, which affected daily activities immensely (WHO, 2020). But none have had such an adverse effect on human health worldwide like Covid-19. It has recorded the highest number of positive cases ever for any epidemic or pandemic (WHO, 2020). Affected countries took necessary measures to curb the spread of the virus by implementing home confinements, travel restrictions, border shutdowns, social distancing measures and wearing masks. The unprecedented change in our life has brought daily activities to a standstill. Home confinement and bored shutdowns resulted in the primary, secondary and tertiary sectors halting operations and were forced to introduce tele-working where applicable. For countries worldwide the health crisis transformed into a major socio-economic crisis as well, like never before (Nicola et al., 2020). Consequently the global energy demand of all economic sectors saw a significant reduction (IEA, 2020b). This led to the largest annual CO_2 emission drop of 5.8% compared to 2019 and road transport saw the biggest decline in activity resulting in 50% of global CO_2 emissions from oil use accounting for 1100 $MtCO_2$ drop . Although the transportation sector is a high energy consuming sector and accounted for 16.2% of global greenhouse gas (GHG) emissions in the previous year (Ritchie, 2020b), the energy demand of the transportation sector, and notably passenger transport activity has been low during the pandemic. Buses, trains, trams, airplanes, and other ride sharing modes of public transport have been deemed as highly contagious environments and have been recommended avoiding on the basis of past experiences dating back to the 1900's dealing with epidemics like influenza (Bell et al., 2004). This is purely due to the nature of the virus, the airborne transmission of aerosols occurs when there is close contact between humans and is more likely in crowded environments (World Health Organization, 2020). As a result, public transport use has been declining rapidly, leaving authorities to operate at a very low capacity to adhere to social distancing measures (UITP, 2020a). This leaves people with no choice but to adapt to private modes of transportation such as private vehicles, cycling or walking leading to a modal shift away from public transport (UITP, 2020a) . The increasing use of private vehicles for long distance travel instead of public transport is unfortunately steering away from sustainable mobility. Sustainable mobility is defined in terms of less traffic congestion, clean and safe travel, and switching to public transport to mitigate climate change (WWF, 2020). On the brighter side of things, there has been a 40% increase of electric vehicle sales mostly supported by the policies in EU and stimulus measures in China (IEA, 2021) and active mobility modes such as cycling, and walking have increased by huge numbers during the pandemic in different countries (Intertraffic, 2020) which is an encouraging sign to green and clean global recovery.

Since covid-19 virus was declared a global pandemic on March 11th, 2020 by WHO (Director General WHO, 2020), papers and research related to transport mobility is relatively new and limited in the scientific research world. As activity within all sectors were limited, the transport sector mobility showed the highest reduction as it is indeed the backbone of them all (IEA, 2021). To gain further understanding on how the mobility sector and related emissions have been affected by covid-19 measures and risk perception, relevant emission and mobility analysis papers are reviewed.

1.1 Covid-19 related emissions

Even before the pandemic affected our lives we were in and still are in an environmental crisis. About 21% global emissions (Climate Watch, 2018) and 24% of energy related emissions (IEA, 2018) are produced by the transport sector. Out of one-fifth of the global emissions surface passenger transport (road and rail) emissions constitute 46% (Ritchie, 2020a). According to Le Quéré et al. (2020) under each level of confinement, level 1 being, policies targeted to a group of people, level 2 being, policies targeted regionally and level 3 being policies targeted nationally, activity reduction and related CO_2 emissions are estimated using real data until April end for 6 different sectors, power, surface transport, residential, public , industry, aviation. The aviation sector and the surface transportation sector had the highest and second highest reduction in activity estimated for 69 countries. Using TomTom congestion index, apple mobility trends, US mobility data MS2 and UK cabinet daily data until April 17th, surface transport emissions were calculated, and has a 36% reduction with an absolute reduction of -7.5MtCO_2/day and aviation have 60% reduction with an absolute change of -1.7 MtCO_2/day. The paper also estimates an annual emission reduction of -4% if the confinement duration lasts till June end and a -7% reduction if it lasts till the end of 2020 (Le Quéré et al., 2020). As per the paper written by the international research initiative Carbon Monitor (Z. Liu et al., 2020), near real time CO_2 emissions were calculated for the major sectors for different countries. There has been an 8.8% (-1551 MtCO_2) reduction of global CO_2 emissions in the first half of 2020 compared to 2019. This aggregate change in CO_2 for the first half of 2020 is the highest reduction in CO_2 emissions in comparison to any economic crisis ever faced. Before covid-19 the greatest change compared to the previous year was for world war 2 with a reduction of -800 MtCO_2. Using the congestion index of TomTom, a global reduction of -613.3 MtCO_2 for ground transport was calculated to be the largest contributor to the emission reduction, the power sector with -341.4 MtCO_2 as the second largest and aviation sector with a -200 MtCO_2 decrease for the first half of 2020 (Z. Liu et al., 2020). By the end of May 2020, when restrictions are slightly relaxed and economic activities are resumed the emission deficit is found to be reduced in almost all the countries (Z. Liu et al., 2020). Forster et al., 2020 adapts a similar sector analysis method to Le Quéré et al., 2020 to estimate GHG emissions using google and apple mobility data. The surface transport, residential, public and industry sectors in Le Quéré et al are substituted with google mobility changes in areas like transit, residential, retail and recreation, and workplaces respectively (Forster et al., 2020). When it comes to daily surface transport emissions estimate, Le Quéré et al., 2020, google mobility data, apple mobility data and Liu et al., 2020 ranges from

-7 to -8 $MtCO_2$/day showing a similar trend between datasets. All dataset's represent around 58-60% of total global CO_2 emissions and estimating other sectors using google mobility data was found to be an overestimation. Another study by Gensheimer et al., 2020, analyzes the relationship between mobility datasets like Apple and TomTom database and government traffic data for Munich, Oslo, San Francisco, Cape town, Norway and California. The mobility dataset's compared to local government data to find the change in trace gas emissions. When apple data is used as a road transport proxy there is a -7% emission difference and -51% for TomTom (Gensheimer et al., 2020). The two major error sources of the dataset mentioned in this study are the time-point to which the dataset is referenced and what the dataset actually represents.

1.2 Surface transport mobility demand

The transport emission reductions as a result of countries going to lockdown, translates directly to a reduction in transport demand. By the end of March global road transport activity was reduced by more than 50% compared to 2019 (IEA, 2020b). In Europe passenger transport demand was severely affect during when the first lockdown measures were implemented, countries like, Spain(12%) , France(22%) and Italy(24%) had all time low of weekly vehicle miles travelled (VMT) compared to pre-covid level nationwide weekly VMT (100%) (INRIX, 2020). 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 (G. Falchetta & Noussan, 2020). An assessment of the effect of government policies on the citymapper's mobility index is analyzed for 41 cities in 22 countries for march by Vannoni et al. (2020). Citymapper mobility index represents public transport mobility data for different cities. A fixed effects regression is run between the citymapper's mobility index and the different government response stringency index. Government policies such as closure of public transport, schools and workplaces have the highest association to citymapper's mobility index across different countries. Since the study was conducted during early stages of covid-19, the citymapper mobility index is only representative of the initial policies implemented. Similarly, transport mobility case studies for different cities like Spain, show a reduction in travel demand, especially in public transport during the first half of covid-19 because of the resulting government policies implemented (Ahangari et al., 2020; Aloi et al., 2020; Dumbliauskas & Grigonis, 2020; L. Liu et al., 2020). Public transit is deemed as a highly contagious environment by WHO since it is a closed space with a high number of people (World Health Organization, 2020). Surveys conducted for various countries across the world by McKinsey & Company (Chechulin et al., 2020) and Abdullah et al. (2020) show that the factors which influence choice of transport mode have changed completely before and during covid-19. Risk perception of travelling is the most influential factor to choose a transport mode during covid-19, as individuals value their health above all. Case studies on different cities such as Gdansk, Poland by Dumbliauskas & Grigonis (2020), Vilnius city, Switzerland by Przybylowski et al.,(2021) & a survey conducted in the US by L. Liu et al. (2020) on travel behavior and mode choice also yields. Though mobility demand is reduced as a whole, public transport has experienced a longer lasting reduction than private transport (Apple Maps, 2020). As public transit demand has reduced significantly, transit modes are operating at very minimal or no capacity. As a result of this most governments have implemented public transit services reduction and reduced service frequencies to cope with the reduction in ridership (UITP, 2020a). Countries like US, Italy, UK, Spain, 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). In the latest report by the International association of public transport (UITP, 2020b), it is stated that "with the right measures taken the risk of catching covid-19 in public transport is very low". Even though this might be true, the road to recovery for public transport will take longer than anticipated because as long as cases are increasing, only necessity for low income working groups and essential workers who cannot resort to private transport would overlook the perceived risk.

Previous literature is mainly focused on the global CO_2 reduction during the first half of 2020 and the effects of the 1st wave, with road transport being the major contributor. It is responsible for more than 50% of the CO_2 deficit influenced by covid-19. This is due to the drop in global mobility demand, especially public transit demand has reduced drastically as a result of risk perception and confinement measures implemented. Surveys worldwide display that factors that influence transport mode choice pre covid-19 such as, time, comfort and money have taken a backseat to safety and risk of being infected. It is understood from literature review conducted that as long as confinement measures are in place activity and related CO_2 emissions decrease. With the world being amidst the second wave, it should be asked whether the surface transport emission deficits are similar to the second wave? Will mobility behavior and trends change during the different waves? Is this a short-term or medium-term modal switch to private transportation?

Even though we are informed about the emissions reduction as a result of confinement measures during the 1st half of 2020, an in-depth analysis of the surface passenger transportation modes during the 1st and 2nd wave in relation to confinement measures are lacking. Hence, the focus of this study is to understand how the CO_2 emission reduction and transport activity varies during the waves, across different countries. Using activity change data, the CO_2 emission reduction of public passenger transport, such as bus, rail, tram, subway, and private passenger transport vehicles are estimated during the study period of March 1st 2020 to January 31st 2021. To acknowledge the gap identified in previous literature sufficiently, a research question is formulated:

What are the environmental implications of covid-19 confinement measures on public and private transport across countries?

- How does public and private transport activity vary across waves?
- Will risk perception and human travel behavior change, resulting in a quicker road to recovery post lockdown?

2. Material and Methodology

2.1 Research Framework

To answer the research questions and 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. In this research the private and public transport activity change data is used to indirectly estimate the related CO_2 emissions. Hence, different data sources with relevant activity change data for public and private transport is explored. The change in activity data and related CO_2 emissions will be analyzed to interpret their relation to the different confinement levels as well as 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 CO_2 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 included in the study. 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; World Bank, 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 formula used to estimate surface passenger transport CO_2 emission change is adapted from previous research papers (Le Quéré et al., 2020 ; Z. Liu et al., 2020 ; Forster et.al., 2020). The CO_2 emission change is estimated by calculating the product of mean daily transport CO_2 emissions and the fraction of emissions of a respective transport mode as well as the activity change data. Execution of these methods will help yield the required results to answer the research questions formulated. The difference in activity change and CO_2 emissions between countries can be interpreted from the results of the methods. The later sections will focus and explain in detail the individual aspects of the research framework.

2.2 Data Availability

Mobility databases were explored to collect data related to daily public transport and private transport activity change. Daily transport activity data was collected from mobile GPS navigation systems like Apple (Apple Maps, 2020), Google maps (Google Maps, 2020) and Waze(Waze, 2020b) and built-in car navigation systems like Tom-tom (Tom-Tom, 2020) navigation. After careful evaluation of the datasets, it was decided not to use the google mobility data since it represents percentage change in activity of different areas like parks, workplaces, residence, grocery stores etc.,(Google Maps, 2020) and did not represent change in activity of a certain mode of transport. The nature of the apple mobility data was more suited to achieve the aims of this research since it represented the change in mobility of private transport, public transit which includes buses, rail, tams, etc., and walking globally for each country. The data shows the daily percentage change in search route requests received per country/region relative to a baseline volume of Jan, 13th 2020 (Apple Maps, 2020). The Apple mobility data, in Apple's words, *Data that is sent from users' devices to the Maps service is associated with random, rotating identifiers so Apple doesn't have a profile of individual movements and searches. Apple Maps has no demographic information about our users, so we can't make any statements about the representativeness of usage against the overall population* (Apple Maps, 2020). So, it does not have personal information about an individual user but considers the change in volume of search requests for a whole country/ region. Although apple data is available from Jan 13th onwards and includes almost all the countries across the globe from, the data availability of public and private transport change in activity is limited to around 28 countries. Hence, only countries with public and private transport activity change will be considered further along in the process of country selection. The Waze navigation database represents 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 a 2-week period from February 11th to February 25th, 2020 (Waze, 2020b). This dataset represents real life travel since it shows change in activity in KM/miles driven from March 1st, 2020 and is essential in our work. The other car built-in navigation database available is TomTom traffic index which represents the traffic congestion in cities. If there is 60% traffic congestion that means a 30-minute trip will take 60% more time compared to the uncongested baseline, which is the exact same minute, hour, and day of the previous year (Tom-Tom, 2020). The TomTom database is used in the preliminary stages to study the correlation between the different datasets of a country to validate their credibility.

2.2.1 Country selection

To get an idea of how mobility is affected during the lockdown measures implemented and how it varies through the waves across different countries globally, we have included at least one country from each continent to achieve latitudinal coverage depending on data availability of the private and public transport activity. For the study period from March 1st, 2020, to January 31st, 2021 there are 21 countries included, Argentina, Australia, Belgium, Brazil, Canada, Czechia, France, Germany, Indonesia, Italy, Mexico, Netherlands, Philippines, Russia, Singapore, South Africa, Spain, Sweden, Switzerland, United Kingdom and United states of America. Based on available data the countries selected have a large account for high transport emissions and mobility in their respective continent. Developed economies as well as developing economies in different regions are included in this study. Hence, it is possible to explore the region specific and economic development specific approaches enforced to deal with covid-19 and the implication on the ground transport sector. Apple mobility data and has been a popular data source in analyzing the mobility trend of countries in many research papers such as (Le Quéré et al., 2020 ; B. Y. G. Falchetta & Noussan, 2020; Forster et al., 2020; Gensheimer et al., 2020) since it provides change in activity for public and private transport. Considering that apple data only represents the volume of search route requests (Apple Maps, 2020) it cannot be translated as real-life travel and because only apple provides data on public transport change in activity it is relevant to this research to show that it can in a way represent mobility of the transport sector. Waze and TomTom's database represents real life travel as it provides change in KM's/miles and traffic congestion index respectively, hence a Pearson's correlation test is carried out on the private transport activity of Waze, Apple, and TomTom data for different countries to validate that apple's dataset does indeed have a similar trend to real-life travel and can be used to represent mobility. The selection of countries had to be limited to 21 because only countries that were available and matched in these datasets were considered. The selected countries together represent 44% of global transport sector CO_2 emissions and 52% of global transport sector CO_2 emissions excluding international bunkers (marine and aviation) of 2018 (IEA, 2020a) and most of the countries also account for the major share of transport emission from their respective continents except Africa and Asia. Major transport sector polluters in Asia like China, India, Japan, and Korea as well as the majority of the countries in the African continent lack change in activity data for public and private transport sectors in the apple and waze database respectively during the covid-19 period. 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. Although not as popular as google maps, waze gathers around 130M+ monthly active users worldwide (Waze, 2020a) and the United states alone has 25.6M waze and 23.3M apple maps monthly unique users (Statista, 2021). Data regarding global apple maps monthly active users are unavailable.

Countries	Apple & waze	Apple & tom-tom
Argentina	86%	69%
Australia	82%	64%
Belgium	86%	67%
Brazil	81%	50%
Canada	83%	29%
Czechia	85%	57%
France	88%	58%
Germany	84%	68%
Indonesia	78%	52%
Italy	94%	52%
Mexico	85%	89%
Netherlands	64%	39%
Philippines	90%	-
Russia	67%	32%
Singapore	84%	60%
South Africa	81%	67%
Spain	90%	49%
Sweden	83%	4%
Switzerland	78%	63%
United Kingdom	88%	65%
United States	74%	18%

Table 1: Pearson's correlation between private transport activity change of apple & waze as well as apple & tomtom databases.

Table 1 displays the correlation coefficients of the different mobility datasets that represent real life travel, in this case tomtom and waze datasets compared to the apple database. The Pearson's correlation test was conducted for two mobility datasets of private transport activity change for each country using excel. From the above table, we can understand that waze and apple databases have a better correlation than tomtom and apple. A high correlation between the waze and apple database tells us that the change in km driven and the change in volume of search route requests respectively has a similar trend of increase and decrease in activity. Hence, we can say that the apple database does have a similar trend to real life mobility demand, and it can be used to analyze mobility of public transport. Although private transport activity of waze and apple have a high correlation the actual percentage change values of the datasets differ. The apple database change in activity has a higher value than waze for most countries. The data is partly affected because the baseline date of both the datasets are different by a month. The baseline date cannot be adjusted to our conveniences as the absolute baseline value is unavailable to public use for both the datasets. Below plotted is the change in km driven by waze and change in volume of search route requests of apple maps for few countries that display different trends.

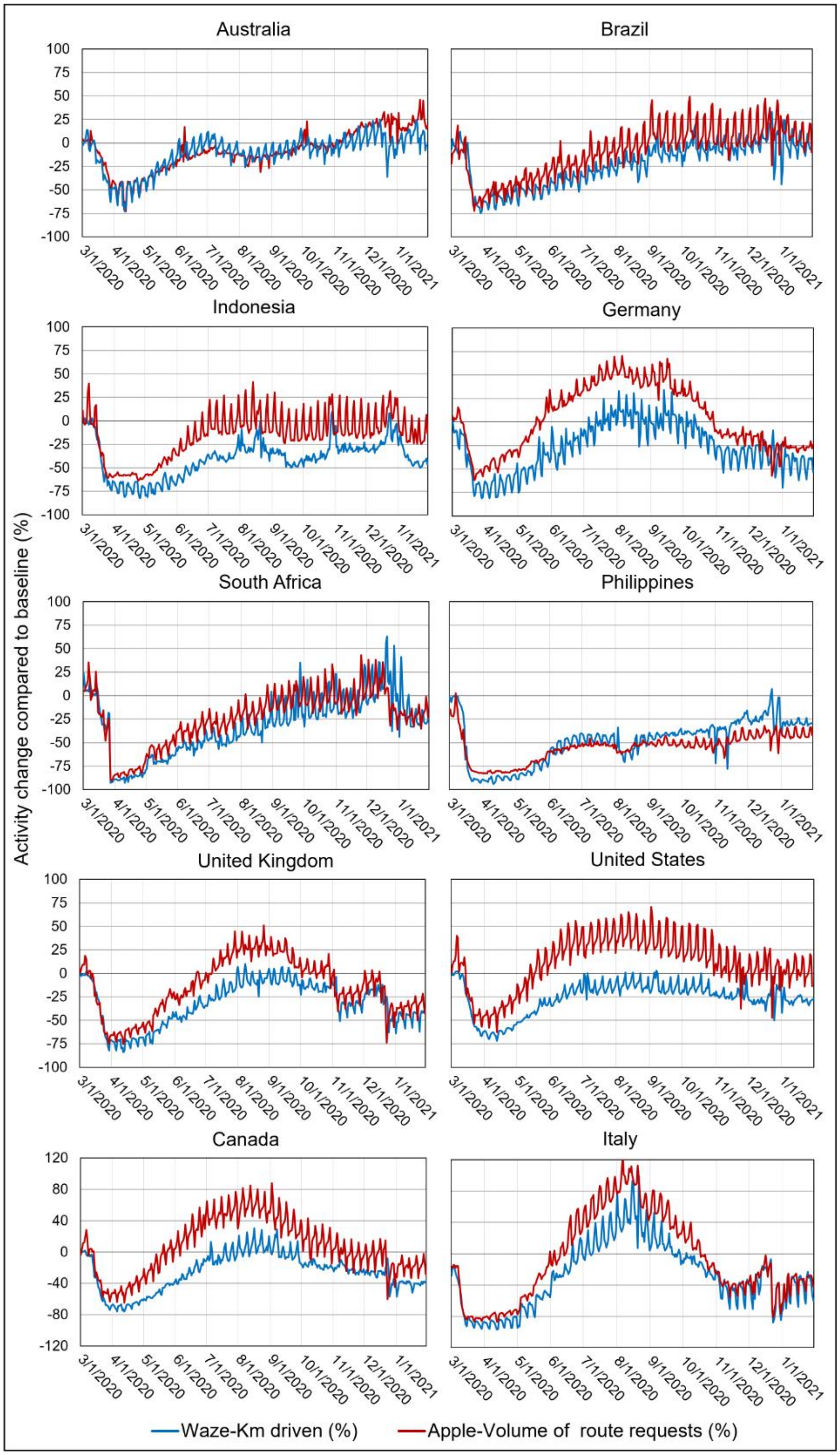

Figure 1: Private transport activity change (%) for waze and apple database for selected number of countries.

From the above figure where 0 is the baseline value, it is noticeable that there is a weekly surge, during the weekends and a difference between the activity change values of waze and apple private transportation data for different countries. The difference between both the datasets are quite substantial at around 40- 60% during a certain period in countries like Canada, Germany, UK and the US. Apart from the limitation of different baselines, it is assumed that such a huge difference between the two databases is due to the nature of the data represented by the database. The fact that people using the waze app will probably cut out travelling long distances i.e., holiday road trips and just make essential short-distance trips due to travel restrictions within states/ regions and due to risk perception would explain the low increase in percentage change. At the same time, in the case of apple maps, any routing request will also add to the increase in percentage, irrespective of the actual distance travelled or if they travelled at all. In most of the countries with such a large difference, we can notice that the percentage change of activity for apple map users increases after the first dip, which is exactly when measures were relaxed after the first wave (Hale et al., 2021). From the graphs we can also notice that this happens around the same time as the seasonal switch to summer, which quite naturally increases mobility in countries as people move around and use maps to search for routes which shows a high increase in apple database. The seasonal increase in mobility is also shown in the waze database and there is a similar trend between both the databases throughout the whole study period. Hence, even though there is a difference between the values of both the database's they follow a similar trend which means that the apple database does indeed represent mobility demand trends to an extent.

2.2.2 Confinement levels

Mobility reduction varies across waves for different countries and the reduction is dependent on the severity of the measures implemented in the country. The degree of measures implemented vary according to the number of covid-19 cases in a region/state. Since our study compares mobility activity and emission change on a country level, we use the country level stringency index (SI) published by University of Oxford (Hale et al., 2021). The Oxford stringency index (SI) 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 it by converting them into a daily index rating ranging from 0-100 (100 being the strictest). The SI is calculated by considering the level of measures of different policy indicators like, C1-closure of school, C2-work offices, C3-stay at home orders, C4-closure of public transport, C5-international travel ban, C6-restriction on gathering, C7-restrictions on internal gathering, C8-cancelling public events and H1-public information campaign. These categories are further coded on an ordinal scale based on the levels of implementation, i.e., 0, 1, 2, 3, 4 (0-no measures to 4-extreme measures) only a couple of indicators have 4 levels, while the others have 2 and 3 levels. Binary flag is also used to represent whether the measures are implemented in a particular region(0) or for the whole country (1). In-order to split the stringency index into 3 levels of confinement we calculate the stringency index values based on the weight of the indicators. The sub index of an indicator is calculated for any indicator *(j)* for a given day *(t)* using the formula adapted from (Hale et al., 2021):

$$I_j = 100\,\frac{v_{j,t} - 0.5(f_{f,t}/F_j)}{N_j} \qquad \text{..... 1}$$

$v_{j,t}$ -> The level of implementation for that indicator on a given day

$f_{f,t}$ -> The binary flag variable for that indicator on a given day

N_j -> The maximum level of implementation of that indicator

F_j -> If a binary flag variable is available F_j= 1, if not 0.

I_j -> Sub-index score

Once the sub-index scores are calculated using formula 1, the sum of all the sub-indexes are divided by the number of subindexes to calculate the stringency index (SI). Adapted from (Hale et al., 2021) where *k* is the number of indicators

$$index = \frac{1}{k} \sum_{j=1}^{k} I_j \qquad \text{...... 2}$$

Using equations 1 and 2 we calculate different stringency indexes based on policies implemented to classify SI into 3 different levels. Level 1- Low measures implemented, this is calculated by assigning 1 for $v_{j,t}$ and 0 for $f_{f,t}$ for all the indicators, this means all measures are only recommended and for a specific region/ state, which gives us an index of 24. If we change the $f_{f,t}$ into 1 for a couple of the indicators they will have an index below 35 and will still be considered as a low measure. Hence, we consider level 1 to be from 0-35. Level 2 – Partial measure, for the lower end of this level, we assign 1 for $v_{j,t}$ and 1 for $f_{f,t}$ which means measures are recommended but for the whole country which gives us an index of 38. For the higher end of this level, we consider 2 for $v_{j,t}$ and 0 for $f_{f,t}$ which says all policy measures are required to be followed but only for a certain region/state which is an index of 62. If the SI is in-between 35-65, it is considered as level 2. Level 3- Strict measures implemented, the lower end of this level is when policies implemented are required to be followed by the whole country for few indicators such as stay-at-home orders, closure of school and work from home it is considered as strict measure, 2 for $v_{j,t}$ all and 1 for $f_{f,t}$ for few of the indicators, giving an index value of 68. The higher end is the maximum level of implementation of each indicator for the whole country which gives us an index value of 100. Hence, 65 to 100 is considered a strict measure.

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 implemented are recommended for the whole country -> mandatory to follow for a targeted region.	35-65
Strict restrictions	Ranges from: policies implemented are required to follow for the specific regions -> mandatory to follow for the whole country with increasing levels of indicators	>65

Table 2: Confinement level classification and range based on SI

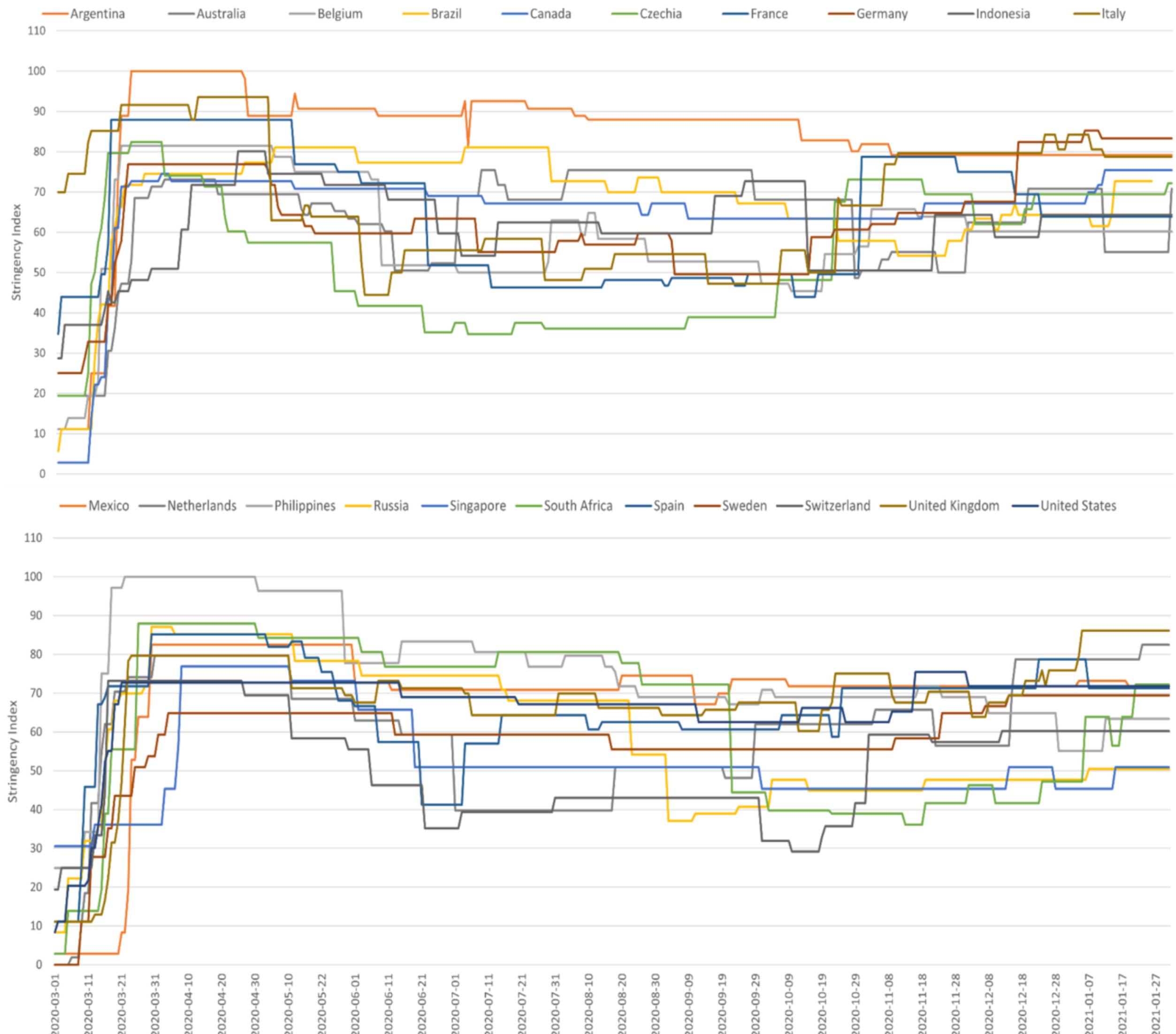

Figure 2 : Stringency Index of measures implemented by the governments of all the 21 countries during the entire period of this study

Figure 2 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 (except Switzerland) even though the cases dropped eventually to conclude the first wave. It is interesting to notice than although countries have a much higher daily cases and a prolonged duration during the second wave (John Hopkins University, 2020), which starts around late August early September for most countries the SI in generally lower than the first wave except for Argentina, Mexico and Indonesia, who have a consistent wave throughout. In the following section 4, the difference in effect of SI during the first and second wave on the transport mode activity change will be analyzed.

2.2.3 Covid-19 waves

The covid-19 pandemic has had an unprecedented effect on our life from March 2020 with a surge of positive cases to which most countries took controlled measures to prevent the rapidly increasing numbers (BBC News, 2020). Once the cases were controlled, the measures were relaxed which led to people letting their guards down to go back to normality and enjoy their summer (Reynolds, 2020). Although, there was a lack of precautions taken when the cases were reducing which led to another surge in cases in most of Europe and other western countries by the end of summer (Deutsche Welle, 2020). Even though there is not a strict definition of an "epidemic wave", epidemiologists characterize it as a surge in infection cases, which leads to a peak and then gradually a decline (Wagner, 2020). In this research From the standpoint of the novel covid-19 there has been 2 notable waves in most countries, except for few Asian countries, who tackled the first wave and took necessary precautions to avoid the second wave according to WHO's special envoy (Deutsche Welle, 2020). The second wave in all the countries considered in this study has a higher number of daily covid-19 cases and lasts for a longer time period than the first wave (John Hopkins University, 2020). Although the second wave is more severe and lasts for a longer period than the first wave, mobility reduction in the second wave does not follow the same pattern. The effect of stringency index on mobility change in both the waves across different countries will be analyzed in detail in section 3.2. 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 rate of change of covid-19 positive cases. The end of the wave is declared if the number of positive cases gradually decline below the initial value at which the wave starts. Countries which 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 is sourced from the covid-19 dashboard by the Center of System Sciences and Engineering (CSSE) 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).

2.3 Methods

2.3.1 Regression Analysis

This paper tries to understand the influence of confinement measures and risk perception on mobility reduction across different countries. Since risk perception cannot be quantified, we are unable to analyze its influence on mobility reduction in this study. Instead we investigate surveys that show risk perception and how it has affected mobility from article and paper surveys. According to an article published by McKinsey (Chechulin et al., 2020) which produces aggregated survey results from Italy, Germany, France, UK, US, Japan and China on key factors affecting choice of transport mode. In pre-covid 19 period, time to destination, convenience, price of trip and space and privacy were the top 4 (out of 9) factors with risk of infection at 6th for private trips and business trips. During covid-19 the order of the factors affecting mode choice have changed to risk of infection being the top priority moving price of trip down to the 5th. During the pandemic, health is the most important factor for an individual and will quite naturally try to avoid transport mode with increased chances of infection. Another paper by Abdullah et al., (2020) also conducts a survey of 1203 responses from various countries around the world to find that the resulting factors affecting choice of transport mode have indeed changed significantly before and during the pandemic. According to a multinomial logistic regression conducted by Abdullah et al., 2020 based on the survey they found a significant switch from public to private and active transport modes and distance travelled has been reduced. Intercity travel by train and airplanes have been replaced by private transportation and an access to private transport is valued now more than ever (Furcher et al., 2020)

Due to the limitations of the data being in percentage change of activity which does not translate into switching behavior and since no surveys have been conducted based, we are unable to analyze the switch from public to private during both the waves. Instead, we use a stringency index, which is the other main factor to analyze its influence of mobility reduction for public and private transport for different countries. To understand the effect of SI on change in transport activity for the 1st and 2nd wave for different counties we carry out a panel data fixed effect regression for public and private transport separately. Fixed effects regression is a statistical tool used to predict the dependent variable as a time varying function of the independent variable. 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 function) as a result of stringency index (independent variable) for different countries. 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') (Hanck et al., 2020). 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, the individual specific being countries in our analysis. So in this case, how the stringency index affects the change in transport activity for country specific (individual) can be found out.

$$Y' = \beta_0 + \beta_1 X_1 + F_i + \varepsilon \qquad \text{...... 3}$$

Where,

Y' -> Predicted dependent variable
β_0 -> Intercept
β_1 -> Coefficient of independent variable
X_1 -> Stringency index (Independent variable)
F_i -> Country specific fixed effects (individual)
ε_{it} -> Standard error

Now, we add in the time varying fixed effects to understand the change in how stringency index affects the change in transport activity for a country specific effect over a certain period, in this study, time variable is the 1st and the 2nd wave occurring over different time periods. We create a dummy variable for each wave for a specific country. Hence, the final equation of the fixed effects model to calculate the effect of stringency index for a specific individual *i= 1,…,N* (country) at specific time periods *t= 1,…,T* (Waves) on the change in transport activity, will be (Hanck et al., 2020; Schmidheiny, 2020) :

$$Y'_{it} = \beta_0 + \beta_1 X_{it} + F_i + T_t + \varepsilon_{it} \qquad \text{..... 4}$$

Where,

T_t -> Waves fixed effects (time varying)

Fixed effects regression can be carried out in R using the plm package & lm function through the least square dummy variable (LSDV) method yielding the same outcome (Torres-Reyna, 2010). For the input variables of the fixed effects regression, activity change of transport is considered as the dependent variable, the SI is considered as the independent variable, a dummy variable is created for countries and waves separately which are the fixed effect independent variables. Argentina is considered as reference for the country's dummy variables and the no wave period (0) is considered as reference for the waves. The regression is carried out separately for private transport activity change using waze's KM change database to understand the influence of SI for different countries. The public transport activity change is analyzed by using the apple's search route request change as the dependent variable. Statistics of both the regression and their results are compared in section 4.

2.3.2 CO_2 change estimation

The research question formulated requires us to understand how covid-19 and the measures implemented have affected the emissions related to the surface transport sector over a span of 11 months. Just as how emission estimation is carried out in Liu et al., 2020 , Le Quéré et al., 2020 and Forster et al., 2020, this paper too estimates change in CO_2 emissions based on change in activity data. Unlike the above-mentioned papers which estimate emissions of all the main sectors for the first half of 2020, this paper estimates change in CO_2 emissions for public and private transport for different confinement levels and looks into change in CO_2 emissions across the duration of both waves. Le Quéré et al., 2020 is the most relevant paper to this study since both papers work with change in activity data of the transport sector compared to a pre-covid 19 baseline dates in 2020 to estimate change in CO_2 emissions.

Hence, the change in CO_2 emissions of a country's (c), private and public transport sector (ppt) for each day (d) is calculated using a formula adapted from (Le Quéré et al., 2020).

$$\Delta CO_2^{c,ppt,d} = CO_2^{c,t} * \delta ppt^c * \Delta A^{ppt,d,c} \qquad \text{..... 5}$$

$\Delta CO_2^{c,ppt,d}$ -> Daily change in CO_2 emissions of each countries public & private transport sector ($MtCO_2$/day)

$CO_2^{c,t}$ -> Each country's mean daily CO_2 emissions of the total transport sector ($MtCO_2$/day)

δppt^c -> Fraction of emissions of private and public transport sector of each country

$\Delta A^{ppt,d,c}$ -> daily change in activity of public and private transport sector of each country

$CO_2^{c,t}$ Each country is obtained from the IEA's annual transport sector CO_2 emissions for the latest year available 2018 (IEA, 2020a) is divided by the number of days to get mean daily CO_2 emissions. δppt^c for most countries are obtained from respective government websites for the year 2018. For 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. $\Delta A^{ppt,d,c}$ is the percentage change of daily activity from a given baseline which is a date prior to 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-week period from 11th Feb – 25th February, 2020 (Waze, 2020b). 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 of the year 2020, we assume that there has been non-significant change in the CO_2 emissions of the latest year available to 2020.

3. Results

In this section, the private and public transport activity change and consequently the CO_2 emissions are estimated for the 17 countries and private transport alone is estimated for 4 countries. Initially we focus on the activity change of private and public transport across the entire study period for the different countries. Followed by the predicted activity change to understand the effect of stringency index across both the waves using the fixed effects model formula described in the section 3.2.1. As activity change directly translates into CO_2 emissions, the CO_2 emissions trends of each country for the public and private transport sector is looked at. Later, based on the activity change, the difference in CO_2 emissions between countries during; each of the confinement levels, the 1st, and the 2nd wave, and between the private and public transport is estimated.

3.1 Activity Change

The activity change compared to baseline for private and public transport is obtained from the waze and apple database, respectively. The trends observed throughout the study period for public and private transport activity change vary across countries. The variation is dependent on the measures implemented in the respective country. Although, it is possible to segregate the activity trends of certain countries to their specific region and based on their economic development. This segregation was validated upon conducting a correlation test between all the countries included in the study for public and private separately during the entire study period. The correlation coefficient is important to identify the similarity in activity change trends and segregate them accordingly, either among similar regions or countries with similar economic development. This is further used to identify and compare the recovery rate of the public and private transport sector of different regions and to interpret the regression results carried out in this study. The European countries (EU9) included in this study and the UK, displaying a high correlation coefficient, $r > 0.75$ among themselves for public and private transport. Canada and the US also have a correlation, $r > 0.90$ between themselves for public and private transport. Both Canada and the US show a correlation, $r > 0.65$ between them and EU9 + UK. Latin American countries, Mexico, Argentina and Brazil's correlation, $r > 0.75$. Asian countries, Indonesia, Philippines, and Singapore also show a correlation of $r > 0.75$. Developing countries like Argentina, Brazil, Mexico, Philippines, Indonesia and South Africa as well as developed countries like Australia and Singapore show a correlation, $r > 0.65$ within themselves. It can be understood that they have a similar trend from the correlation coefficient. For further reference of the correlation coefficient, refer to Appendix A. It is understood that countries in the same region (e.g.: South America, North America, and Europe) have a higher correlation, compared to countries with similar economic development. It should also be noted that Russia does not show a correlation $r > 0.65$ with any of the countries in the study. This will be discussed in the latter sections. Public transport sector correlation between countries also shows a similar correlation coefficient for the activity change for the entire study period. EU9 & and UK have a correlation, r > 0.75. North American countries display correlation, r = 0.94. Latin American countries, Brazil and Mexico show a correlation r > 0.9. In Australasian countries, Australia and Philippines display a correlation, r = 0.9 , and Singapore display a correlation r > 0.65 to Australia and Philippines.

Figure 3 shows the average activity change of certain regions , Brazil, and Mexico (Latin America); Belgium, Czechia, France, Germany, Italy, Netherlands, Spain, Sweden, Switzerland, and UnitedKingdom (EU9 & UK); and Canada and US (North America); Australia, Philippines, and Singapore (Australasia) throughout the entire study period. Only countries with private and public data available were used in the figure to make an even comparison. All the regions in the figure show a large decline in activity until May for public and private transport. This is because all the countries implemented stringent measures to curb the virus. Now focusing on private transport alone, there is a sudden rebound in the activity change for Europe and North American countries since May. The rebound effect is caused by the increase in activity change influenced by the relaxation of restrictions. As global mass restrictions and stay at home orders were an unfamiliar concept for over half a century, people took liberty of the relaxed measures and resumed activities and travel as the first wave declined in EU9 & UK and North America. EU9 and UK saw a larger rebound effect compared to North American countries as their stringency index dropped significantly since May-mid. Even though North American countries did not experience much of a reduction in stringency index, seasonal change impacted the activity increase. Consequently, a second wave was incident upon these countries, making it necessary to tighten the measures implemented. This saw another decline in the activity change, although not as severe as the first wave. In terms of Latin American and Australasian countries, the rebound effect is absent. The slight increase noticeable during June for Australasian countries is because Australia and Singapore had a short first wave after which their stringency index dropped, and activity change increased slightly. Latin American and other developing countries experienced a prolonged first wave or a first wave directly leading to a second wave, demanding the stringency index to remain approximately constant throughout the study period. The activity change for private transport increases gradually during the second phase in these countries as economic activities are resumed by reducing the stringency index to maintain their economy (UNCTAD, 2021)

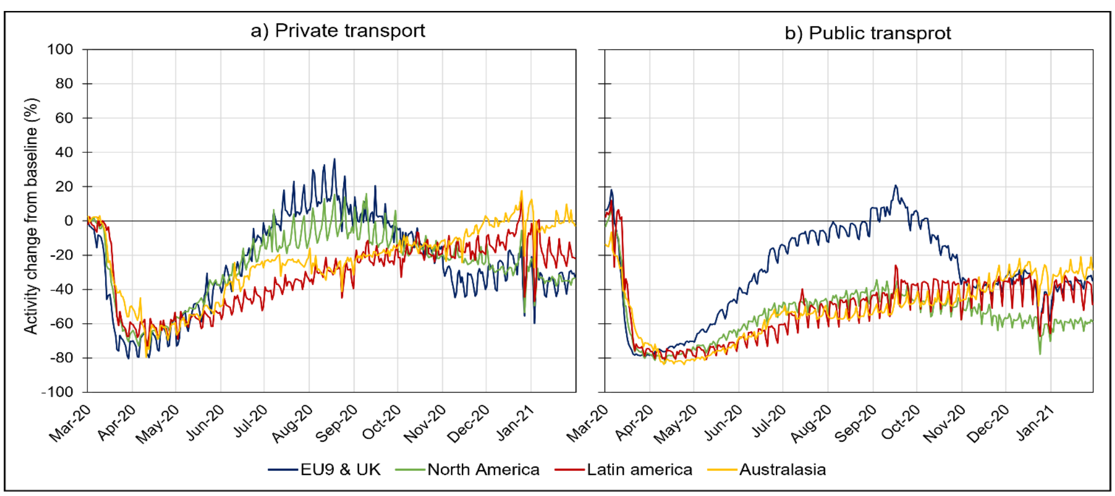

Figure 3 : Average activity change compared to the baseline for private and public transport sector for specific regions throughout the entire study period

Public transport also follows a similar trend of slow and gradual increase in the activity for Australasian and Latin American countries as time progresses. In North American countries the public transport demand increases slightly during mid 2020 but drops again as the second wave hits. Unlike private transport the activity increase in public transport is minimal since people have steered away from public transport causing a modal shift. EU 9 & UK show a rebound in activity after the first wave period in the countries included in this study. The reason for the rebound effect is similar to the private transport sector, although not as much of an increase as shown in the private sector. This is because of the modal shift experienced in EU9 & UK, the modal shift is also prominent in other countries as well (UITP, 2020a). The slow and gradual increase in public transport activity compared to private transport in the focused countries is directly linked to the stigma around risk perception of public transport and contracting the virus. Since it is also recommended by the CDC to avoid non-essential travel on public transport unless necessary and no other means are available, the recovery is expected to be slow (CDC, 2021). In sections to follow we take a closer look at the CO_2 emissions change of private and public transport resulting from activity change in different countries, during the various confinement levels and across waves.

3. 2 Predicted the effect of stringency index on activity change across the 1st and 2nd wave

Using a fixed effects regression model explained in section 3.2.1, the effect of the independent variable (stringency index) on the dependent variable (activity change of countries) as a time varying (waves) function is predicted using the R software. We compare the statistics of the regression model of private and public transport to understand which mode's activity change has a more prominent effect as stringency index varies across the different waves.

In the case of private transport, the predicted activity change (AC), i.e., change in km's driven is calculated using a fixed effects model formula based on the coefficient estimates of the regression given below in table 3.

$$\text{Predicted AC} = 37.06 - 0.88 * (\text{Stringency index}) - 26.89 * (\text{Wave 1}) - 3.01 * (\text{Wave 2}) + \beta_4 (\text{Country}) \quad \text{....6}$$

Where, wave 1 is coded as, 1= wave 1, 0 = remaining waves, and wave 2 is coded as 1 = wave 2, 0 = remaining waves. Whereas country is coded as 1= specific predictor country, 0 = remaining countries and β_4 is the coefficient that describes the relation between a countries activity change to stringency index. To interpret the equation, the km's driven change of private transport decreases by 0.88 km with a unit increase of stringency index keeping all other variables constant and a decrease of either 26.89 km's or 3.01 km's during the 1st or 2nd wave, respectively. From the coefficients of the waves it is clear that the stringency index during the 1st wave reduced the activity change higher than the 2nd wave. The independent variables, stringency index and dummy variables, wave 1 and wave 2 are significant predictors of activity change, with p- values < 0.05 and adjusted **$R2 = 0.596$**. Hence, we reject the null hypothesis, H0 and accept the alternate hypothesis H1 which is, there is a significant change in transport activity of a country during the 1st and 2nd wave as a result of stringency index. The table below shows the estimated coefficient (β_4) of each country and their p-values while taking Argentina as the reference country :

<table>
<tr><td colspan="5">Coefficients:</td></tr>
<tr><td>Variables</td><td>Estimates</td><td>Std. Error</td><td>t-value</td><td>Pr (>|t|)</td></tr>
<tr><td>(Intercept)</td><td>37.1</td><td>1.7</td><td>22.3</td><td>< 2e-16 ***</td></tr>
<tr><td>Stringency Index</td><td>-0.9</td><td>0.0</td><td>-55.0</td><td>< 2e-16 ***</td></tr>
<tr><td>Wave 1</td><td>-26.9</td><td>0.7</td><td>-36.8</td><td>< 2e-16 ***</td></tr>
<tr><td>Wave 2</td><td>-3.0</td><td>0.7</td><td>-4.4</td><td>0.0 ***</td></tr>
<tr><td>Australia</td><td>16.3</td><td>1.5</td><td>10.7</td><td>< 2e-16 ***</td></tr>
<tr><td>Belgium</td><td>-5.2</td><td>1.5</td><td>-3.4</td><td>0.0 ***</td></tr>
<tr><td>Brazil</td><td>20.2</td><td>1.5</td><td>13.5</td><td>< 2e-16 ***</td></tr>
<tr><td>Canada</td><td>6.0</td><td>1.5</td><td>4.0</td><td>0.0 ***</td></tr>
<tr><td>Czechia</td><td>12.3</td><td>1.6</td><td>8.0</td><td>0.0 ***</td></tr>
<tr><td>France</td><td>10.0</td><td>1.5</td><td>6.6</td><td>0.0 ***</td></tr>
<tr><td>Germany</td><td>-2.1</td><td>1.5</td><td>-1.4</td><td>0.2</td></tr>
<tr><td>Indonesia</td><td>3.5</td><td>1.5</td><td>2.3</td><td>0.02 *</td></tr>
<tr><td>Italy</td><td>3.7</td><td>1.5</td><td>2.5</td><td>0.01 *</td></tr>
<tr><td>Mexico</td><td>10.9</td><td>1.5</td><td>7.2</td><td>0.0 ***</td></tr>
<tr><td>Netherlands</td><td>-6.2</td><td>1.5</td><td>-4.1</td><td>0.0 ***</td></tr>
<tr><td>Philippines</td><td>7.7</td><td>1.5</td><td>5.1</td><td>0.0 ***</td></tr>
<tr><td>Russia</td><td>28.9</td><td>1.5</td><td>19.0</td><td>< 2e-16 ***</td></tr>
<tr><td>Singapore</td><td>6.0</td><td>1.6</td><td>3.9</td><td>0.0 ***</td></tr>
<tr><td>South Africa</td><td>2.8</td><td>1.5</td><td>1.9</td><td>0.06 *</td></tr>
<tr><td>Spain</td><td>-0.9</td><td>1.5</td><td>-0.6</td><td>0.55</td></tr>
<tr><td>Sweden</td><td>15.8</td><td>1.5</td><td>10.4</td><td>< 2e-16 ***</td></tr>
<tr><td>Switzerland</td><td>-20.4</td><td>1.6</td><td>-13.1</td><td>< 2e-16 ***</td></tr>
<tr><td>United Kingdom</td><td>-0.1</td><td>1.5</td><td>0.0</td><td>1.0</td></tr>
<tr><td>United States</td><td>11.8</td><td>1.5</td><td>7.9</td><td>0 ***</td></tr>
</table>

Table 3 : The estimated coefficients of stringency index and the different countries obtained from private transport fixed effects regression

The countries with p-value > 0.05, like Germany, South Africa, Spain and UK, signify that their values are not significant with respect to the reference country, Argentina. This is usually due to the multicollinearity between these datasets. In the predicted activity change formula, β_4 will be assigned the value of the estimated coefficients of that country. For example to predict the km's change when stringency index of Australia is 65 during the 1st wave, the formula is:

$$37.06 - 0.88 * (65) - 26.89 * (1) - 3.01 * (0) + 16.33 (1) \qquad ....7$$

Similarly, in the case of public transport, the predicted activity change(AC) i.e., volume of search route requests) can be calculated by using the coefficient estimates in table 4. The formula of the fixed effects regression model is:

$$\text{Predicted AC} = -7.72 - 0.51 * (\text{Stringency index}) - 34.36 * (\text{Wave 1}) - 9.10 * (\text{Wave 2}) + \beta_4 (\text{Country}) \quad ....8$$

Where, variables are assigned similar to the private transport regression. To interpret the equation, the volume of search route requests of public transport decreases by 0.51 km with a unit increase of stringency index keeping all other variables constant and a decrease of either 34.36 km's or 9.10 km's during the 1st or 2nd wave, respectively. Like private transport, from the coefficients of the waves it is clear that the stringency index during the 1st wave reduced the activity change higher than the 2nd wave. The independent variables stringency index, and dummy variables, wave 1 and wave 2 are significant predictors of activity change in public transport, with p- values < 0.05 and adjusted **R2 = 0.53**. Hence, we reject the null hypothesis, H0 and accept the alternate hypothesis H1 which is, there is a significant change in transport activity of a country during the 1st and 2nd wave as a result of stringency index.

Coefficients:				
Variables	Estimates	Std. Error	t-value	Pr (>|t|)
(Intercept)	-7.7	1.6	-4.7	2.23E-06 ***
Stringency Index	-0.5	0.0	-26.3	< 2e-16 ***
Wave 1	-34.4	0.8	-41.3	< 2e-16 ***
Wave 2	-9.1	0.8	-11.6	< 2e-16 ***
Belgium	27.9	1.6	17.7	< 2e-16 ***
Brazil	21.2	1.6	12.9	< 2e-16 ***
Canada	1.6	1.6	1.0	0.313
Czechia	8.4	1.6	5.2	1.61E-07 ***
France	40.5	1.6	25.3	< 2e-16 ***
Germany	42.0	1.6	26.4	< 2e-16 ***
Italy	9.0	1.6	5.7	1.63E-08 ***
Mexico	24.5	1.7	14.6	< 2e-16 ***
Netherlands	2.3	1.6	1.4	0.156
Philippines	16.1	1.7	9.6	< 2e-16 ***
Singapore	10.6	1.6	6.6	4.61E-11 ***
Spain	22.5	1.6	14.0	< 2e-16 ***
Sweden	39.6	1.6	24.6	< 2e-16 ***
Switzerland	17.1	1.6	10.7	< 2e-16 ***
UnitedKingdom	7.8	1.6	4.9	9.53E-07 ***
UnitedStates	13.5	1.6	8.3	< 2e-16 ***

Table 4 : The estimated coefficients of stringency index and the different countries obtained from public transport fixed effects regression

Now, on comparing the constants and intercept of private and public transport fixed effects regression model it can be interpreted that the public transport activity change will have a higher reduction compared to private transport at a similar stringency index. 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 an intercept of positive value (37.06), and the coefficients of the waves are negative but lower than the public transport.

To look at the difference in the predicted activity change of public and private transport influenced by stringency index during the different waves, the average activity reduction during each confinement level, which is classified based on stringency index, is considered. Different countries are classified into regions based on their location and the correlation coefficients mentioned in section 3.1 .

Private transport avg activity change (%)				
Regions	Waves	L1	L2	L3
North America	1	6%	-23%	-54%
	2	30%	1%	-30%
Latin America	1	8%	-21%	-52%
	2	31%	2%	-29%
EU9 & UK	1	1%	-28%	-59%
	2	24%	-5%	-36%
Australasia	1	6%	-23%	-54%
	2	29%	1%	-30%
South Africa	1	0%	-29%	-60%
	2	24%	-5%	-36%
Russia	1	26%	-3%	-34%
	2	50%	21%	-10%

Table 5 : Average private transport activity change (Km's driven) of different regions during the 1st and the 2nd wave across different confinement levels

Public transport avg activity change (%)				
Regions	Waves	L1	L2	L3
North America	1	-42%	-59%	-77%
	2	-17%	-33%	-51%
Latin America	1	-27%	-43%	-61%
	2	-3%	-20%	-38%
EU9 & UK	1	-28%	-45%	-62%
	2	-5%	-21%	-39%
Australasia	1	-41%	-57%	-75%
	2	-15%	-32%	-50%

Table 6 : Average private transport activity change (Km's driven) of different regions during the 1st and the 2nd wave across different confinement levels

When comparing the average activity change of private and public transport services, the above-mentioned interpretation becomes more evident. Within private transport, there is a 29% and 31% decrease between L1 to L2 & L2 to L3, respectively. In the case of public transport, it is 17% and 18% between L1 to L2 & L2 to L3, respectively. Naturally, wave 2 shows an increased activity change compared to wave 1, as predicted from the coefficients of the waves. In terms of activity reduction between public and private for the 1st and the 2nd wave, the largest difference between the transport modes is noticed during L1 confinement level, followed by L2 and L3. Northern America and Australia show the highest reduction in between the transport modes followed by Latin America and EU9 & UK. By predicted average activity change of the surface passenger transport modes it is understood that demand for private transport is higher during L1, whereas demand for public transport is very low in comparison. This is mainly due to the social distancing measures which reduced capacity as well as the stigma around public transport being a contagious environment to contract the virus(World Health Organization, 2020). As the confinement levels increase the reduction of activity reduces because private transport has a higher difference between levels due to restrictions limiting mobility. Whereas, for public transport in L2 and L3 the restrictions only limit the necessary commuters which are low in number either way.

3.3 CO_2 emissions trends for countries

Based on activity change from mobility data sources, the CO_2 change in private and public transport is indirectly estimated in this section using the formula mentioned in section 3.2.2. The focus is on analyzing the different trends of CO_2 emissions change of different countries during the first and the second wave. It is interesting to interpret the effect of stringency index on the CO_2 emissions across the waves as well. As we know, the change in activity of transport modes translates into CO_2 emission change based on the ratio of their daily mean transport emissions. Although, the value of CO_2 emission change depends on the emission fractions of the mode of transport, and this varies across countries (Appendix B). This means that two countries with similar activity reduction could display varying CO_2 emission change. For example let us consider the month of April, which had the highest reduction in activity change. Argentina, Italy, Philippines, South Africa, and Spain, portrays an average activity reduction of -87%, -88%, -88%, -86% and -89%, respectively. Although the change in CO_2 emissions for these countries are on a different scale. The average emission reduction throughout the month in Argentina was -44.5 ktCO_2/day, -160.5 ktCO_2/day in Italy, -47 ktCO_2/day in Philippines and South Africa and -130.37 ktCO_2/day in Spain. Argentina, Philippines, and South Africa show a much lower CO_2 emissions change compared to Italy and Spain despite having a similar average change in activity. As per the formula used to indirectly estimate CO_2 change, it can be explained that the variation is purely based on the mean daily CO_2 emission of the private transport sector in the country. According to the IEA (2020a), Italy and Spain account for a higher share of private transport emissions compared to the other 3 emerging economies. The graphs below display the scale of CO_2 emission change from baseline for private and public transport in relation to the stringency index for the entire study period.

By focusing on the trends of different countries, a similarity is identified in the initial drop of CO_2 emissions change. From March-mid to May-mid, in some cases till June, the CO_2 change drops and remains below -100 ktCO_2/day for private transport in major transport emitting countries, i.e., Germany, France, Spain, Italy, UK, Mexico, Brazil, Canada, Russia, and Indonesia. The United States follows the same trend with a drop of -1 MtCO_2/day. Other countries included in the study also show a significant drop compared to the baseline, on their respective scales. Even though the activity change of private and public transport during this time period is comparable, the CO_2 emission change of the public transport sector is on a much lower scale. The emission fraction data collected from different sources (Appendix B) shows that, public transport accounts from a range of 1- 12% of transport emissions the 21 countries. The daily CO_2 emission change drops and remains below -20 ktCO_2/day for public transport reliant countries like Italy, Spain and Mexico from March-mid to June. For Brazil, a -20 ktCO_2/day reduction is estimated until August. The United States is again on a higher scale with a reduction below -80 ktCO_2/day till June. The initial reduction in CO_2 emissions for both transport modes is inversely proportional to the stringency index. Since a virus like COVID-19 was unfamiliar to humans at the time, the government responses implemented were of high stringency index. As the first wave was coming to an end in the EU9 & UK, Russia, and Australia, the stringency index was dropped as measures were relaxed. Consequently, limited activities were resumed, resulting in an increase in transport activity, which led to a rebound in CO_2 emissions above the baseline. The EU 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. As for the UK and Australia, the CO_2 emissions rebound was not as strong as EU9 and Russia since L3-strict restrictions (SI>65) were implemented during this time period. A different trend interpreted based on the results is for US and Canada, the stringency index remains almost constant, at times dropping by an index value of 5. Canada experiences a rebound effect towards the end of the first wave as the stringency index remains at the lower ends of L3 and higher ends of L2. The United States also follows the same trend as Canada, but the CO_2 rebound remains below the baseline. This could be explained due to the demographic size of both the countries, notably the United States. Since the restrictions are usually targeted to the affected region and in some cases the surrounding area, the transport activities in other states still continue, which translates to CO_2 emissions. An SI index of below 70 means that 6 out of the 9 government response indicators (mentioned in section 3.1.2) are required to follow for the whole country, and the other 3 are targeted to a specific region. Since these countries expand over a larger area and have high populations, the non-affected areas also add up to the increase in CO_2 emission change. Seasonal variation during the months of rebound effect also definitely influences the rise in activity and related emissions, especially after experiencing a strict lockdown.

The public transport sector of the countries addressed above also follows the same trend, i.e., an initial drop in the CO_2 emissions followed by a rebound effect. The CO_2 emissions change remains below the baseline for most countries during the rebound effect. Except for France, Germany and Belgium that show an increase in CO_2 emission change above the baseline, Spain and Czechia also show minimal increase above the baseline during the month of April (Refer appendix C for C. It can be deduced from the graphs that the CO_2 emissions increase in the months leading up to September, and the highest CO_2 increase occurs during September. There is a slow but steady increase in the activity of public transport which results in CO_2 emissions as the first wave concludes and economic activities slowly resumes. This is the impact of EU9 & UK, US and Canadian public transport authorities adapting and implementing the necessary health and safety measures to reduce the risk perception of contracting the virus and making travel safe (UITP, 2020c).

After the first wave, as a result of increased activity and countries not enforcing necessary precautions to maintain a flat curve, the covid-19 cases started surging, leading to a second wave. As the stringency index increases to tackle the second wave of covid-19, the CO_2 emissions change decreases. But it is noticed that the CO_2 emissions deficit is reduced compared to the first wave for both private and public transport, for all the countries with a rebound effect. This is because the stringency index is not as high as the first wave despite the second wave being more severe, in terms of daily number of cases and the duration of the wave. For EU9 & UK, the private and public transport cumulative CO_2 emissions have increased by 41% (-73.1 $MtCO_2$ to -43.$MtCO_2$) and 44% (-6.9 $MtCO_2$ to -3.8$MtCO_2$) 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$MtCO_2$ to -76.4 $MtCO_2$) and 14%(-10.7 $MtCO_2$ to -9.2 $MtCO_2$) for private and public transport, respectively. This increase in CO_2 emissions during the second wave can be credited to the adaptation of governments and its citizens to the "new normal". During the second wave more economic activities like non-essentials are operating at limited capacity, prior booking, and by adhering to social distancing measures, creating a safe environment to operate.

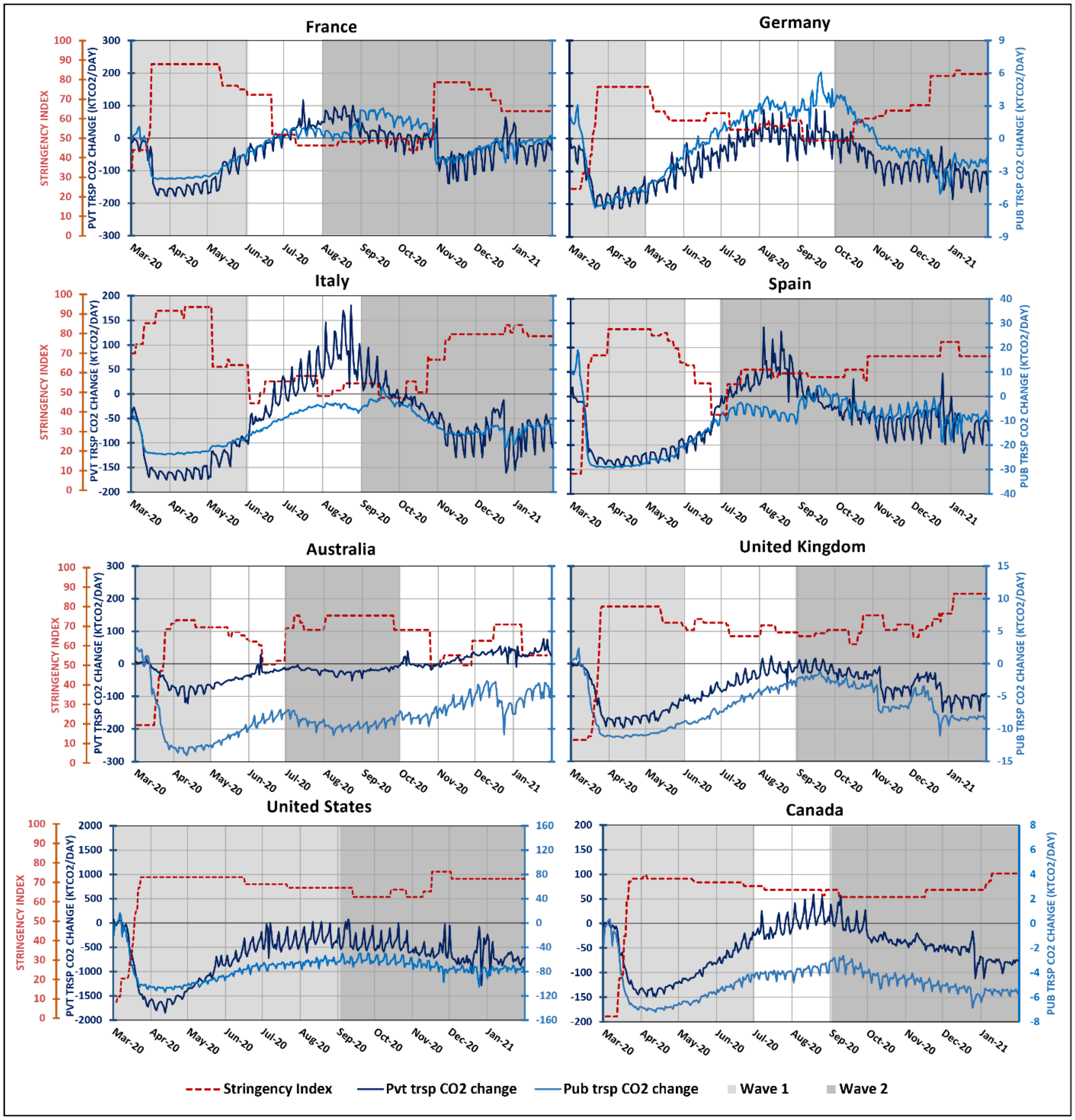

Figure 4 : Displays the daily CO_2 trend of private and public transport, as well as the stringency index implemented while highlighting the 1st and 2nd wave for selected countries across the entire study period.

Another CO_2 emissions trend, different from above mentioned countries, is identified for Latin American countries- Mexico, Argentina, Brazil; Asian countries- Philippines and Indonesia, and South Africa. It is quite interesting to notice that these are all developing economies (UN, 2019) and portray a similar trend. They all experience either a constantly increasing wave throughout the study period or have a longer first wave compared to other countries, which is soon followed by the second wave. Although developing economies have the necessary health and safety infrastructure to curb the virus, their resources are limited to an extent, in terms of procuring additional health care equipment. Especially with the lockdown, the revenue of the country comes to a halt, which makes the situation even more concerning. As a result of the high number of daily cases lasting for more than half a year, the stringency index remains above L3 - strict restriction. Naturally, the emissions remain low, and the rebound effect experienced in other countries is absent. Except for the private transport sector in Indonesia, which shows a slight rebound in the CO_2 emissions when the stringency index drops throughout the study period. Another developing country included in this study but shows a very different trend is Russia, the reason for its peculiar trend will be addressed in section 4.5. For the other developing countries, you can notice an increase in the CO_2 emissions for the private and public transport sector. Private sector shows a more pronounced increase in CO_2 emissions during the second half of 2020, be it the first or second wave in these countries. The later months of the study period (Oct'20 - Jan'21) show a cumulative CO_2 emission increase of 57% (-49MtCO_2 to -20.9MtCO_2) compared to the peak 1st wave period (Marc'20 - Jun'20) for private transport. For the 3 developing countries with data on public transport, namely, Brazil, Mexico, and Philippines, there is a 35% (-6.4 MtCO_2 to 4.12 MtCO_2) increase in CO_2 emissions in the later months in the public passenger transport sector. The reason for this increase is similar to the developed countries mentioned above, governments and countries have adapted to the "new normal" and have taken necessary measures to increase economic activities in a safe space. The CO_2 emission trends of the remaining countries along with their stringency index is available in Appendix C

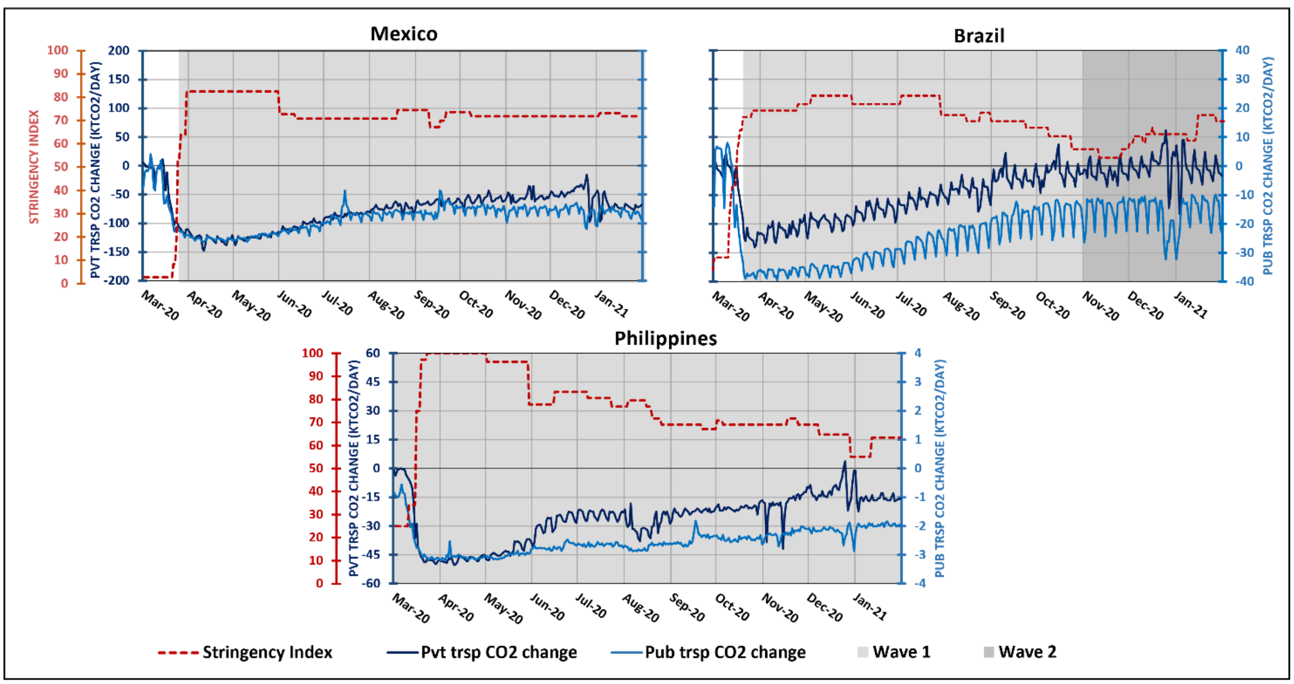

Figure 5: Displays the daily CO_2 trend of private and public transport, as well as the stringency index implemented while highlighting the 1st and 2nd wave for selected countries across the entire study period.

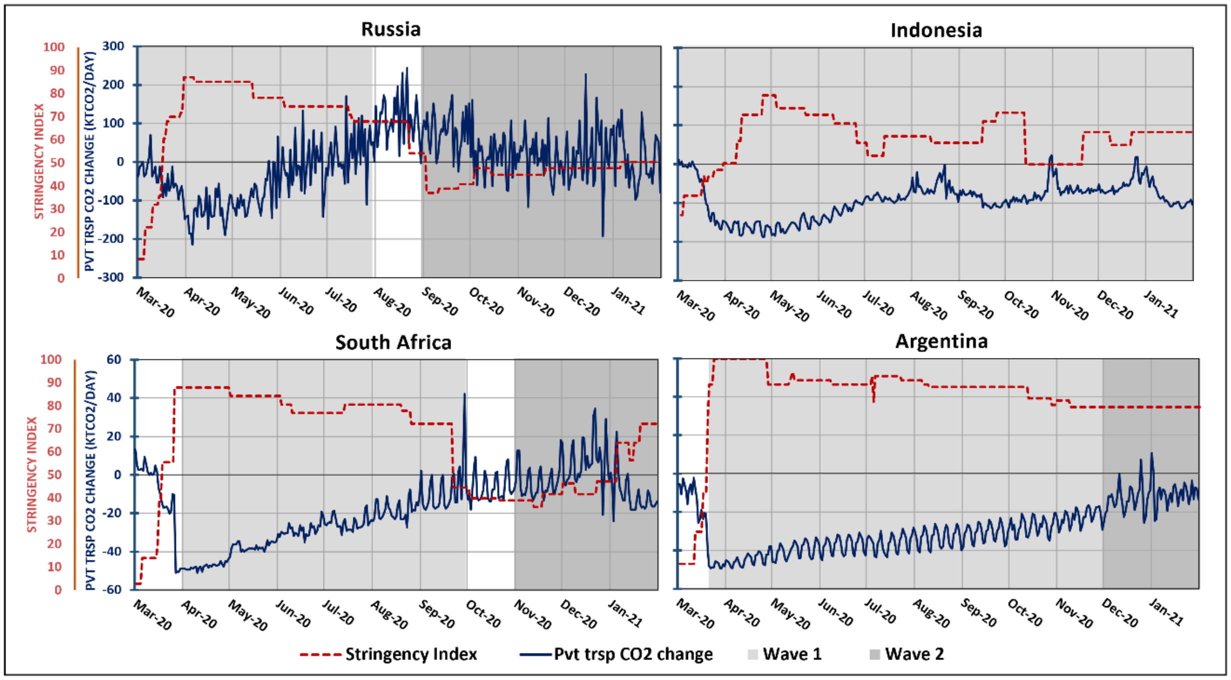

Figure 6: Displays the daily CO_2 trend of private transport, as well as the stringency index implemented while highlighting the 1st and 2nd wave for the entire study period. These are countries with data only available on private transport.

3.4 Cumulative implication of activity change

During the 11-month period, it is estimated that a total of 510 $MtCO_2$ 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 sector CO_2 emissions and a -1.5% reduction of the total global CO_2 emissions of 2018. Private transport was responsible for a high 89% (454 $MtCO_2$) and public transport was responsible for the remaining 11% (55 $MtCO_2$) of the surface passenger transport CO_2 reduction. Compared to private transport, public transport CO_2 emission reduction is on a much smaller scale as it was not a major contributor to CO_2 emissions in the transport sector pre-covid either. Since the study duration is 11 months and the baseline transport emissions of each country is for 12 months, the mean daily CO_2 reduction is considered. Figure 7 displays the percentage of mean daily CO_2 reduction of each country's transport sector by surface passenger transport emissions cuts. Philippines transport sector has the highest reduction of -29%, followed by Switzerland (-26%), 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%).

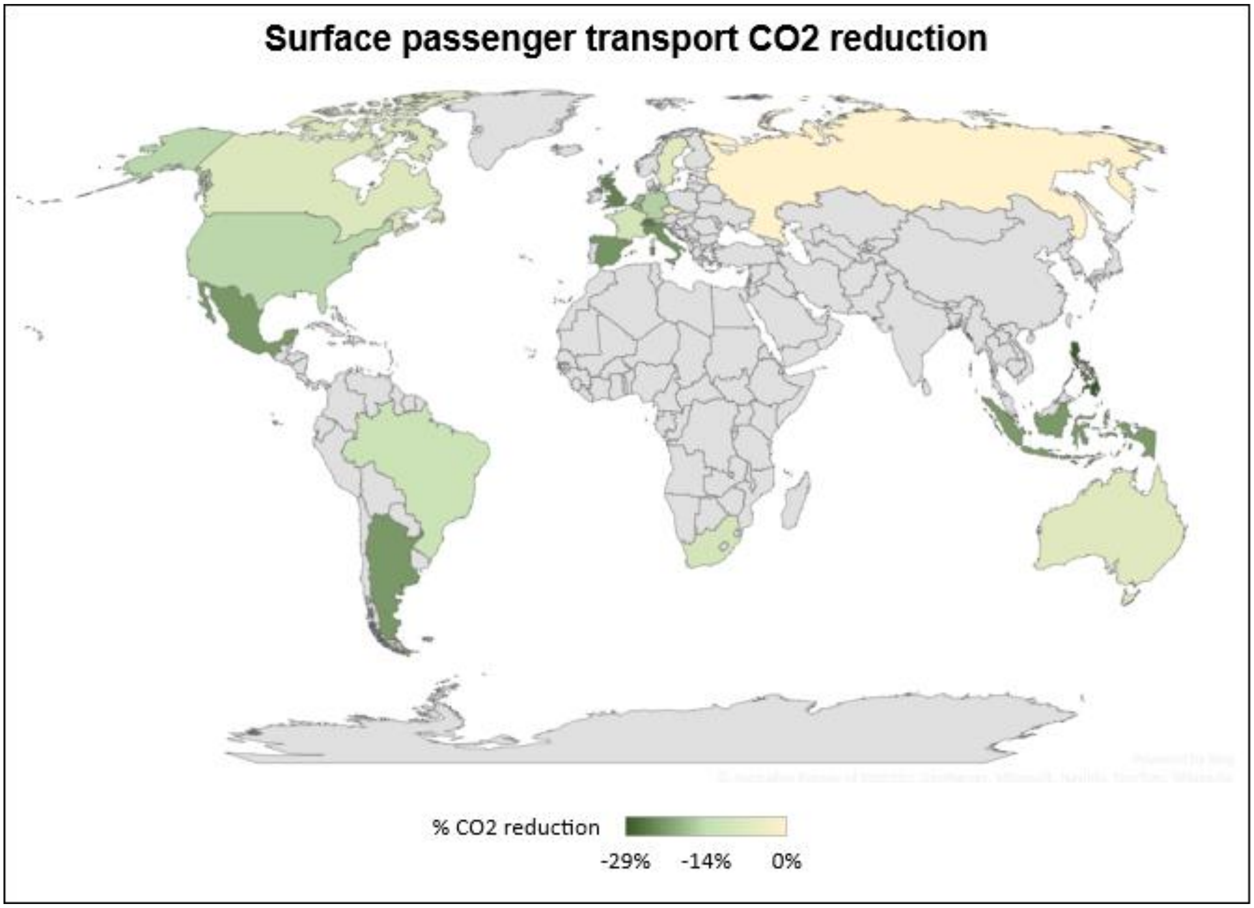

Figure 7 : The map displays the mean daily CO_2 reduction (%) in the transport sector of a country as a result of the emission cuts of surface passenger transport of that country, over the entire study period.

Compared to their mean daily baseline transport emissions, a few countries, namely, Czechia, Singapore, and Sweden, show minimal reduction and Russia shows no reduction with respect to the rest of the countries. From the earlier sections, it is established that in the 1st half of the study period (March-Sept), all countries experienced a similar trend of large CO_2 reductions. Now, it is interesting to analyze the recovery of private and public transport in terms of CO_2 emissions during the 2^{nd} half (Sept'20 – Jan'21) of the study period. As this would explain the minimal or no reduction in the CO_2 emissions during the study period. Table 7 below displays the percentage increase/decrease of CO_2 change in the 2^{nd} half compared to the 1^{st} half for all the countries included in the study. It is evident that Russia has a total of 0% reduction as there is a CO_2 increase of 209% in the 2^{nd} half of the study period, offsetting the CO_2 reduction of the 1^{st} half. This table can therefore be used to understand the total reduction of the transport sector of each country. While referring to the table to better explain the graph, it should be kept in mind that surface passenger transport's CO_2 emissions share contributing to the transport sector varies for countries, resulting in slight discrepancy.

CO_2 change 1st half vs 2nd half (%)				
Countries	**Private transport**		**Public transport**	
	% Change	**1st to 2nd half change ($MtCO_2$)**	**% Change**	**1st to 2nd half change ($MtCO_2$)**
Argentina	53%	-6.6 to -3.1	-	-
Australia	131%	-6.6 to 2.0	42%	-1.0 to -0.72
Belgium	53%	-2.4 to -1.2	77%	-0.25 to -0.06
Brazil	91%	-13.3 to -1.3	53%	-5.2 to -2.4
Canada	70%	-10.4 to -3.1	48%	-0.89 to -0.46
Czechia	-128%	-0.14 to -0.3	-5%	-0.19 to -0.20
France	49%	-7.7 to -4	101%	-0.2 to 0.002
Germany	31%	-14.2 to -9.8	101%	-0.19 to 0.002
Indonesia	44%	-19.8 to -11.1	-	-
Italy	21%	-9.6 to -7.6	37%	-2.7 to -1.7
Mexico	48%	-17.6 to -8.8	35%	-3.5 to -2.3
Netherlands	20%	-2.8 to -2.2	8%	-0.14 to -0.13
Philippines	56%	-6.0 to -2.6	32%	-0.50 to -0.34
Russia	209%	-3.6 to 3.93	-	-
Singapore	100%	-0.19 to 0.003	73%	-0.24 to -0.06
South Africa	87%	-5.0 to -0.65	-	-
Spain	29%	-9.13 to -6.48	70%	-2.8 to -0.86
Sweden	-77%	-0.38 to -0.68	20%	-0.00013 to -0.0001
Switzerland	42%	-2.3 to -1.3	44%	-0.0002 to -0.00013
United Kingdom	46%	-16.3 to -8.79	39%	-1.3 to -0.8
United States	41%	-141.6 to -82.9	26%	-14.2 to -10.5

Table 7: Displays the change in CO_2 emissions in the 2nd half of the study period compared to the 1st half of private and public transport. The CO_2 change is displayed in percentage increase/decrease (%) and in absolute value ($MtCO_2$).

3.5 Impact of confinement levels on CO_2 emissions

In this section, the focus is on how the CO_2 emissions differ in various confinement levels across countries. As mentioned earlier, the confinement levels are classified based on the stringency index, and as the stringency index increases, transport activity is limited and a reduction in the CO_2 emissions is estimated. Private and public transport of each country display a different average CO_2 change value in each level of confinement. Countries that exhibit peculiar results will be focused to understand what causes the CO_2 emission change during different confinement levels.

3.5.1 Private transport

Figure 8 focuses on few countries that show an interesting CO_2 change for private transport as a result of confinement levels. The other countries (Appendix D) show a typical trend where the average CO_2 emissions reduce 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. Looking at Australia and France, they show an average increase in CO_2 emissions of 6.3 ktCO$_2$/day and 11.6 ktCO$_2$/day respectively in L2- partial restrictions. Based on the government response in Australia, it is clear that they were hopping from L2 to L3 restrictions 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 time 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 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 of this, the average CO_2 emissions deficit reduces in 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 CO_2 emission was above the baseline due to the reopening of socioeconomic activities. Another interesting result here is for the L2 confinement in Indonesia, which is the opposite of Australia and France. Indonesia shows the highest average CO_2 reduction of -74.1 ktCO$_2$/day in the L2 confinement among all the countries included in the study, except the US. Despite Indonesia having a constant wave, which got worse towards the end of the study period, the stringency index was at the higher end of the L2 confinement level for most of the time since July. The reason behind relaxing the measures was to recover the economy and adapt to the "new normal" since June (Sparrow et al., 2020). Low income developing countries cannot afford to go into strict lockdown for longer durations like high income countries. In countries like Indonesia, the strict restrictions implemented for a long duration will affect the wellbeing of individuals and family, putting them through financial hardships (Gaduh et al., 2020). Even after relaxing the measures in an attempt to recover the economy the covid-19 cases were soaring high, forcing people to stay at home and making it hard to resume economic activities. Considering the fact that Indonesia is quite dependent on the tourism sector and travel is scarce due to travel bans, the transport activity is also minimal. All this accounts to the high reduction in CO_2 emissions in L2 confinement. Italy, on the other hand, shows the highest average CO_2 reduction of -199.5 ktCO$_2$/day in the L3 confinement and a large CO_2 deficit reduction in the L2 confinement of 0.1 ktCO$_2$/day. Italy was in fact one of the hardest hit countries during the first and the second wave of covid-19 with an alarming death rate as well (Pietromarchi, 2020). Rightfully so, to tackle the peak in cases during the waves a high stringency index measures were implemented limiting all activities to a minimum, resulting in a large decrease in CO_2 emissions. The average CO_2 deficit reduction in the L2 confinement is the result of the rebound effect caused by the relaxation of measures from June until October. Socioeconomic activities resumed, increasing the emissions so high almost offsetting the reduction in CO_2, this phenomenon is known as the revenge effect (Carabantes, 2021).

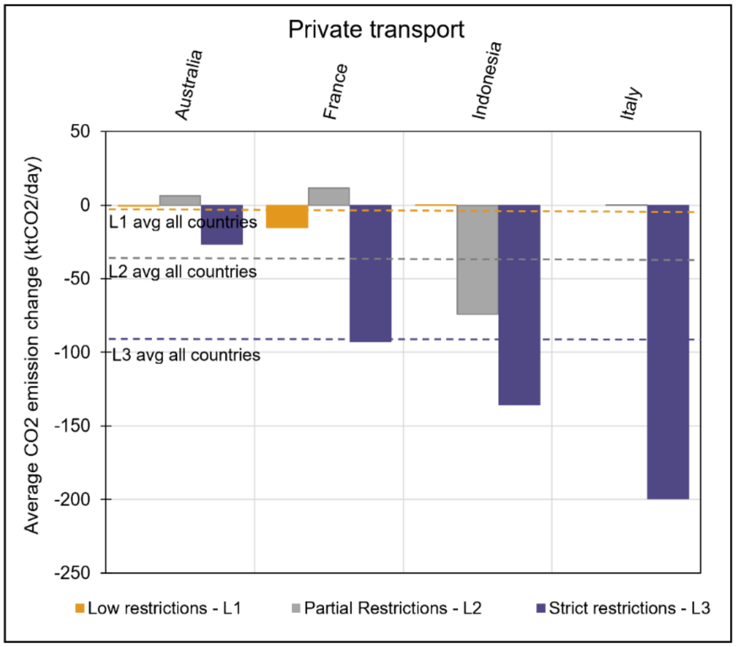

Figure 8 : Average CO_2 change ($ktCO_2$/day) of private transport mode across different confinement levels for selected countries

3.5.2 Public transport

Now, the effect of the stringency index on public transport CO_2 emissions also yields some interesting results as interpreted in figure 9. Brazil, France, Germany and Mexico are the focused countries in this section as they stand out among the other countries, which display a usual and similar trend (Appendix D). The CO_2 increase shown in the low restriction level 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. This is the same for Brazil, Germany and the other countries that show an increase in average CO_2 change in L1 (Appendix D). From this figure it is clear that Brazil and Mexico show the largest reduction in average daily CO_2 emissions in L3 of -27.5$ktCO_2$/day and -18.3$ktCO_2$/day respectively, except for the US. Both the countries have a large number of public transport users and account for 10% and 8% (Appendix B)of their respective transport sector CO_2 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 CO_2 emissions. In Mexico, the L2 confinement has a higher reduction than L3 confinement because, as the stringency index increased rapidly, there was an exponential drop in CO_2 emissions of the public transport sector in Mexico. The L2 confinement only lasted for less than a week and then it switched into the L3 confinement and never switched back to L2. Hence, not much can be deduced from this apart from the fact that we can reassure our findings about stringency index having a direct influence on the CO_2 emissions. Brazil shows a typical reduction in the CO_2 emissions deficit in L2 confinement. The L2 confinement period was during the last 3 months of the study period, indicating that the demand of public transport is slowly but steadily increasing during this period. It is also 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 CO_2 emissions of public transport.

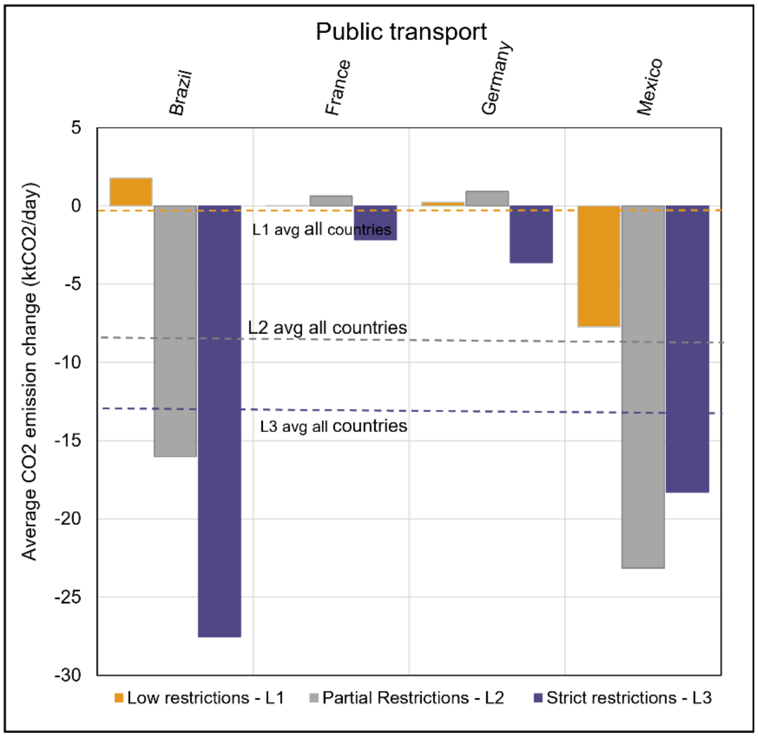

Figure 9 : Average CO_2 change ($ktCO_2$/day) of public transport mode across different confinement levels for selected countries

In the case of France and Germany the L1 and L2 confinement shows a very small average increase in CO_2 emissions of < 1$ktCO_2$/day. This is an increase above the baseline, nonetheless, showing some ray of hope in the recovery of the public transport sector. The average CO_2 emission increase is the result of the rebound effect that occurred over the span of 4-5 months when the stringency index was in L2 confinement. No other country showed an increase in the public transport activity, which resulted in CO_2 emissions. This should be credited to the public transport authorities in both these countries, as they are more developed and have solid infrastructure compared to other developing countries. Hence, they are able to cope with the virus by implementing required health and safety measures and providing the necessary financial aid required to make travel safe and reduce the risk perception of the citizens.

3.6 Difference in CO_2 emissions across waves

Since the effect of confinement levels on the average CO_2 emission change has been addressed, we now focus on the difference in CO_2 emissions between the 1st and the 2nd wave across different countries. From section 4.3 we concluded that the CO_2 emissions in the 2nd wave (or 2nd half) are higher than the 1st wave (or 1st half). A closer focus is on countries that show an interesting difference between both the waves.

3.6.1 Private transport

As we all experienced, most of the countries took drastic measures to tackle the virus during the first wave, which led to the largest decline in 2020, during the months of April and May. The second wave was tackled quite differently for different countries, as a result you can notice that the dotted lines show a 50% rebound in the average CO_2 emissions during the 2nd wave (-45.2 ktCO_2/day) compared to the 1st (-94 ktCO_2/day). Canada is chosen here as it has a typical first and second wave with more or less a constant stringency index, but still shows a difference in the average daily CO_2 emissions between the waves. This is due to the fact that initially, Canada took very stringent measures to curb the virus, leaving around 1 million people jobless with the closure of all non-essentials and economic activities. Once the 1st wave declined, the stringency index dropped resuming non-essential activities like pubs, gyms, restaurants, and cinemas, at limited capacity as well as outdoor and indoor gatherings up to 250 and 50 people, respectively (The Canadian Press, 2020). This continued well into the 2nd wave, up until November, as part of adapting to the new normal and recovering the economy. Although, the stringency index slightly rises thereafter when the cases start increasing and measures were tightened in specific regions which were the epicenter of the covid-19 cases(The Canadian Press, 2020). Allowing other regions to continue operating with socioeconomic activities. This strategy and adaptation to the new normal, explains the increase of average CO_2 emissions in the second wave. 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 CO_2 emissions.

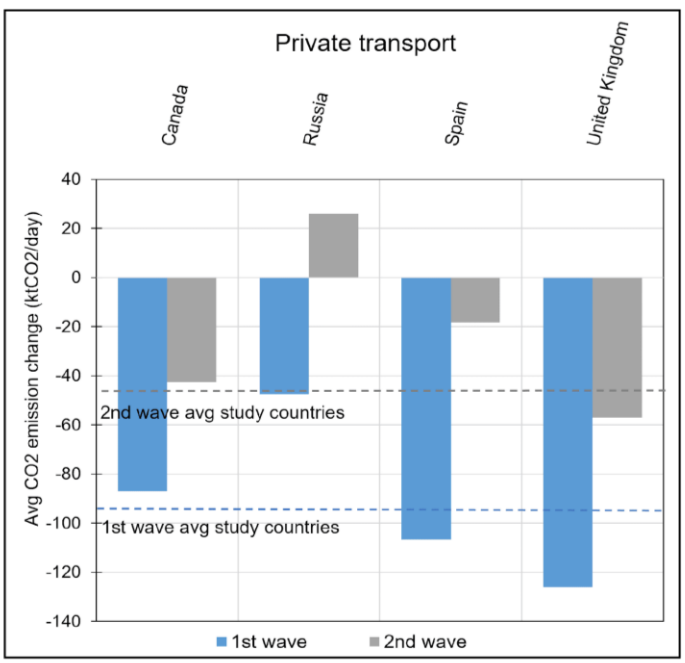

Figure 10 : The difference between average CO_2 change (ktCO_2/day) of private transport mode during the 1st and the 2nd wave for selected countries

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 CO_2 emissions deficit in the 2nd wave. Once the stringency index was increased, the emissions gradually decreased, still remaining higher than the first wave. Now, in the case of Russia, they completely avoided L3 confinement during the 2nd wave. The whole country was under the middle and low range of L2 confinement since August mid. The main reason for this was to recover their economy during the 3rd and 4th quarter of 2020, giving hope to individuals and families that face financial distress and to make up for the loss attained during the 1st wave (Cordell, 2020). The country also wanted to lift the spirits of the people before the political event taking place in 2020, relaxing the measures after Spring (Sauer, 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 CO_2 emission change ended up rebounding the 1st wave reduction and the CO_2 change in the latter half of 2020 completely offset the CO_2 emission reduction during the 1st half. The difference between the waves for the remaining countries can be found in Appendix E.

3.6.2 Public transport

From the average public transport CO_2 emission change of all countries included in the study, it can be deduced that the change between the waves is quite less compared to private transport. The 1st wave & 2nd wave average CO_2 emissions are -12ktCO_2/day and -8 ktCO_2/day, respectively. Focusing on Spain and Brazil, they show the highest average CO_2 reduction during the 1st wave for developed and developing countries. These two countries have a large population using public transport as the main transport mode and contribute significantly to the transport emissions in their respective countries (Appendix B). They both show a significant reduction in CO_2 deficit during the 2nd wave, Spain, more prominent with more than a 50% rebound. Adaptation and necessity to travel definitely plays a role in the increase in emissions in both countries. But also, as explained in section 4.4.2, the developed infrastructure in European countries, Spain taken as an example here, plays a major role as well. 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. These policies have to be followed up by regular inspection to make sure public transport modes are made safe and suitable for travel. This will help get rid of the stigma around public transport not being a safe mode of transport. 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 size that were using public transport pre-covid and the number of people using it now.

Australia displays an unusual trend unlike other countries, showing higher reduction during the 2nd wave of covid-19. If you look back at the CO_2 emission trend graph in section 4.3 you can notice the 2nd wave came quite early in Australia, lasting from July to September. At the time, the fear of contracting the infection and the stigma of public transport being a contagious environment steered people away from public transport, leading to a modal shift into private transport(Infrastructure Australia & L.E.K, 2020) . The stringency index was even higher in the 2nd wave, which led to a constant low in the public transport activity of -60% to-70 %. For the 1st wave, the mobility was declining from the baseline to the lowest peak and remained at the peak for a short while. Hence, the 2nd wave has a higher reduction in CO_2 emissions compared to the first. The difference in CO_2 emission change of the 1st and 2nd wave for public transport of the remaining countries can be found in Appendix E.

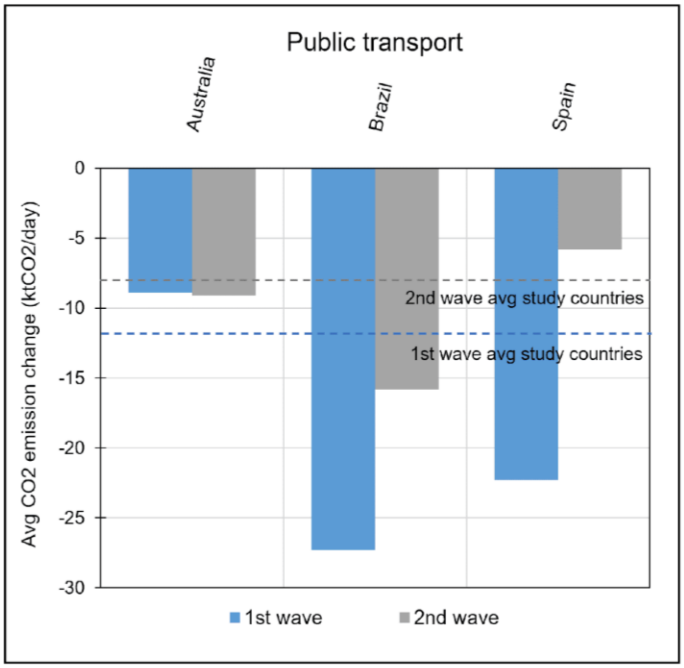

Figure 11 : The difference between average CO_2 change ($ktCO_2$/day) of public transport mode during the 1st and the 2nd wave for selected countries

4. Discussion

The CO_2 emission reduction and mobility trends of surface passenger transport estimated in this study will be discussed in light of known literature and recognized environmental agencies, to validate the findings of this study. An emphasis will be laid on how the activity change and CO_2 emissions trends estimated across different countries can be pragmatic to the road to recovery of surface passenger transport. The short and medium-term effect of human travel behavior resulting in a modal switch from public to private will also be addressed. Followed by the limitations and uncertainties encountered over the course of the study.

As a result of activity changes in the surface passenger transport sector from March 1st, 2020, to Jan 31st , 2021, this study estimates a reduction of 510 $MtCO_2$ in total by the 21 countries included in this study. The CO_2 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 992$MtCO_2$ from March '20 to Jan'21 (Z. Liu et al., 2020) . This estimate is based on tom-tom's traffic congestion data which presumably includes freight transport. There is no disaggregation between passenger and freight neither in carbon monitor nor in the IEA, which estimates a reduction of 1100$MtCO_2$ within the global road transport sector in 2020 (IEA, 2020b). Although, the International Transport Forum (ITF) projects global urban and inter-urban transport emissions to drop by 22% during covid-19 (OECD, 2020). Even if 22% is reduced from the carbon monitor estimate, it cannot validate the findings of this study as global ground transport emissions include major CO_2 emitters like China where a prominent rebound in emissions was experienced (Myllyvirta, 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 2.6GtCO_2eq (1.8 to 3.3 GtCO_2eq) 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), Energy intensity (Improving efficiency of transport modes), and Fuel carbon intensity (using sustainable low-carbon fuels for transport) (IPCC, 2014b). 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 in the dark clouds. 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-month period of this study is continued for the years to come, the 2050 transport sector emissions goals will 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 interpret that the CO_2 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 in fact 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 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 mode's post covid-19 (Stansbury & Alport, 2020). Based on the stringency index and public transport activity data, the activity change in a post-covid-19 world, with no waves and restrictions below stringency index of 30 (L1) can be predicted using the fixed effects model. The average predicted activity change of L1 confinement in North American, Latin American, EU9& UK and Australasian countries is -7.7%, 7.5%, 6.4% and -6.3% compared to baseline of Jan 13^{th,} 2020, respectively. As the predicted activity change is based on data collected from March 1st , and since the surveys conducted cannot be quantified as the outcome is still yet to happen, a comparison made would be invalid. A future research possibility lies within this gap to determine or model the demand of public transport post covid-19. 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 policy makers 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 the needs of the public. To attract and build back the trust of transport user, the vehicle must be disinfected after every trip, travelling 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'Incà & Cresci, 2020). For example, New York uses UV light to disinfect the subways and buses, while France uses AI to check whether people are wearing masks; additionally, the UK uses AI to prevent overcrowding and encourage social distancing (D'Incà & Cresci, 2020). Data regarding how crowded the public transit mode is should also 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 Netherlands, Singapore, UK, France, US, and Canada (UITP, 2021). Other emerging economies that are dependent on their transit modes, namely Philippines, Indonesia, South Africa, Brazil, Mexico, and Argentina are also urged to be proactive and join other countries to take part in the transition to ZEB while rebuilding their infrastructure. The cost of successfully executing and sustaining these extra safety measures would be quite high, financial support and subsidies from the governments to public transit authorities and operators is a necessity. It will particularly be harder in emerging economies to maintain this level of extra measures since an economic downfall was also experienced as a result of covid-19 confinements. It is up to the governments and transport authorities to find a financial solution to reverse the covid-19 modal switch theme.

4.2 Transit service reduction

As public ridership reduced 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, CO_2 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 CO_2 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 transit authorities were unable to pay their employee wages and 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'Incà & Cresci, 2020). As London experienced a major reduction in number of passengers, 40 transit stations were shut down, followed by cutting down on routes and frequencies of bus, train, and tram services; additionally , Washington D.C saw a 40-50% reduction in frequency of train services as 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 baseline which makes it difficult to estimate the CO_2 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 CO_2 reduction of 30-50%. On average, this would be a close overestimate based on the CO_2 reduction estimated from activity change.

4.3 Limitations and Assumptions

During the course of the study, multiple limitations have been encountered, in terms of data availability, heterogeneity of data sources, age of data, sample size of study, etc., which will all be addressed in this section. One of the main limitations encountered is that private and public passenger transport CO_2 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 CO_2 estimation using activity change gave rise to multiple uncertainties. Firstly, the direct CO_2 emissions from the transport sector are unable to be accounted for, due to the insufficient real time data. Secondly, both the mobility data sources provided have a different baseline in early 2020. This affects seasonality of the dataset (Schultes-Fischedick, 2021)and the comparison to 2019 activity change values impractical. 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 fraction of transport modes, most emerging economies had data only available for the year 2014 or earlier. It was scaled up to 2018 for countries with information regarding growth rate, otherwise it was assumed transport mode emission fractions levels of 2014 or earlier remain the same in 2018 (Appendix B). These uncertainties hinder the possible capacity of CO_2 estimation during covid-19. As mentioned in the above section, lack of data regarding service reduction in different countries also limits the scope of CO_2 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, 2020b). 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 4 countries included in this study. Moreover, the percentage change in volume of search route requests provided by apple, also leads to a discrepancy of CO_2 estimation within the study.

5. Conclusions

Within the scope of this study, CO_2 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 CO_2 emissions were estimated for 21 countries and public transport for 17 countries. As per the estimates a total of 510 $MtCO_2$ were saved during the 11-month period, which signifies a 5.9% reduction in the global transport sector and 1.6% reduction in the total global CO_2 emissions. It was determined that the EU9 countries & UK had a similar trend throughout the study period, in terms of CO_2 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 CO_2 , 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 CO_2 emissions through the second half of the study period. The private transport showed a much more pronounced recovery relative to public transport. Australia's recovery of the private and public transport sector was dependent on the waves and the stringency index. Public transport CO_2 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 estimated after the 1st wave. The CO_2 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 1st half CO_2 emissions in Russia.

In general all countries exhibited an increase in CO_2 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 CO_2 emission was more pronounced in private transportation of emerging economies as it was critical to recover 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 stringent measures (Beswik, 2020). In the case of Czechia, the rebound effect offset the CO_2 reduction during the 1st wave and hence a pronounced CO_2 reduction during the 2nd wave was exhibited. By highlighting the CO_2 difference between the waves, despite a significant stringency index, the research question formulated is acknowledged. The CO_2 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 CO_2 reduction in public transport as they are more dependent on public transit mode. Public transport sector in EU9 & UK showed a quicker recovery compared to other regions in the study. This is credited to the adaptation and implementation of necessary measures to make travel safe and comfortable again.

Lastly, the road to recovery and human travel behavior post covid-19 was discussed. The crucial pathway for the road to recovery is that; it should primarily be focused on redesigning public transport infrastructure by implementing extra measures in order to create a safe, comfortable , and convenient environment to regain the confidence of transit users. It is of extreme importance to attract the transit users who have shifted toward private modes of transport. The estimations of the study give us an idea of public transport activity trend during covid-19 and when stringency index is low. The post-covid-19 short- and medium-term transit demand is speculated to gradually increase, provided necessary measures are implemented in all countries included in the study. 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.

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7. Appendix

Appendix A: Activity change correlation coefficients of all 21 countries

Country	Argentina	Australia	Belgium	Brazil	Canada	Czechia	France	Germany	Indonesia	Italy	Mexico	Netherlands	Philippines	Russia	Singapore	SA	Spain	Sweden	Switzerland	UK	USA
Argentina	1.00	0.83	0.36	0.83	0.23	0.01	0.32	0.17	0.68	-0.01	0.75	0.10	0.83	0.24	0.69	0.68	0.23	-0.04	0.43	0.35	0.41
Australia	0.83	1.00	0.53	0.82	0.36	0.17	0.41	0.25	0.66	0.19	0.72	0.26	0.86	0.40	0.79	0.79	0.32	0.05	0.46	0.44	0.54
Belgium	0.36	0.53	1.00	0.61	0.90	0.81	0.85	0.85	0.63	0.81	0.61	0.90	0.68	0.64	0.59	0.57	0.82	0.68	0.84	0.86	0.91
Brazil	0.83	0.82	0.61	1.00	0.54	0.27	0.52	0.47	0.77	0.30	0.85	0.38	0.86	0.47	0.80	0.81	0.47	0.19	0.63	0.62	0.64
Canada	0.23	0.36	0.90	0.54	1.00	0.83	0.84	0.88	0.64	0.86	0.58	0.90	0.54	0.66	0.53	0.49	0.89	0.73	0.82	0.90	0.90
Czechia	0.01	0.17	0.81	0.27	0.83	1.00	0.83	0.87	0.32	0.87	0.20	0.83	0.30	0.57	0.19	0.16	0.83	0.80	0.77	0.68	0.70
France	0.32	0.41	0.85	0.52	0.84	0.83	1.00	0.88	0.61	0.82	0.45	0.72	0.54	0.65	0.45	0.36	0.90	0.80	0.91	0.76	0.80
Germany	0.17	0.25	0.85	0.47	0.88	0.87	0.88	1.00	0.52	0.83	0.44	0.81	0.44	0.63	0.38	0.33	0.86	0.82	0.89	0.81	0.79
Indonesia	0.68	0.66	0.63	0.77	0.64	0.32	0.61	0.52	1.00	0.39	0.87	0.51	0.79	0.52	0.77	0.77	0.63	0.35	0.65	0.70	0.72
Italy	-0.01	0.19	0.81	0.30	0.86	0.87	0.82	0.83	0.39	1.00	0.26	0.80	0.31	0.67	0.33	0.25	0.86	0.78	0.75	0.73	0.72
Mexico	0.75	0.72	0.61	0.85	0.58	0.20	0.45	0.44	0.87	0.26	1.00	0.47	0.82	0.43	0.85	0.86	0.47	0.19	0.54	0.73	0.67
Netherlands	0.10	0.26	0.90	0.38	0.90	0.83	0.72	0.81	0.51	0.80	0.47	1.00	0.46	0.55	0.41	0.43	0.78	0.69	0.70	0.81	0.86
Philippines	0.83	0.86	0.68	0.86	0.54	0.30	0.54	0.44	0.79	0.31	0.82	0.46	1.00	0.44	0.78	0.79	0.48	0.23	0.62	0.59	0.70
Russia	0.24	0.40	0.64	0.47	0.66	0.57	0.65	0.63	0.52	0.67	0.43	0.55	0.44	1.00	0.47	0.45	0.67	0.49	0.63	0.65	0.60
Singapore	0.69	0.79	0.59	0.80	0.53	0.19	0.45	0.38	0.77	0.33	0.85	0.41	0.78	0.47	1.00	0.84	0.48	0.16	0.50	0.64	0.61
SA	0.68	0.79	0.57	0.81	0.49	0.16	0.36	0.33	0.77	0.25	0.86	0.43	0.79	0.45	0.84	1.00	0.37	0.07	0.41	0.63	0.63
Spain	0.23	0.32	0.82	0.47	0.89	0.83	0.90	0.86	0.63	0.86	0.47	0.78	0.48	0.67	0.48	0.37	1.00	0.79	0.84	0.82	0.78
Sweden	-0.04	0.05	0.68	0.19	0.73	0.80	0.80	0.82	0.35	0.78	0.19	0.69	0.23	0.49	0.16	0.07	0.79	1.00	0.73	0.64	0.62
Switzerland	0.43	0.46	0.84	0.63	0.82	0.77	0.91	0.89	0.65	0.75	0.54	0.70	0.62	0.63	0.50	0.41	0.84	0.73	1.00	0.76	0.79
UK	0.35	0.44	0.86	0.62	0.90	0.68	0.76	0.81	0.70	0.73	0.73	0.81	0.59	0.65	0.64	0.63	0.82	0.64	0.76	1.00	0.83
USA	0.41	0.54	0.91	0.64	0.90	0.70	0.80	0.79	0.72	0.72	0.67	0.86	0.70	0.60	0.61	0.63	0.78	0.62	0.79	0.83	1.00

Table 8: The correlation coefficients of private transport activity change(Waze's % change in km's driven) for all countries included in the study.

Country	Australia	Belgium	Brazil	Canada	Czechia	France	Germany	Italy	Mexico	Netherlands	Philippines	Singapore	Spain	Sweden	Switzerland	UK	USA
Australia	1.00	0.45	0.83	0.54	0.25	0.32	0.21	0.17	0.80	0.32	0.90	0.68	0.63	0.11	0.31	0.49	0.68
Belgium	0.45	1.00	0.64	0.80	0.80	0.95	0.89	0.88	0.66	0.79	0.55	0.50	0.90	0.80	0.93	0.84	0.78
Brazil	0.83	0.64	1.00	0.68	0.35	0.53	0.45	0.39	0.90	0.46	0.84	0.74	0.78	0.30	0.52	0.71	0.78
Canada	0.54	0.80	0.68	1.00	0.82	0.74	0.79	0.68	0.80	0.92	0.57	0.38	0.82	0.73	0.81	0.89	0.95
Czechia	0.25	0.80	0.35	0.82	1.00	0.79	0.85	0.82	0.45	0.94	0.29	0.14	0.72	0.85	0.89	0.71	0.69
France	0.32	0.95	0.53	0.74	0.79	1.00	0.90	0.92	0.56	0.76	0.41	0.48	0.84	0.83	0.93	0.79	0.70
Germany	0.21	0.89	0.45	0.79	0.85	0.90	1.00	0.94	0.52	0.86	0.30	0.33	0.80	0.93	0.97	0.84	0.72
Italy	0.17	0.88	0.39	0.68	0.82	0.92	0.94	1.00	0.44	0.79	0.28	0.40	0.80	0.90	0.94	0.75	0.61
Mexico	0.80	0.66	0.90	0.80	0.45	0.56	0.52	0.44	1.00	0.61	0.81	0.70	0.79	0.39	0.56	0.80	0.88
Netherlands	0.32	0.79	0.46	0.92	0.94	0.76	0.86	0.79	0.61	1.00	0.38	0.24	0.76	0.84	0.86	0.83	0.81
Philippines	0.90	0.55	0.84	0.57	0.29	0.41	0.30	0.28	0.81	0.38	1.00	0.69	0.73	0.21	0.39	0.55	0.72
Singapore	0.68	0.50	0.74	0.38	0.14	0.48	0.33	0.40	0.70	0.24	0.69	1.00	0.68	0.19	0.38	0.53	0.52
Spain	0.63	0.90	0.78	0.82	0.72	0.84	0.80	0.80	0.79	0.76	0.73	0.68	1.00	0.69	0.86	0.85	0.85
Sweden	0.11	0.80	0.30	0.73	0.85	0.83	0.93	0.90	0.39	0.84	0.21	0.19	0.69	1.00	0.91	0.74	0.65
Switzerland	0.31	0.93	0.52	0.81	0.89	0.93	0.97	0.94	0.56	0.86	0.39	0.38	0.86	0.91	1.00	0.82	0.75
UK	0.49	0.84	0.71	0.89	0.71	0.79	0.84	0.75	0.80	0.83	0.55	0.53	0.85	0.74	0.82	1.00	0.87
USA	0.68	0.78	0.78	0.95	0.69	0.70	0.72	0.61	0.88	0.81	0.72	0.52	0.85	0.65	0.75	0.87	1.00

Table 9: The correlation coefficients of public transport activity change (Apple's % change in volume of search route request) for all countries included in the study.

The segregation of the countries into their regions was carried out based on the correlation coefficient results shown in table 8 and 9. The values highlighted in green show that there is a high correlation between those countries, whereas red show a low correlation. It can be noticed that EU 9 & UK have a high correlation among themselves in private and public transport. Similarly, Latin American countries and North American countries have high correlation as mentioned in section 3.1 .

Appendix B: Emission factor of private and public transport in different countries pre-covid-19

Country	Annual transport CO_2 emission ($MtCO_2$) [1]	Emissions factor (%)		Source & Year
		Private transport	Public transport	
Argentina	48.0	39%	-	https://www.researchgate.net/publication/341379506_Decarbonising_Argentina's_Transport_System_Charting_the_Way_Forward (2014)
Australia	104.4	61%	6%	https://www.bitre.gov.au/publications/2020/australian-infrastructure-statistics-yearbook-2020 (2018)
Belgium	25.6	55%	6%	https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16 (2018)
Brazil [2]	192.0	45%	10%	https://iema-site-staging.s3.amazonaws.com/2014-05-27inventario2013.pdf (2012)
Canada	193.3	39%	1%	https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=tran&juris=on&rn=8&page=0 (2018)
Czechia	19.9	61%	6%	https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16 (2018)
France	126.2	53%	1%	https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16 (2018)
Germany	164.2	59%	2%	https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16 (2018)
Indonesia	154.2	53%	-	https://www.esdm.go.id/assets/media/content/content-indonesia-energy-outlook-2019-english-version.pdf (2018)
Italy	103.6	64%	9%	https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16 (2018)
Mexico	157.1	46%	8%	http://www.aire.cdmx.gob.mx/descargas/publicaciones/flippingbook/inventario-emisiones-2016/mobile/inventario-emisiones-2016.pdf (2016)
Netherlands	31.7	57%	2%	https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16 (2018)
Philippines	35.7	54%	4%	https://openknowledge.worldbank.org/bitstream/handle/10986/27900/647540WP0Box360ort0and0Pow00PUBLIC0.pdf?sequence=1&isAllowed=y (2007)
Russia	294.1	44%	-	https://aiche.onlinelibrary.wiley.com/doi/epdf/10.1002/ep.12671 (2018)
Singapore	8.1	20%	12%	https://cms.uitp.org/wp/wp-content/uploads/2020/08/The-Governance-of-PT-Market-Singapore-report.pdf ; https://www.lihaoyi.com/post/SmartNation/StatisticsInBrief.pdf (2015)
South Africa	60.0	33%	-	https://www.fiafoundation.org/media/461198/south-africa-pv-emission-stds_icct-white-paper_17012018_vf-1.pdf (2015)
Spain	93.5	57%	12%	https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16 (2018)
Sweden	16.5	61%	10%	https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16 (2018)
Switzerland	15.9	74%	10%	https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16 (2018)
United Kingdom	121.9	71%	40%	https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16 (2018)
United States	1 767.8	53%	20%	https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100ZK4P.pdf (2018)

Note:
1- Transport emissions data available at (IEA, 2020a) -> check reference
2- Private and public transport 2012 emissions factor has been scaled up to 2018 by using emission growth rate/ year. https://theicct.org/sites/default/files/publications/ICCT%20Roadmap%20Energy%20Report.pdf

Table 10: Displays the annual transport CO_2 of all the 21 countries included in the study as well as the emissions factor of the private and public transport and the source of the data.

The data displayed in table 10 is used to estimate the CO_2 emission change of the transport modes. The latest year of data available for all EU9 + UK countries, Canada, United states and Australia is 2018. The latest year of data available for the other countries are before 2018. In cases where the emission growth rate is available the emission factor is scaled up to the year 2018. Otherwise it is assumed that there has been no change in the transport infrastructure and emissions factors from the respective year to 2018.

Appendix C: Private and public transport CO_2 emission trends of the remaining countries.

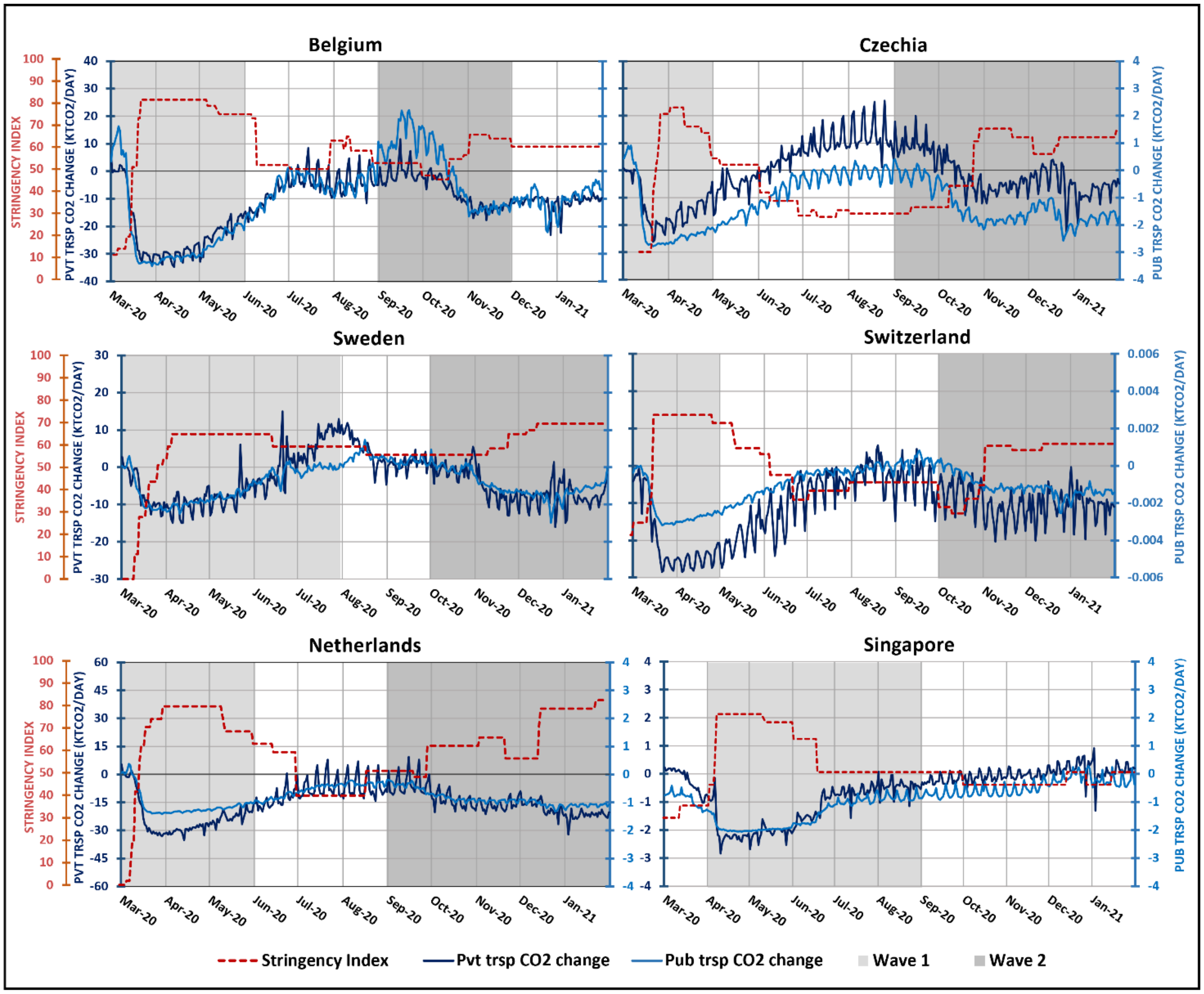

Figure 12 : Daily CO_2 emission trend of private and public transport for the remaining countries over the entire study period.

From figure 10 it can be noticed that the EU countries follow a similar trend to the EU9+UK countries as mentioned in section 3.3. They display a mid-study period rebound effect after the first wave and before the start of the second followed by a dip during the second wave. It can also be noticed that Sweden has a higher stringency index and displays a slightly higher CO_2 reduction during the 2nd wave. This is because they aimed to achieve herd immunity during the first wave and failed to do so, forcing them to implement more stringent measures during the 2nd wave (Beswik, 2020). Whereas Singapore only has one wave after which covid-19 cases have been under countrol in the country. Consequently the stringency index remains low as socio-economic activities resume. This explains the quicker reduction in CO_2 deficit compared to other Asian countries included in the study.

Appendix D: Average CO_2 change of all 21 countries during different confinement levels

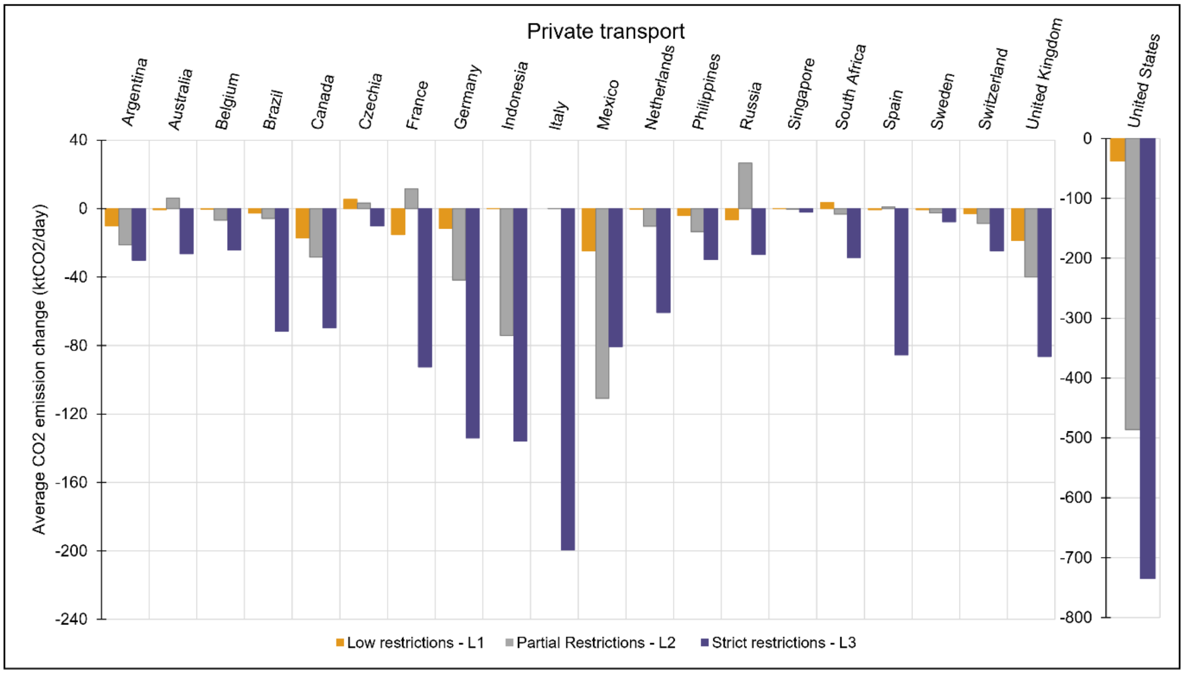

Figure 13 : Average CO_2 change ($ktCO_2/day$) of private transport mode across different confinement levels for all countries

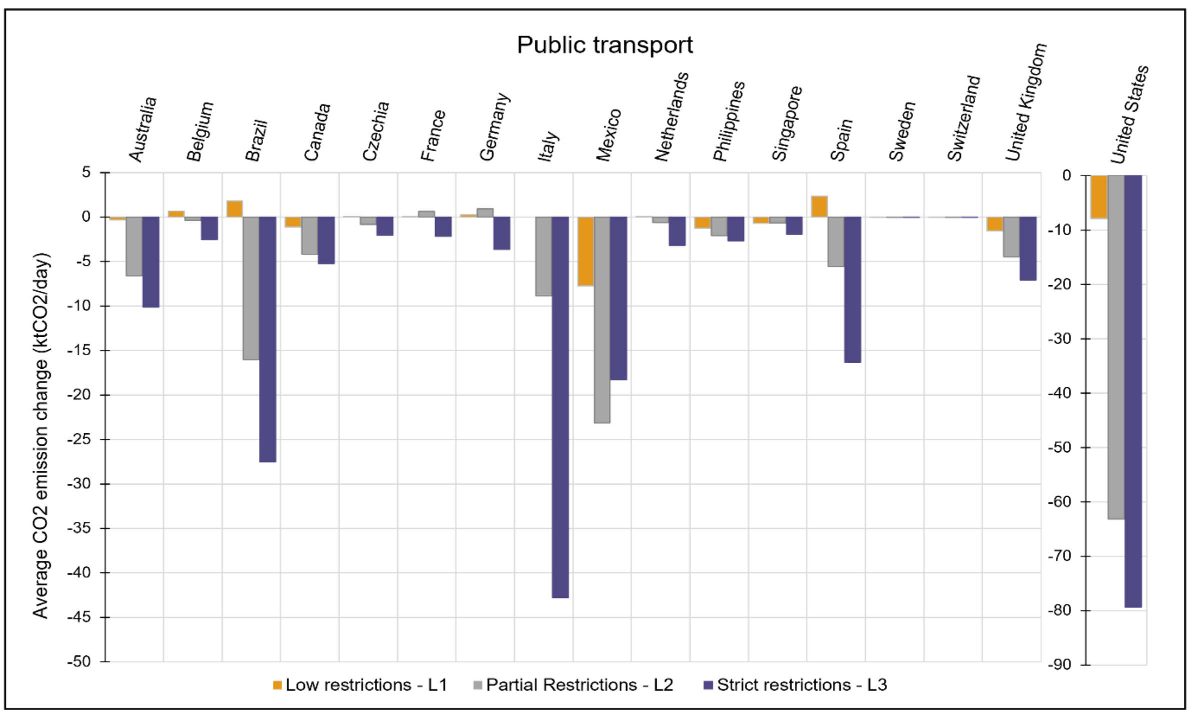

Figure 14 : Average CO_2 change ($ktCO_2/day$) of public transport mode across different confinement levels for all countries

Appendix E: Average CO_2 change during the 1st and 2nd wave of all 21 countries

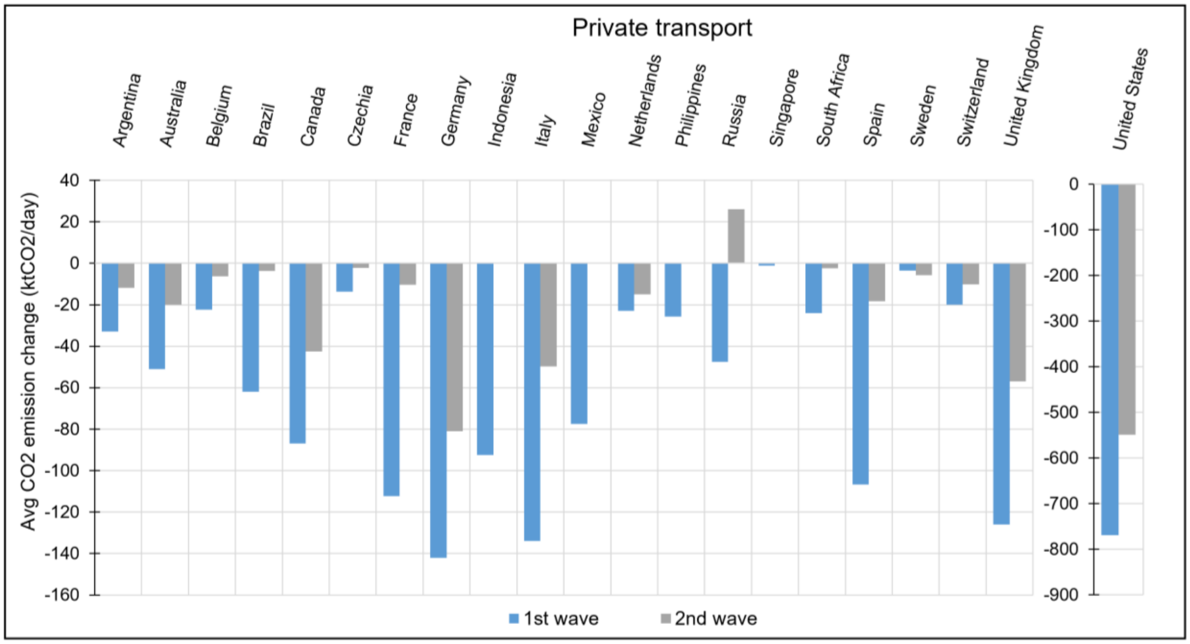

Figure 15 : The difference between average CO_2 change ($ktCO_2/day$) of private transport during the 1st and the 2nd wave

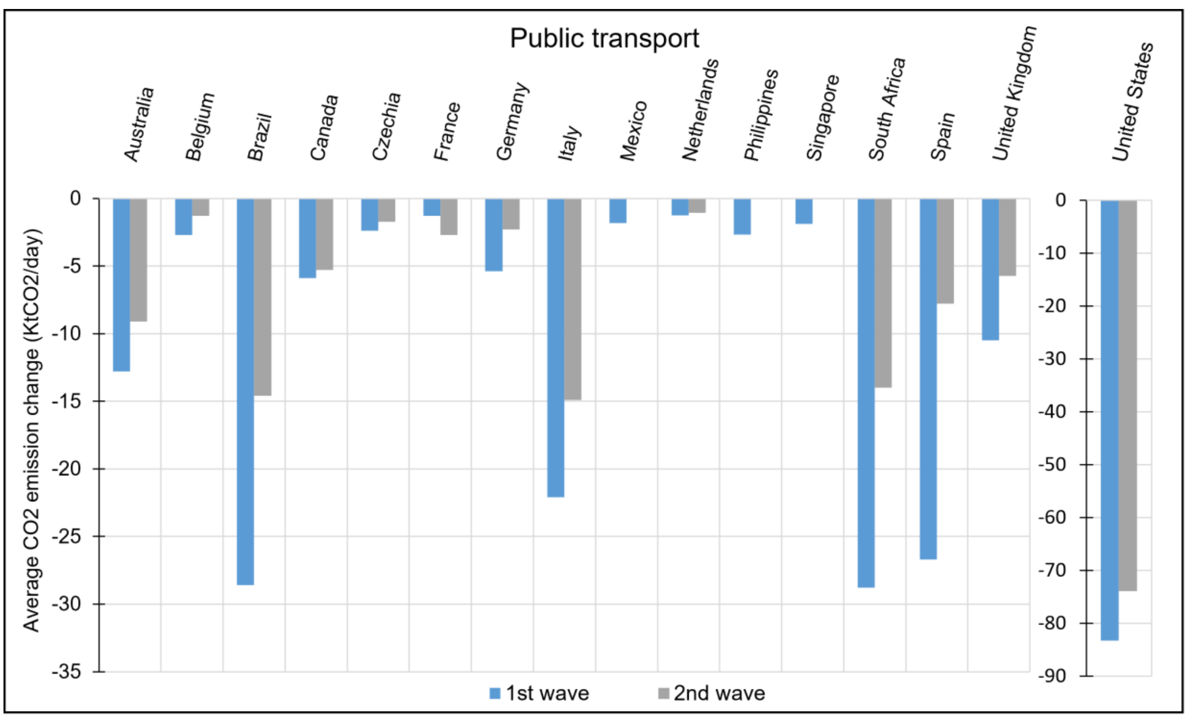

Figure 16 : The difference between average CO_2 change ($ktCO_2/day$) of public transport during the 1st and the 2nd wave

Appendix F: Cumulative CO_2 reduction of all 21 countries.

Countries	Cumulative CO2 change	Mean daily CO2 change	Total transport emissions pre covid-19 (2018) [1]	Mean daily CO2 change pre covid-19 (2018)	CO2 reduction compared to 2018 baseline	% CO2 reduction
	MtCO2	MtCO2/day	MtCO2	MtCO2/day		
Argentina	-9.74	-0.03	47.99	0.13	-0.22	-22%
Australia	-7.62	-0.02	104.36	0.29	-0.08	-8%
Belgium	-4.12	-0.01	25.60	0.07	-0.18	-18%
Brazil	-23.94	-0.07	191.98	0.53	-0.14	-13%
Canada	-21.28	-0.06	193.32	0.53	-0.12	-11%
Czechia	-0.89	0.00	19.93	0.05	-0.05	-5%
France	-11.96	-0.04	126.16	0.35	-0.10	-10%
Germany	-24.25	-0.07	164.16	0.45	-0.16	-16%
Indonesia	-30.97	-0.09	154.24	0.42	-0.22	-22%
Italy	-21.70	-0.06	103.56	0.28	-0.23	-23%
Mexico	-31.78	-0.09	157.15	0.43	-0.22	-22%
Netherlands	-5.46	-0.02	31.72	0.09	-0.19	-19%
Philippines	-9.51	-0.03	35.73	0.10	-0.29	-29%
Russia	0.34	0.00	294.10	0.81	0.00	0%
Singapore	-0.51	0.00	8.12	0.02	-0.07	-7%
South Africa	-5.75	-0.02	60.02	0.16	-0.10	-10%
Spain	-19.30	-0.06	93.47	0.26	-0.22	-22%
Sweden	-1.07	0.00	16.49	0.05	-0.07	-7%
Switzerland	-3.74	-0.01	15.91	0.04	-0.26	-26%
United Kingdom	-27.30	-0.08	121.88	0.33	-0.24	-24%
United States	-249.42	-0.74	1767.77	4.84	-0.15	-15%

Table 11: Displays cumulative CO_2 reduction during the entire study period and the % CO_2 reduction of all 21 countries. [1] refer to (IEA,2020a)