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Beyond short-term impact of COVID-19 on transport decarbonization: a scenario analysis of passenger and freight transport by mode in China, 2020–2030

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Abstract

Background The processes of transport decarbonisation are complicated. In this paper, we adopt the Activity-Modal Share-Energy Intensity-Carbon Intensity of Fuel (ASIF) approach and propose a conceptual framework on the direct and indirect impact of COVID-19 on transport CO_2 emissions. In the Chinese context, changes of carbon emissions associated with passenger and freight transport (including urban, rural, and inter-city transport) across different transport modes are estimated. Scenario analysis is then used to estimate the impact of COVID-19 on total transport carbon emissions up to 2030. Four scenarios, from minimal to significant behavioural changes and global recession associated with COVID-19, are generated.

Results Under the pandemic, the transport system in China was estimated to have produced 28% less CO_2 emissions (1044.2 Mt) in 2020, when compared to 2019. Compared with the business-as-usual scenario, the estimated total transport carbon emissions in 2030 would drop by 6%, 15%, and 21% and 23% under the minimal-impact, low-impact, moderate-impact, and severe-impact scenarios, respectively.

Conclusions The results suggest that the processes triggered by COVID-19 alone will not be sufficient to meet the ambitious transport decarbonisation targets. To meet China's pledge under the United Nations Framework on Climate Change, the medium-term effects of COVID-19 must be combined with strong transport decarbonisation measures of modal shift and new energy applications. With these additional measures, it may be possible to advance the transport carbon peak before 2030. Lessons are relevant to other developing countries.

Keywords COVID-19, Transport decarbonisation, China, Modal shift, Renewable energy

Background

Carbon dioxide (CO_2) from energy consumption has been the primary source of greenhouse gas emissions and has attracted worldwide attention due to its association with climate change [1]. Despite the success of decarbonisation measures in various key sectors such as electricity generation, the past few decades have seen the worsening of transport CO_2 emissions in absolute terms, except during brief periods of natural disasters and economic crisis [2]. From 2008 to 2018, the share of transport in the total world CO_2 emissions rose from 23.5% to 24.6%

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[3]. During this period, the total world CO_2 emissions have also increased steadily from 29,209.4 Mt in 2008 to 33,513.3 Mt in 2018 [3].

Historically, development has been closely linked to rapid motorisation and industrialisation [4]. Hence, the reduction of transport-related carbon emissions poses a significant challenge for emerging and developing economies. According to the United Nations, the three largest developing economies in the world are China, India, and Brazil [5]. In China, CO_2 emissions from the transport sector increased from 512 Mt in 2008 to 925 Mt in 2018 (44.69% increase). During the same period, India saw a rise from 163 to 305 Mt (87.12% increase), and Brazil's emissions grew from 151 to 192 Mt (27.15% increase). In contrast to the world's average annual growth rate of 1.9%, China, India and Brazil experienced much faster rates at 6.1%, 6.5%, and 2.4%, respectively. The global spread of Coronavirus (COVID-19) in 2019 was associated with reductions in transport-related carbon emissions worldwide due to varying levels of travel restriction policies. While most existing studies focused on the pandemic's short-term impact on transport carbon emissions, they have largely neglected its medium- and long-term effects, such as changes in people's travel behaviour and the onset of an economic recession [6–8]. The potential medium- to long-term effects of COVID-19 on transport-related carbon emissions remain uncertain.

Theories from diverse disciplines offer insights into the pathways of transport decarbonisation. For instance, in the realm of the development of economics, the Environmental Kuznets Curve suggests that as economic development progresses, environmental pollution initially exacerbates and then gradually ameliorates. In developing countries, rapid economic growth triggers a substantial surge in transport demand, outpacing the rate of energy transition. Consequently, transport-related carbon emissions continue to rise, except during special circumstances such as natural disasters, pandemics or economic crises, which temporarily mitigate emissions. The potential of transforming short-term shock effects into sustained reductions of transport-related carbon emissions in developing regions remains unknown. From the perspective of energy economics, enhancing energy efficiency within a transport system can effectively reduce transport-related carbon emissions. These measures include improving fuel efficiency, promoting the development of electric and hybrid vehicles, and transitioning from conventional fuels to renewable energy sources. While 80% of the world's total power production comes from fossil fuels, this percentage has been steadily declining due to ongoing energy transitions [9]. Nevertheless, the extent to which COVID-19 accelerates or hampers the transformation of energy structure in developing countries remains a topic of debate [10, 11]. From an ecological economics viewpoint, the willingness to pay to mitigate carbon emissions in transport varies across demographic groups. For instance, younger individuals with stronger environmental awareness are more inclined to pay to reduce air pollution and actively lower their personal travel-related carbon emissions [12]. However, research addressing the long-term impact of COVID-19 on individual travel behaviour is still lacking. In summary, there is insufficient theoretical and empirical attention to the medium- and long-term effects of the pandemic on transport-related carbon emissions. Hence, this study aims to incorporate previously overlooked "shock events" like COVID-19 into the overall framework of energy and ecological economics. Specifically, it seeks to explore the medium- and long-term energy-environmental impact and their influence on transport carbon emissions by addressing the following research questions: Will COVID-19 bring medium- and long-term impact on transport-related carbon emissions? Will the effects differ by different transport modes? What are the underlying mechanisms?

This paper uses the Activity-Structure-Intensity-Fuel (ASIF) approach to delve into the effects of COVID-19 on CO_2 emissions from the transport sector in China. The ASIF approach was first proposed by the International Energy Agency (IEA) in 1997 [13] and was expanded based on the IPAT framework, which considers environmental impact (I) as the product of population (P), affluence (A), and technology (T). As an extension, the ASIF approach models transport carbon emissions as the result of travel activities (A) measured in passenger-km or ton-km, modal structure (S) represented by the modal share of passenger-km or ton-km share, the fuel intensity of each mode (I) indicated by the fuel consumption per passenger-km or ton-km, and the carbon emission factor of the fuel (F) captured by the carbon emission per litre of fuel [14].

Under the ASIF approach, A is, in turn, influenced by population, income, and urban form, among other factors. S is affected by income, motorisation rate, infrastructure, service provision, relative costs, and urban form. I is influenced by engine type, vehicle load, vehicle age, congestion levels, capacity mix, and urban form. F is shaped by fuel type, engine type, vehicle technology, vehicle age, temperature, and altitude [14]. Since the late 1990s, the ASIF approach has been widely used [15–18] because it provides a flexible "bottom-up" framework with minimal data requirements. The approach can be applied to the entire transport sector or specific transport modes. Furthermore, differences in factors influencing transport carbon emissions across different regions and in different time periods can be compared

[19]. Besides, as each factor encompasses several more detailed driving forces, the approach can be used for decomposition analysis and for deriving policy implications based on the underlying mechanisms [20]. Notably, the strategy of "switch, improve, and finance" has been proposed to enhance urban and transport planning for achieving transport decarbonisation [21]. In sum, the ASIF approach has been widely used for (1) modelling, analysing, and forecasting transport carbon emissions; (2) evaluating the impact of new infrastructure or technology on transport carbon emissions; and (3) providing policy implications for transport decarbonisation [22, 23].

To estimate and forecast the impact of COVID-19 on transport CO_2 emissions, the first step is to estimate changes during the pandemic (from 2019 to 2022) when strict travel restrictions and other quarantine measures were implemented. Due to the lack of real-time monitoring data of transport carbon emissions, the estimation methods from [24] and [25] are adopted to examine changes in transport carbon emissions by different transport modes for both passengers and freight in the short term. Then, scenario analysis is used to estimate the long-term impact up to 2030. The following two sections introduce the conceptual framework and the methodology, respectively. Both the conceptual framework and methodology are applicable to other developing countries where people are not (yet) automobile-dependent, and the economy is highly dependent on primary and secondary industries. Subsequently, estimations regarding changes in CO_2 emissions from different transport modes are presented. Finally, some implications for reducing transport carbon emissions are discussed.

Methods

Conceptual framework

In December 2019, COVID-19 began to spread in Wuhan, China. In January 2020, the Chinese government took drastic actions and implemented strict lockdown measures to restrict out-of-home activities in most parts of the country [6]. A study suggests that carbon emissions in China were cut by nearly a quarter in early February 2020 [7]. With the global spread of the pandemic, other countries also started implementing various non-pharmaceutical interventions (NPIs), forcing behavioural changes across different life domains [26, 27]. According to the IEA [8], the drop-in energy demand during COVID-19 might have resulted in an annual decline in carbon emissions of about 8% worldwide. In Canada, transport carbon emissions in 2021 were about 75% compared to the business-as-usual scenario [28]. In Lahti, Finland, COVID-19 led to a 40% reduction of mobility and a 40% reduction of urban transport carbon emissions in the spring of 2020 [29]. In Indonesia, a 33% reduction was recorded due to the lockdown policies from March to November in 2020 [30]. Beyond the short-term impact, a study on the transport sector in selected global cities argues that the impact of COVID-19 is likely to persist due to fundamental shifts in transport demand and preferences [28]. However, the extent to which these behavioural changes may persist after the pandemic is uncertain.

The short-term impact of COVID-19 also varied by different transport modes. Global air transport suffered significantly with a substantial drop in passenger travel demand, though not in cargo transport; some also argued that COVID-19 may accelerate the development of low-carbon air transport by combining policies on using synthetic fuels and increasing fuel efficiency during the pandemic recovery [31, 32]. It was also expected that the pandemic would provide an opportunity for a switch to railways from carbon-intensive air travel [33]. Concerning urban transport, the increased use of private cars and decreased public passenger patronage can negatively impact transport decarbonisation [34, 35]. Furthermore, the mechanisms influencing COVID-19's impact on transport carbon emissions go beyond behavioural changes. Changes in the economy, such as the shutdown of factories and services, decline in investment, reductions in household consumption expenditure, and lower production efficiency across different transport modes, may also be long lasting [36, 37]. It still remains unclear whether COVID-19 would lead to lower transport carbon emissions in the medium- and long-term. Additionally, none of the existing studies have focused on the transport sector in developing countries, providing an in-depth analysis by different transport modes [8, 38, 39].

The processes of transport decarbonisation are heavily dependent on technological breakthroughs and various socio-economic transitions, such as lifestyle transformations and shifts in economic structure [40, 41]. Hence, a conceptual framework incorporating behavioural changes and global economic influences is proposed to capture the direct and indirect mechanisms associated with the COVID-19 recovery. As depicted in Fig. 1, the total transport CO_2 emissions are mainly affected by the four components (A, S, I and F) of the ASIF approach. Factors like transport demand and modal shares depend on travel behaviour and are directly influenced by COVID-19 in the short run due to various NPIs. In the long run, the influence will be more indirect, primarily through behavioural and economic changes. With the mechanisms shown in Fig. 1, this study attempts to trace and assess the possible effects of COVID-19 on transport CO_2 emissions and recommend measures to accelerate transport decarbonisation [42].

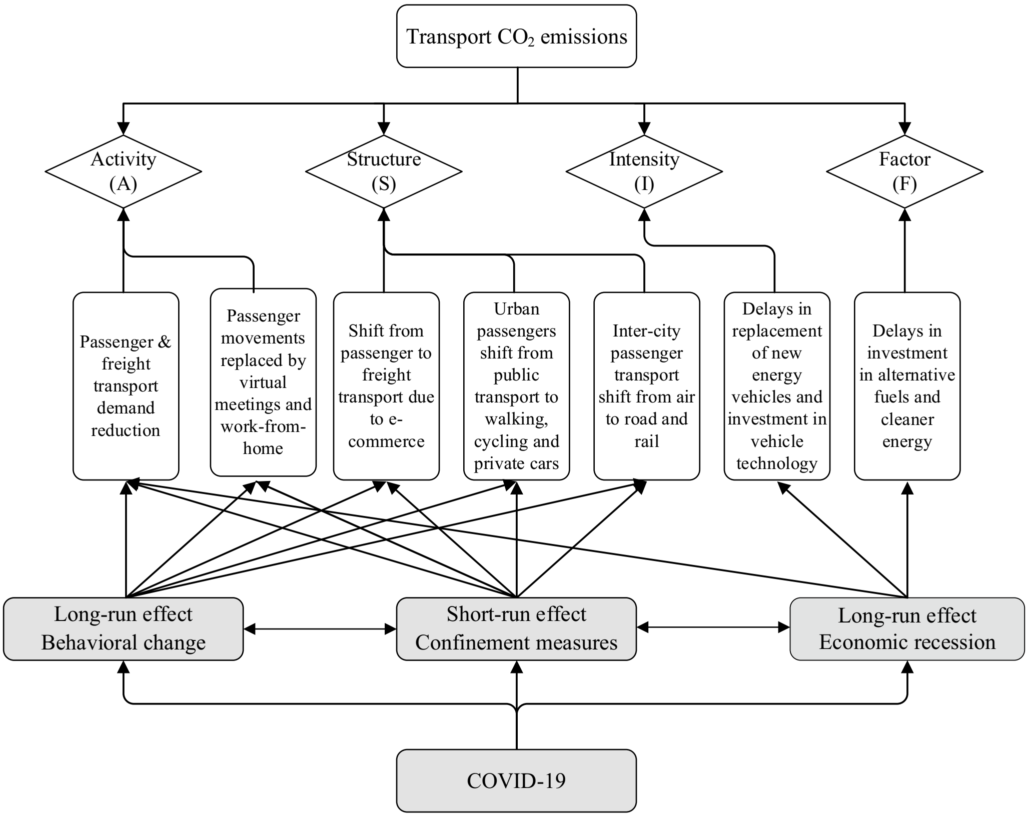

Fig. 1 A conceptual framework about COVID-19 and transport CO_2 emissions

Under COVID-19, various NPI measures have been implemented. They include social distancing, restrictions on human mobility/gatherings, and lockdowns [27]. These measures have implications for both passenger and freight transport. For instance, journeys to work may be replaced by e-working and flexible work-from-home (WFH) arrangements [43]. Other passenger movements may be substituted by telecommunications through online teaching and learning, e-shopping, and other virtual activities. Some passenger travels may also have shifted to freight transport through home delivery services. Additionally, people's travel preferences may change. In order to reduce the risk of infection, some cities have witnessed increased walking, cycling, and private car usage, at the expense of public transit [44]. While a modal shift towards active transport (such as walking and cycling) contributes to lower transport carbon emissions, increased private car usage will have a negative impact on transport carbon emissions. In China, most NPI measures were lifted by the end of 2022. However, the long-term indirect impact may persist for an extended period, even without mandatory NPI measures.

In the long run, there may be additional behavioural changes, such as a reduction in passenger demand due to the substitution of face-to-face communications, a shift from passenger to freight transport due to e-commerce, a transition of urban passenger transport from bus and metro to active travel modes, and/or a modal shift in inter-city passenger transport from air to rail transport due to stricter flying requirements [45]. For instance, Zhang et al. [46] suggested that COVID-related NPI measures might lead to a long-term transformation of human travel behaviour favourable to transport decarbonisation.

Also, transport activities are directly related to economic activities. The success of decoupling transport carbon emissions from income growth relies on context-specific strategies [47–50]. Without transport decoupling, COVID-19 may result in reduced transport demand due to the slowing down of the economy or even a global recession. However, many transport decarbonisation measures, such as vehicle fleet replacement and the use of renewable energy, require infrastructure investment; hence, the development of green innovations may be delayed by an economic downturn [51]. In other words, the associated changes may present both opportunities and challenges for transport decarbonisation in the coming years. Based on the conceptual framework, the influence of COVID-19 on transport carbon emissions in both the short run and the long run could be better estimated and addressed by corresponding policies.

Short-term impact analysis

To quantify empirical changes in transport CO_2 emissions during the COVID-19 pandemic and shortly afterwards (from 2019 to 2021), the disaggregate distance-based method is employed. Following the ASIF approach, the method involves using mode-specific transport activity data (A) multiplied by CO_2 emission intensity (I and F). Similarly, when analysing transport CO_2 emissions from 2000 to 2021 for the long-term scenario analysis, the estimation of annual transport CO_2 emissions also uses the same methodology. The formula is expressed as follows:

$$G_{i,t,y} = T_{ity} \times EI \tag{1}$$

where $G_{i,t,y}$ represents the CO_2 emissions of transport mode i in month t of year y, $T_{i,t,y}$ represents the passenger turnover volume (in *pkm*) or freight turnover volume (in *tkm*) of transport mode i in month t of year y, $EI_{i,y}$ represents the CO_2 emission intensity (*g/pkm* or *g/tkm*) of transport mode i in year y.

Empirically, the $T_{i,t,y}$ data of rail, road, air, and water transport from January 2019 to December 2021 were sourced from the National Bureau of Statistics in China [52]. $EI_{i,y}$ is determined by multiplying the energy consumption intensity (I) with the CO_2 emission factor (F) for each type of transport fuel

$$EI_{i,y} = EC_{i,y} \times EF_i \tag{2}$$

where $EI_{i,y}$ represents the CO_2 emission intensity (*g/pkm* or *g/tkm*) of transport mode i in year y; $EC_{i,\,y}$ represents the energy consumption intensity of transport mode i in year y (obtained from the annual statistical reports from the Ministry of Transport in China [53]). In cases where $EC_{i,y}$ was unavailable for freight transport, the $EI_{i,y}$ of freight transport modes were estimated using the $EI_{i,y}$ of each passenger transport mode and the conversion rate between passenger turnover volume and freight turnover volume (1 for rail transport, 11.11 for air transport, and 3 for water transport [54, 55]). Since the $EI_{i,y}$ data are available for both passenger and freight road transport, no conversion is needed. EF_i reflects the CO_2 emission intensity of a mode-specific fuel type, and is assumed to be the same over the years [10].

Yet, it should be noted that $EI_{i,y}$ in Eq. (2) changes over time as the energy mix of a mode changes. For instance, an increased use of electricity instead of diesel as fuel in rail transport would result in a reduction in $EI_{i,y}$, despite the constant EF_i values for electricity and diesel over time. Tables 1 and 2 provides a summary of the key parameters.

Furthermore, several transport sub-modes are not covered by the transport statistics of the National Bureau of Statistics [24]. Firstly, national statistics on road transport volume only include buses and trucks running on intercity highways. In other words, buses and trucks operating within cities are not accounted for. Similarly, taxis,

Table 1 The CO_2 emission intensity of different intercity transport modes in China

	Passenger transport				**Freight transport**			
	Road	**Rail**	**Air**	**Water**	**Road**	**Rail**	**Air**	**Water**
Energy consumption intensity (EC) (in unit of gce/pkm or tkm, except air which is in g jet kerosene/pkm or tkm)								
2000	15.9	5.7	36.0	2.4	58.0	5.7	400.0	7.2
2005	18.5	4.4	30.2	1.8	72.0	4.4	336.0	5.5
2010	16.7	3.7	25.6	1.3	40.0	3.7	284.0	4.0
2015	12.6	3.0	26.5	1.1	19.0	3.0	294.0	3.2
2019	13.1	2.5	25.7	0.9	17 0	2.5	285.0	2.6
2020	13.0	2.7	28.4	0.8	16.9	2.7	316.0	2.5
2021	12.9	2.5	27.8	0.8	16.8	2.5	305.0	2.5
CO_2 emission intensity (EI) (in unit of g/pkm or tkm)								
2000	39.0	13.9	113.5	2.9	143.2	13.9	1261.3	17.7
2005	45.5	10.7	95.4	4.5	177.7	10.7	1198.2	13.4
2010	40.9	9.1	80.6	3.2	97.3	9.1	1135.1	9.7
2015	31.0	7.5	83.4	2.6	46.7	7.5	1116.2	7.8
2019	32.2	6.0	80.9	2.1	41.8	6.0	898.6	6.3
2020	31.9	6.6	89.7	2.1	41.5	6.6	996.4	6.2
2021	31.7	6.1	87.7	2.0	41.2	6.1	974.3	6.0

The energy consumption intensity for road transport from 2000 to 2007 was from [53]. The EF I was 2456.67 kg CO2/ton for standard coal

Table 2 EF values of different fuel types in China

Fuel Type	Mode	CO_2 emission factor (EF) (in kg CO_2/ton fuel, except electricity which is kg CO_2/kWh)
Electricity	Rail (electric locomotive; urban rail transit); Road (urban public buses; taxis; motorcycles; private cars)	0.722 (in 2000)
		0.687 (in 2005)
		0.619 (in 2010)
		0.538 (in 2015)
		0.489 (in 2019)
		0.479 (in2020)
		0.475 (in 2021)
Jet Kerosene	Air	3153.15
Diesel	Rail (diesel locomotive); Water; Road (intercity public buses and trucks; private trucks; rural freight vehicles)	3186.30
Motor gasoline	Road (intercity public buses and trucks; urban public buses; taxis; motorcycles; private cars and trucks)	3069.99

Electricity consumption is transformed into coal because most electricity is generated by coal in China. The CO_2 emission factor for standard coal is 2456.67 kg CO_2/ton coal. According to *China Electric Power Statistical Yearbook*, the proportion of China's power generation from coal-fired power stations decreased from 81.0% in 2000 to 68.9% in 2019, and the standard coal consumption for coal-fired power stations also decreased from 363 g/kWh in 2000 to 288.8 g/kWh in 2019, which leads to 1.9% annual reduction of CO_2 emission intensity of electricity in China in the period of 2012–2019

motorcycles, and private cars are not included. The CO_2 emissions of these sub-modes are estimated by multiplying the vehicle number with the annual average mileage, average gasoline/diesel consumption, and fuel emission factor. Secondly, the national rail transport volume only encompasses intercity railways, excluding urban rail transit or metros. The CO_2 emissions of urban rail transit are estimated by multiplying the passenger volume with average travel distance and CO_2 emission per pkm. Based on the reduction of passenger volume in each month of 2020 and 2021 compared with the same month in 2019, the short-term effects of COVID-19 on urban rail-related CO_2 emissions are calculated.

Medium- and long-term scenario analysis

What will be the legacy of COVID-19 on the transport sector? Drawing lessons from the Severe Acute Respiratory Syndrome (SARS) period in 2003, recovery can occur very rapidly. There were no new SARS cases reported since the end of June 2003. Consequently, freight transport in China began to grow in July, and passenger transport followed in September of the same year. Therefore, the effect of SARS on transport carbon emissions was mainly due to the reduction in transport volume in 2003 and did not last any longer. However, COVID-19 has persisted much longer, with NPI measures in place for nearly three years in China. It is challenging to estimate whether and when the transport sector will resume rapid growth, akin to the pre-pandemic period. Both formal statistical data and informal sources (such as *Baidu chuxing*) indicate a relatively swift recovery in China's transport system in 2020. However, due to the increased infectiousness of the COVID-19 virus, the Chinese government re-introduced large-scale lockdown policies again in 2021. Although the Chinese government has stopped all lockdown policies since December 2022, the longer-run impact of COVID-19 on transport carbon emissions remains uncertain. The actual trajectory may depend on various factors, including the actual duration and magnitude of the COVID-19 outbreak, the effectiveness of containment measures, consumer confidence, and economic conditions [45]. If the adverse effects of COVID-19 on transport disappear quickly and the economy rebounds, there might be minimal medium-term impact. However, if COVID-19 triggers a global recession and substantial changes in travel behaviour, there could be significant medium-term effects on transport turnover volume and transport carbon emissions [50]. In essence, the impact may shift from a temporary reduction to a long-term transformation.

To explore the long-term influence of COVID-19 and to estimate its impact on transport carbon emissions, this study aims to forecast mode-specific transport activities and CO_2 emission intensity for all transport modes from 2022 to 2030. Following the ASIF methodology, the equation is as follows:

$$G_{i,y} = T_{i,2021} \times EI_{i,2021} \times (1+\alpha_i)^{y-2021} \times (1+\beta_i)^{y-2021} \tag{3}$$

where $G_{i,y}$ represents the CO_2 emission of transport mode i in year y, $T_{i,2021}$ represents the passenger turnover volume (in *pkm*) or freight turnover volume (in *tkm*) of transport mode i in 2021, $EI_{i,2021}$ represents the CO_2 emission intensity (*g/pkm* or *g/tkm*) of transport mode

i in 2021, α_i represents the growth rate of transport volume for transport mode i, and β_i represents the change rate of carbon emission intensity of transport mode i during the period 2022–2030. For sub-modes beyond the national statistics, the estimated $T_{i,2021}$ and $EI_{i,2021}$ are used for forecasting the carbon emissions.

Given the uncertainties about the impact of COVID-19 (in terms of extent, aspects, and duration), this study employs simulations to measure the varying degrees of COVID-19's influence on transport carbon emissions across different scenarios, where the predicted growth rate of transport activity and rate of change in CO_2 emission intensity for different transport modes vary by different levels. Guided by the conceptual framework in Fig. 1, five scenarios are established to estimate the effects of COVID-19 on annual transport carbon emissions in the period of 2022–2030. Table 3 summarises the business-as-usual scenario and four other scenarios (L2 to L4), which relate to different combinations of COVID-19's effects on behavioural changes and economic growth. These effects, in turn, have four levels, with "3" denoting "severe impacts"; "2" denoting "moderate impacts"; "1" denoting "slight impacts"; and "0" denoting "no impact". Following Fig. 1, the effects of behavioural change and economic recession affect passenger transport and freight transport, respectively. Generally, passenger transport will be more affected by behavioural changes as people use more online means when there are concerns about the risk of infection in transportation and physical gatherings at work, schools, and other places. In comparison, freight transport will be more affected by a global recession and its magnitude.

To enhance the accuracy of estimations, levels 1–3 are determined by amalgamating findings from existing international studies and the current study (focusing on short-term changes from January 2019 to December 2020). These benchmarks are presented in Table 4. Specifically, "3" indicating severe impacts, employs values from the upper bounds of the observed empirical range of change (i.e., the most significant drop). "2", representing moderate impacts, uses values at two-thirds of the upper bounds, while "1", indicating slight impacts, employs values at one-third of the upper bounds. "0" means no impact. These impacts are applied to the historical growth rates of mode-specific passenger and freight transport in China from 2018 to 2019 (as illustrated in Table 3).

Table 3 Five scenarios established for the medium-term effects of COVID-19

	No impact (Business-as usual scenario)	Minimal impact (L1)	Low impacts (L2)	Moderate impacts (L3)	Severe impacts (L4)
Behavioural changes					
Drop of passenger transport	0	1	2	3	3
Slower economic growth					
Drop of freight transport	0	0	1	2	3
Slower R&D					
Slower technological fixes	0	0	0	1	3

"0" denotes "No impact"; "1" denotes "Slight impacts"; "2" denotes "Moderate impacts"; "3" denotes "Severe impacts"

Table 4 Transport volume change due to COVID-19 based on international exploratory studies and this study

	Passenger			Freight		
	Upper bound %	Lower bound %	This study %	Upper bound %	Lower bound %	This study %
Road	– 90	– 60	– 48	– 22	– 11	– 20
Rail	– 30	– 30	– 44	– 10	– 10	1
Air	– 58	– 45	– 46	– 35	– 17	– 9
Water	–	–	– 59	– 30	– 20	2
Urban transport						
- Metro	– 77	– 30	– 27	–	–	
- Ferries, franchised buses and trams	– 40	– 40	– 40	–	–	
- Taxis	– 35	– 35	– 35	–	–	

Data are summarized based on [55, 57], and [58–63]

In this way, the scenario analysis accounts for the uncertainty due to differential impacts of COVID-19 across various modes of transport. For air transport, the global annual air passenger turnover declined by 46% to 62% in 2020, and global airline passenger revenues dropped by 55% in 2020 compared to 2019 due to COVID-19 [44, 54]. Similarly, maritime shipping activities decreased by 30% in certain regions, and fishing activity plummeted by 80% in China and West Africa due to COVID-19 lockdowns [56]. For railways, global passenger demand witnessed an average decline of up to 30% in 2020 compared to 2019, while the freight sector experienced an average drop of up to 10% [57]. Accordingly, Table 4 summarises both the upper and lower bounds of existing international studies and those in China. The upper bounds used for benchmarking severe impacts are shaded in grey.

Having considered the drops in passenger and freight transport (see Table 3), the next step is to estimate the effects of COVID-19 on the slowing down of R&D and technological fixes under a global economic downturn. Technological advancements, such as enhanced fuel efficiency, are anticipated to lower carbon emission intensity in the medium term (2021–2030). The declining rates of CO_2 emission intensity for various transport modes between 2021 and 2030 are derived from the lower bounds of actual annual decline rates of CO_2 emission intensity observed from 2012 to 2019, and the projected annual decline rates from 2020 to 2030, as provided by the Energy Foundation and Energy Research Institute of National Development and Reform Commission in China [64]. These rates were estimated at − 1.7%, − 2.5%, − 1.6%, and − 3.3% for road, rail, air, and water transport, respectively. Furthermore, with the increasing adoption of electric vehicles (EVs) in intercity buses and hydrogen vehicles in intercity trucks (constituting 20% of the vehicle fleet for road transport), the estimated annual decline rate of CO_2 emission intensity encompassed by national transport statistics is projected to be − 3.4%. For transport modes not covered by national statistics, the growing use of EVs in city buses, taxis, and private cars is expected to contribute to a decrease in CO_2 emission intensity at annual rates of − 3.4% for private cars, − 4.3% for taxis, and − 2.7% for urban rail transit. It is important to note that China's electricity generation remains highly carbon-intensive. Thus, the annual decrease of CO_2 emission intensity was based on the carbon intensity of electricity in China from 2012 to 2019. Focusing solely on the transport sector, transitions in vehicle fuel types will necessitate infrastructural and policy support, which might be influenced by a global recession. Therefore, the four impact levels (no impact, slight impact, moderate impact, and severe impact) are projected to reduce by one-third, halved, and reduced by two-thirds, respectively.

The business-as-usual scenario assumes no behavioural change or economic recession in the medium and long terms, with the growth rate of transport volume and the rate of change in carbon emission intensity to be at the same levels as the period before COVID-19 (from 2018 to 2019). The four other scenarios represent the minimal impact scenario (L1) with only behavioural changes, the low impact scenario (L2) with a more sluggish global economy and minor behavioural changes, the moderate impact scenario (L3) with slow R&D investment and technological improvements as well as a decrease in passenger and freight transport, and the severe impact scenario (L4) with all behavioural changes, a global economic recession, and delays in R&D and technological improvement. Following the explanations about determining various upper and lower bounds for behavioural changes and economic growth, specific underlying data and parameters for all scenarios are summarised in Table 5.

Results

Short-term changes based on empirical passenger and freight volumes

Passenger transport

Figure 2 compares the actual CO_2 emissions from four modes of passenger transport in China by month from 2019 to 2021. Table 6 summarizes the changes in both absolute volume and percentage terms. Due to the COVID-19 lockdown measures, CO_2 emissions from passenger transport in China decreased by 55.15 Mt (− 42%) in 2020 compared to 2019, with water transport experiencing the most significant reduction (-60%), followed by road transport (− 48%) and air transport (− 40%) (Table 6). Although the total passenger CO_2 emissions experienced a slight increase of 3% in January 2020 when COVID-19 began to spread in Wuhan, the volume sharply dropped by − 83% in February when most parts of the country implemented strict confinement. The decline slowed down from March onwards as most parts of China began to resume regular activities. By 2021, CO_2 emissions from passenger transport remained significantly lower than 2019, with an annual total reduction of 57.53 Mt (− 34%), primarily due to substantial falls in road and water transport (− 60%), followed by air transport (− 40%) and rail transport (− 34%). This indicates that the lockdown effects resulting from COVID-19 persisted into 2021.

Freight transport

Figure 3 visualises the levels of CO_2 emissions from four modes of freight transport in China from 2019 to 2021 on

Table 5 The underlying data and parameters used in different scenarios

Transport modes	Variable	Absolute value in 2021	Annual change rate in different scenarios (%)				
			Business-as-usual scenario	L1	L2	L3	L4
Passenger transport-road	Transport volume (pkm)	362754	– 4.6%	– 4.6%*(1–90%/3)	– 4.6%*(1–90%/3*2)	– 4.6%*(1–90%)	– 4.6%*(1–90%)
	Carbon emission intensity (g/pkm)	31.70	– 3.4%	– 3.4%	– 3.4%	– 3.4%/3	0%
Passenger transport-rail	Transport volume (million pkm)	956781	4.0%	4.0%*(1–44%/3)	4.0%*(1–44%/3*2)	4.0%*(1–44%)	4.0%*(1–44%)
	Carbon emission intensity (g/pkm)	6.11	– 2.5%	– 2.5%	– 2.5%	-2.5%/3	0%
Passenger transport-air	Transport volume	652903	9.3%	9.3%*(1–58%/3)	9.3%*(1–58%/3*2)	9.3%*(1–58%)	9.3%*(1–58%)
	Carbon emission intensity (g/pkm)	87.69	– 1.6%	– 1.6%	– 1.6%	– 1.6%/3	0%
Passenger transport-water	Transport volume (million pkm)	3311	0.8%	0.8%*(1–59%/3)	0.8%*(1–59%/3*2)	0.8%*(1–59%)	0.8%*(1–59%)
	Carbon emission intensity (g/pkm)	2.04	– 3.3%	– 3.3%	– 3.3%	– 3.3%/3	0%
Freight transport-road	Transport volume (million tkm)	6908765	5.0%	5.0%	5.0%*(1–22%/3)	5.0%*(1–22%/3*2)	5.0%*(1–22%)
	Carbon emission intensity (g/tkm)	41.25	– 3.4%	– 3.4%	– 3.4%	– 3.4%/3	0%
Freight transport-rail	Transport volume (million tkm)	3319073	4.3%	4.3%	4.3%*(1–10%/3)	4.3%*(1–10%/3*2)	4.3%*(1–10%)
	Carbon emission intensity (g/tkm)	6.11	-2.5%	– 2.5%	– 2.5%	– 2.5%/3	0%
Freight transport-air	Transport volume (million tkm)	27773	0.2%	0.2%	0.2%*(1–35%/3)	0.2%*(1–35%/3*2)	0.2%*(1–35%)
	Carbon emission intensity (g/tkm)	974.32	– 1.6%	– 1.6%	– 1.6%	– 1.6%/3	0%
Freight transport-water	Transport volume (million tkm)	11557751	5.0%	5.0%	5.0%*(1–30%/3)	5.0%*(1–30%/3*2)	5.0%*(1–30%)
	Carbon emission intensity (g/tkm)	6.13	– 3.3%	– 3.3%	– 3.3%	– 3.3%/3	0%
City buses	Carbon emissions (million tons)	Carbon emissions (million tons): 8.5	3.2%	3.2%	3.2%	3.2%	3.2%
	Carbon emission intensity (g/tkm)		– 4.3%	– 4.3%	– 4.3%	– 4.3%/3	0%
Taxi	Transport volume (million pkm)	Carbon emissions (million tons):9.3	0.5%	0.5%*(1–35%/3)	0.5%*(1–35%/3*2)	0.5%*(1–35%)	0.5%*(1–35%)
	Carbon emission intensity (g/pkm)		-4.3%	-4.3%	-4.3%	-4.3%/3	0%
Motorcycles	Transport volume (million pkm)	Carbon emissions (million tons): 11.8	3.4%	3.4%*(1–35%/3)	3.4%*(1–35%/3*2)	3.4%*(1–35%)	3.4%*(1–35%)
	Carbon emission intensity (g/pkm)		– 3.4%	– 3.4%	– 3.4%	– 3.4%/3	0%
Metro	Transport volume (million pkm)	230151	12.2%	12.2%*(1–77%/3)	12.2%*(1–77%/3*2)	12.2%*(1–77%)	12.2%*(1–77%)
	Carbon emission intensity (g/pkm)	11.8	– 2.7%	– 2.7%	– 2.7%	– 2.7%/3	0%
Private and institutional passenger vehicles	Transport volume (million pkm)	Carbon emissions (million tons): 514.5	7.8%	7.8%*(1–35%/3)	7.8%*(1–35%/3*2)	7.8%*(1–35%)	7.8%*(1–35%)
	Carbon emission intensity (g/pkm)		– 3.4%	– 3.4%	– 3.4%	– 3.4%/3	0%
Private and institutional trucks	Transport volume (million tkm)	Carbon emissions (million tons): 158.4	5.0%	5.0%	5.0%*(1–22%/3)	5.0%*(1–22%/3*2)	5.0%*(1–22%)
	Carbon emission intensity (g/tkm)		– 3.4%	– 3.4%	– 3.4%	– 3.4%/3	0%
Rural vehicles	Transport volume (million tkm)	Carbon emissions (million tons): 23.9	5.0%	5.0%	5.0%*(1–22%/3)	5.0%*(1–22%/3*2)	5.0%*(1–22%)
	Carbon emission intensity (g/tkm)		– 3.4%	– 3.4%	– 3.4%	– 3.4%/3	0%

Given the huge variations of vehicle size and model used by various transport sub-modes beyond the scope of national statistics, there exist no uniform carbon emission intensities for vehicles by fuel type. Consequently, the forecast for carbon emissions of each sub-mode is based on the estimated carbon emissions of the respective sub-mode in 2021

a monthly basis. Table 7 provides a summary of changes in 2020 and 2021, compared to 2019. During the pandemic, CO_2 emissions from freight transport in China dropped by 60.55 Mt (– 14%) in 2020 compared to 2019. Road freight CO_2 emissions experienced the most significant reduction (– 20%) (Table 7). Overall, CO_2 emissions from all freight transport dropped by about – 28% in January when COVID-19 began to spread, with the most substantial decrease of -36% recorded in February. The reductions were less pronounced from March to August 2020. The total CO_2 emission volume from freight transport in 2021 remained lower when compared to 2019, with a reduction of 18.86 Mt (– 4%), which may be attributable not only to the lockdown policies but also the onset of an economic recession.

Beyond national statistics: Urban passenger transport, private trucks, and rural freight vehicles

Following the outlined methodology, short-term changes in CO_2 emissions from the missing transport sub-modes are estimated and summarised in Table 8. In 2020, urban passenger transport, including city buses, taxis and urban rail transit, emitted 467.27 Mt of CO_2, signifying a – 35% decline from the 716.69 Mt recorded in

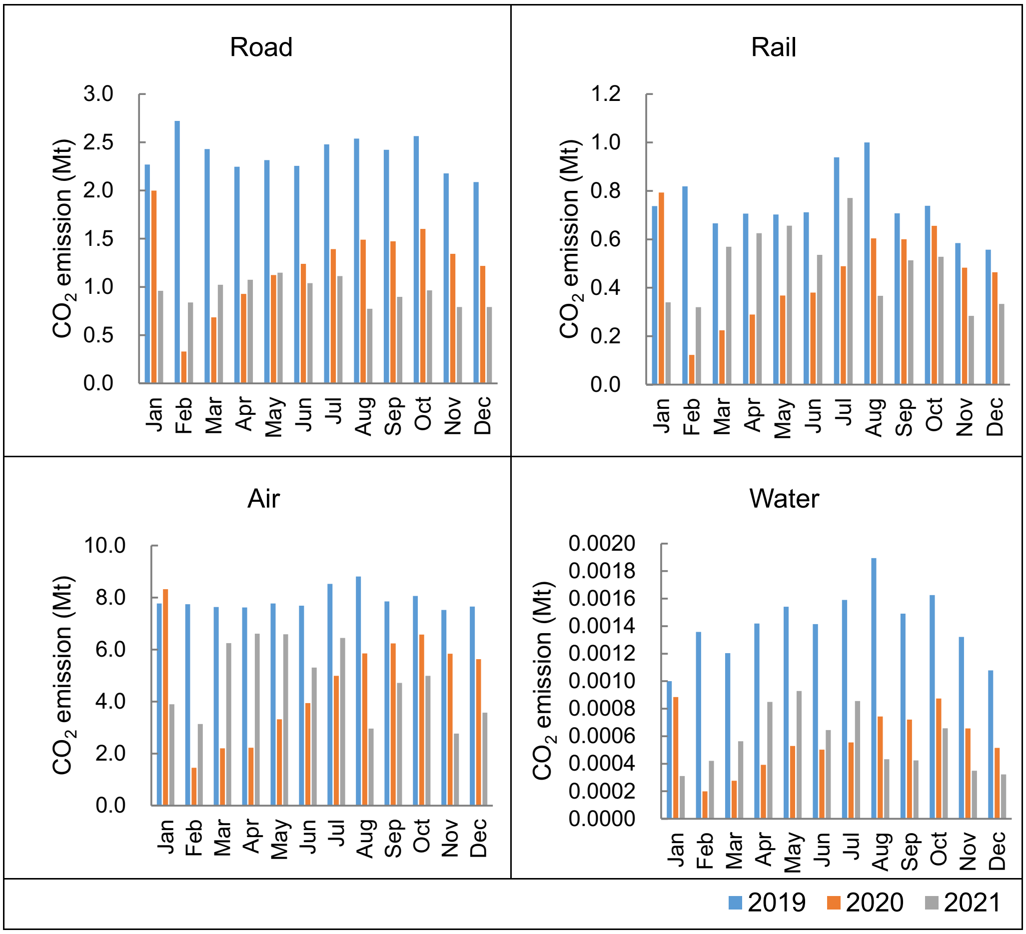

Fig. 2 Estimations of CO_2 emissions from four passenger transport modes in China by month, 2019–2021

2019. As depicted in Fig. 4, the most significant reduction occurred in February (– 83%), followed by March (– 66%) and April (– 45%). Subsequently, urban passenger transport gradually recovered. In comparison to national figures, urban passenger transport was notably more affected by COVID-19. The influence of COVID-19 persisted into 2021, with the total urban passenger transport CO_2 emissions dropped to 509.16 Mt, 29% lower than those in 2019.

Next, CO_2 emissions produced by private trucks and rural goods vehicles in China are estimated. In comparison with 2019, the sub-sector emitted 20% less CO_2 emissions in 2020, totalling 140.41 Mt. Figure 5 shows that the rate of decline has been most pronounced in February (– 53%), followed by January (– 37%) and March (– 32%). Subsequently, local freight transport in China gradually recovered. However, the volume of local freight transport emissions in 2021 was still 7% lower than that in 2019.

When summarising CO_2 emissions from all passenger and freight transport (both intercity and urban), the transport system in China produced 1443.6 Mt CO_2 emission in 2019. This figure dropped to 1044.2 Mt in 2020 and slightly rose to 1146.8 Mt in 2021. According to IEA statistics, the total transport CO_2 emissions in China were approximately 1012.4 Mt in 2020, a figure similar to our estimation, representing a 28% decrease from 2019. As depicted in Fig. 6, the monthly reduction in 2020 was the most significant in February (– 71%), followed by March (– 51%), April (– 35%) and May (– 30%). The total passenger transport, including intercity and urban passenger transport, emitted 848.74 Mt of CO_2 in 2019. This figure dropped to 544.17 Mt in 2020 and further decreased to 583.7 Mt in 2021, marking a reduction of – 36% and – 31%, respectively.

Regarding total freight transport, which includes intercity freight transport, private trucks and rural goods vehicles, it generated 594.81 Mt of CO_2 emission in 2019. This dropped to 500.04 Mt in 2020 and slightly increased to 563.16 Mt in 2021, with reduction rates of 16% in 2020 and 5% in 2021. Overall, COVID-19 has had a more pronounced impact on the passenger than the freight sector in China. From an environmental perspective, all

Table 6 Changes of passenger transport CO_2 emissions in China by month, 2019–2021 (Mt)

2019–2020	Road	Rail	Air	Water	Passenger transport
Jan	−0.27 (−12%)	0.06 (8%)	0.55 (7%)	−0.0001 (−10%)	0.34 (−3%)
Feb	−2.39 (−88%)	−0.70 (−85%)	−6.29 (−81%)	−0.0012 (−85%)	−9.38 (−83%)
Mar	−1.74 (−72%)	−0.44 (−66%)	−5.43 (−71%)	−0.0009 (−77%)	−7.62 (−71%)
Apr	−1.32 (−59%)	−0.42 (−59%)	−5.39 (−71%)	−0.0010 (−72%)	−7.13 (−67%)
May	−1.19 (−51%)	−0.34 (−48%)	−4.45 (−57%)	−0.0010 (−65%)	−5.98 (−55%)
Jun	−1.02 (−45%)	−0.33 (−47%)	−3.75 (−49%)	−0.0009 (−64%)	−5.09 (−48%)
Jul	−1.09 (−44%)	−0.45 (−48%)	−3.54 (−42%)	−0.0010 (−65%)	−5.08 (−42%)
Aug	−1.05 (−41%)	−0.40 (−40%)	−2.96 (−34%)	−0.0012 (−60%)	−4.40 (−36%)
Sep	−0.95 (−39%)	−0.11 (−15%)	−1.62 (−21%)	−0.0008 (−51%)	−2.67 (−24%)
Oct	−0.96 (−38%)	−0.08 (−11%)	−1.49 (−18%)	−0.0008 (−45%)	−2.53 (−22%)
Nov	−0.83 (−38%)	−0.10 (−17%)	−1.68 (−22%)	−0.0007 (−50%)	−2.62 (−25%)
Dec	−0.87 (−42%)	−0.09 (−17%)	−2.03 (−26%)	−0.0006 (−51%)	−2.99 (−29%)
Total reduction from 2019 to 2020	−13.68 (−48%)	−3.40 (−38%)	−38.06 (−40%)	−0.01 (−60%)	−55.15 (−42%)
2019–2021	**Road**	**Rail**	**Air**	**Water**	**Passenger transport**
Jan	−1.31 (−58%)	−0.40 (−54%)	−3.87 (−50%)	−0.0007 (−69%)	−0.40 (−54%)
Feb	−1.88 (−69%)	−0.50 (−61%)	−4.61 (−59%)	−0.0009 (−69%)	−0.50 (−61%)
Mar	−1.41 (−58%)	−0.10 (−15%)	−1.39 (−18%)	−0.0009 (−53%)	−0.10 (−15%)
Apr	−1.17 (−52%)	−0.08 (−11%)	−1.01 (−13%)	−0.0006 (−40%)	−0.08 (−11%)
May	−1.17 (−50%)	−0.05 (−7%)	−1.18 (−15%)	−0.0006 (−40%)	−0.05 (−7%)
Jun	−1.22 (−54%)	−0.18 (−25%)	−2.38 (−31%)	−0.0006 (−54%)	−0.18 (−25%)
Jul	−1.37 (−55%)	−0.17 (−18%)	−2.08 (−24%)	−0.0008 (−46%)	−0.17 (−18%)
Aug	−1.76 (−70%)	−0.63 (−63%)	−5.84 (−66%)	−0.0007 (−77%)	−0.63 (−63%)
Sep	−1.53 (−63%)	−0.19 (−27%)	−3.13 (−40%)	−0.0015 (−72%)	−0.19 (−27%)
Oct	−1.60 (−62%)	−0.21 (−29%)	−3.07 (−38%)	−0.0011 (−60%)	−0.21 (−29%)
Nov	−1.39 (−64%)	−0.30 (−51%)	−4.75 (−63%)	−0.0010 (−74%)	−0.30 (−51%)
Dec	−1.30 (−62%)	−0.22 (−40%)	−4.08 (−53%)	−0.0008 (−70%)	−0.22 (−40%)
Total reduction from 2019 to 2021	−17.09 (−60%)	−3.03 (−34%)	−37.40 (−40%)	−0.01 (−60%)	−3.03 (−34%)

transport sectors witnessed ostensible declines in transport-related carbon emissions in 2020, marking a year of de facto transport decarbonisation in the country.

Medium- and long-term 2030 scenario analysis

Compared with the business-as-usual scenario, Fig. 7 shows four different scenarios of COVID-19 effects on passenger and freight CO_2 emissions in China from 2000 to 2030. It is essential to note that the estimates for transport CO_2 emissions from 2000 to 2021 are based on statistical data, while projections from 2022 to 2030 rely on predictive modelling. This section incorporates both national passenger and freight volumes and supplemental local passenger and freight volumes, similar to the short-term estimations.

In the minimal impact scenario (L1 in Fig. 7), there are few medium-term effects of COVID-19, implying no global recession and minimal behavioural changes but sustained technological advancement (based on historical trends). Consequently, annual transport CO_2 emissions are projected to rise from 1044.2 Mt in 2020 to 1314.3 Mt in 2030. Compared to the business-as-usual scenario without COVID-19, transport carbon emissions between 2021 and 2030 will only change by -6% under the minimal-impact scenario.

In the low impact scenario (L2), the annual transport CO_2 emission volume is anticipated to increase from 1044.2 Mt in 2020 to 1168.3 Mt in 2030. The more sluggish growth rates of passenger and freight transport volumes contribute to this projection. In comparison to the business-as-usual scenario, the total transport carbon emission volume is expected to change by about − 15% during 2021–2030.

In the moderate impact scenario (L3), the annual transport CO_2 emission volume is forecasted to increase from 1044.2 Mt in 2020 to 1111.7 Mt in 2030. Hence, under the moderate-impact scenario, transport carbon emissions are estimated to decline by − 21%

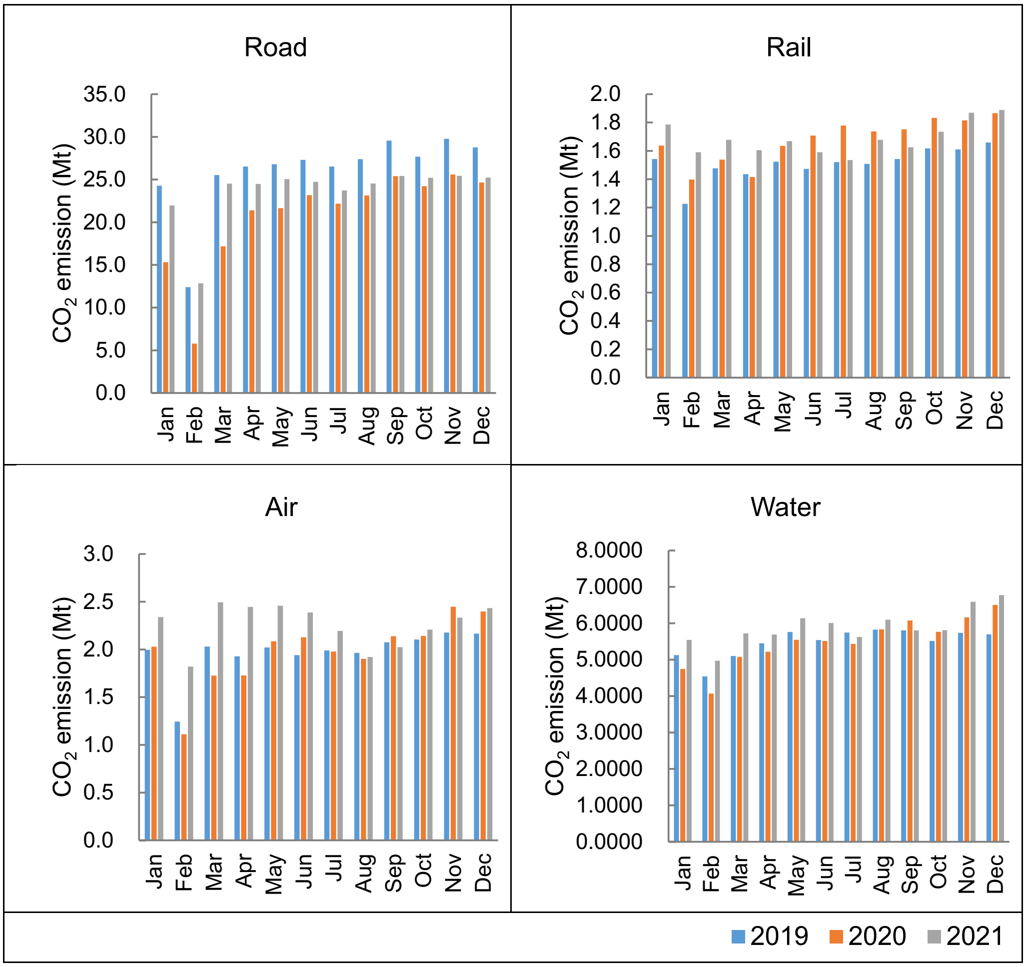

Fig. 3 Estimations of CO_2 emissions from four freight transport modes in China by month, 2019–2021

in contrast to the business-as-usual scenario without COVID-19.

In the severe-impact scenario (L4), the annual transport CO_2 emission volume is expected to change more substantially by about − 23% compared to the business-as-usual scenario. Yet, despite the more considerable drops in passenger and freight volumes, the transport CO_2 emissions are still predicted to rise from 1044.2 Mt in 2020 to 1107.2 Mt in 2030. This is partly due to the slower technological advancements resulting from the global recession, which hinders the anticipated reduction in transport carbon emissions.

Discussion

Since greenhouse gases lead to the rise of surface temperature on Earth, controlling CO_2 and its impact on climate change has become a worldwide emergency. According to the United Nations Framework Convention on Climate Change, China has committed to peaking its carbon emissions by no later than 2030. Additionally, it aims to reduce its carbon emissions per GDP by 40–45% in 2020 and by 60–65% in 2030 compared to previous levels in 2005. These targets have been set to align with the objective of limiting the temperature increase to within 1.5 °C. However, reducing carbon emissions within the transport sector is particularly challenging. On the one hand, the transport industry in China heavily relies on fossil fuels like diesel and gasoline. On the other hand, it has been undergoing rapid increases in travel demand and motorisation rates. Hence, achieving the goal of limiting the temperature increase to within 1.5 °C in China's transport sector necessitates robust carbon reduction policies and measures.

Official data regarding the total quantity and composition of transport-related carbon emissions from the Chinese government remains elusive. More precise estimations of China's transport carbon emissions are imperative for implementing effective reduction strategies. According to the IEA statistics, annual transport-related CO_2 emissions in China have surged from

Table 7 Changes of freight transport CO_2 emissions in China by month, 2019–2021 (Mt)

2019–2020	Road	Rail	Air	Water	Freight transport
Jan	−8.96 (−37%)	0.09 (6%)	0.03 (2%)	−0.38 (−7%)	−9.21 (−28%)
Feb	−6.61 (−53%)	0.17 (14%)	−0.13 (−11%)	−0.47 (−10%)	−7.04 (−36%)
Mar	−8.34 (−33%)	0.06 (4%)	−0.30 (−15%)	0.02 (−0.4%)	−8.60 (−25%)
Apr	−5.13 (−19%)	−0.02 (−1%)	−0.20 (−10%)	−0.23 (−4%)	−5.58 (−16%)
May	−5.15 (−19%)	0.11 (7%)	0.06 (3%)	−0.21 (−4%)	−5.19 (−14%)
Jun	−4.13 (−15%)	0.23 (16%)	0.19 (10%)	−0.03 (−0.5%)	−3.74 (−10%)
Jul	−4.35 (−16%)	0.26 (17%)	−0.01 (−1%)	−0.31 (−5%)	−4.42 (−12%)
Aug	−4.24 (−15%)	0.23 (15%)	−0.06 (−3%)	0.01 (0.1%)	−4.07 (−11%)
Sep	−4.16 (−14%)	0.21 (14%)	0.06 (3%)	0.27 (5%)	−3.62 (−9%)
Oct	−3.45 (−12%)	0.22 (13%)	0.04 (2%)	0.25 (5%)	−2.94 (−8%)
Nov	−4.18 (−14%)	0.21 (13%)	0.27 (12%)	0.43 (7%)	−3.28 (−8%)
Dec	−4.11 (−14%)	0.21 (12%)	0.23 (11%)	0.80 (14%)	−2.86 (−7%)
Total reduction from 2019 to 2020	−62.80 (−20%)	1.98 (11%)	0.17 (1%)	0.10 (0.1%)	−60.55 (−14%)
2019–2021	**Road**	**Rail**	**Air**	**Water**	**Freight transport**
Jan	−2.31 (−10%)	0.24 (16%)	0.34 (17%)	0.42 (8%)	−1.31 (−4%)
Feb	0.45 (4%)	0.36 (30%)	0.58 (46%)	0.43 (10%)	1.82 (9%)
Mar	−0.99 (−4%)	0.20 (14%)	0.46 (23%)	0.62 (12%)	0.29 (1%)
Apr	−2.03 (−8%)	0.17 (12%)	0.52 (27%)	0.24 (4%)	−1.11 (−3%)
May	−1.74 (−7%)	0.14 (10%)	0.44 (22%)	0.38 (7%)	−1.55 (−2%)
Jun	−2.58 (−9%)	0.12 (8%)	0.45 (23%)	0.47 (8%)	−2.69 (−4%)
Jul	−2.79 (−11%)	0.01 (1%)	0.20 (10%)	−0.12 (−2%)	−2.46 (−8%)
Aug	−2.85 (−10%)	0.17 (11%)	−0.04 (−2%)	0.27 (5%)	−4.12 (−7%)
Sep	−4.15 (−14%)	0.08 (5%)	−0.05 (−2%)	−0.00 (−0.1%)	−3.62 (−11%)
Oct	−2.45 (−9%)	0.12 (7%)	0.10 (5%)	0.29 (5%)	−1.94 (−5%)
Nov	−4.34 (−15%)	0.26 (16%)	0.16 (7%)	0.86 (15%)	−3.07 (−8%)
Dec	−3.53 (−12%)	0.23 (14%)	0.27 (12%)	1.07 (19%)	−1.96 (−5%)
Total reduction from 2019 to 2021	−29.32 (−9%)	2.11 (12%)	3.42 (14%)	4.93 (7%)	−18.86 (−4%)

248.0 Mt in 2000 to 1012.4 Mt in 2020 [3]. Despite the much larger volume, the IEA statistics are still likely to be an under-estimation based on this study's estimate at 1044.2 Mt in 2020. This disparity is primarily due to the terminology of official transport energy consumption statistics that encompass the warehousing and postal industries, but fail to account for private transport modes. Furthermore, the official transport energy statistics do not differentiate between carbon emissions attributable to passenger and freight transport or by specific transport modes. Currently, comprehensive estimations of China's transport-related carbon emissions primarily came from academic scholars. For instance, a study by the Chinese Academy of Transportation Sciences suggests an increase in China's transport-related carbon emissions from 340 Mt in 2005 to 1023 Mt in 2020 [68]. Additionally, Tian et al. [69] estimated China's transport industry carbon emissions at approximately 1274 Mt for 2019, slightly lower than the estimate of 1443.6 Mt in this study [69]. A closer look reveals that the discrepancies primarily come from the assessment of carbon emissions associated with road transport [70]. A notable omission prevalent in most existing studies is the neglect of private vehicles (including motorcycles and rural vehicles) and the urban transit system [70]. Moreover, many studies fail to account for the differential rates of using alternative energy sources in different transport modes, which has emerged as a new trend in China.

Thus, this study makes a scientific contribution by adopting a more comprehensive approach in estimating transport carbon emissions. Furthermore, it presents an evaluation of the medium- to long-term impact of the COVID-19 pandemic, diverging from the predominant focus of existing studies on its immediate and short-term effects. This broader scope contributes significantly to devising strategies for low-carbon transport and achieving carbon neutrality in the post-pandemic era.

Table 8 Vehicle number, average annual mileage, average fuel consumption, and emission factor

	Vehicle number in 2019 (10,000 units)	**Average annual mileage (km)**	**Average fuel consumption (km/MJ)**	**Emission factor (g CO_2/MJ fuel)**
City buses				
- Diesel	12	34000	0.1138	74.3
- CNG	10	34000	0.0854	64.0
- LPG	1	34000	0.0854	63.6
- New energy (electric)	36	34000	96 (kwh/100 km)	489 g CO_2/kwh
Taxis				
- Gasoline	28	71000	0.4554	73.2
- CNG	58	71000	0.4484	64.0
- LPG	14	71000	0.4806	63.6
- New energy (electric)	10	71000	12(kwh/100 km)	489 g CO_2/kwh
Motorcycles	9000	4000	1.5327	73.2
Private and institutional passenger vehicles	22204.76	18000	15.07	3069.99
- HDB and MDB-diesel	22	40000	0.1138	74.3
- HDB and MDB- CNG	2	40000	0.0854	64.0
- HDB and MDT- new energy	1	40000	96 (kwh/100 km)	489 g CO_2/kwh
- Car- diesel	220	17000	0.5509	74.3
- Car- gasoline	21573	17000	0.4554	73.2
- Car- new energy	410	17000	12 (kwh/100 km)	489 g CO_2/kwh
Private and institutional trucks				
- MT-gasoline	2	20000	0.4809	73.2
- MT-diesel	2	20000	0.4950	74.3
- LDT-gasoline	560	20000	0.2461	73.2
- LDT- diesel	833	20000	0.2392	74.3
- MDT- diesel	8	24000	0.1570	74.3
- MDT-gasoline	3	24000	0.1245	73.2
- HDT- diesel	201	40000	0.1216	74.3
Rural freight vehicles				
- Tricycle	2051	7000	4.9 (L/100 km)	3186.3 kg/ton fuel
- Low–speed car	504	7000	9.5 (L/100 km)	3186.3 kg/ton fuel

HDB, MDB, MT, LDT, MDT and HDT-D refers to heavy-duty bus, medium-duty bus, mini trucks, light-duty trucks, medium-duty trucks and heavy-duty trucks. The number of each type of private and institutional trucks were estimated according to the method of [54, 65], and the proportion of vehicles using each type of fuels according to [66]

Data source: [9, 53, 54, 65, 67]

While COVID-19 has presented an opportunity for the transport sector to achieve temporary reductions in carbon emissions, it also offers potential for longer-term transformation. Yet, the magnitude of this impact remains insufficient. Compared to 2019, the total volume of passenger and freight transport carbon emissions in China decreased by − 28% and − 21% in 2020 and 2021, respectively. In comparison to the business-as-usual scenario, COVID-19 is expected to result in reductions in the total volumes of passenger and freight carbon emissions in China by − 6% to − 23% during 2021–2023. The total transport carbon emissions are still projected to increase in absolute terms under all different scenarios.

Meeting the 2030 carbon reduction goal in China appears unlikely without robust transport decarbonization policies and measures. The scenario analysis results, considering the impacts of COVID-19, project transport carbon emissions in 2030 under four different scenarios to range between 1107.2 and 1314.3 Mt. Transport CO_2 emissions exhibit rising trends in all these scenarios. Without stronger and more proactive interventions, absolute reductions are difficult. In particular, China's transport sector is unlikely to achieve the carbon reduction target solely by relying on market-driven transport volume reduction [71, 72]. Ensuring mobility and sustaining economic growth require the adoption of robust transport carbon reduction policies and measures,

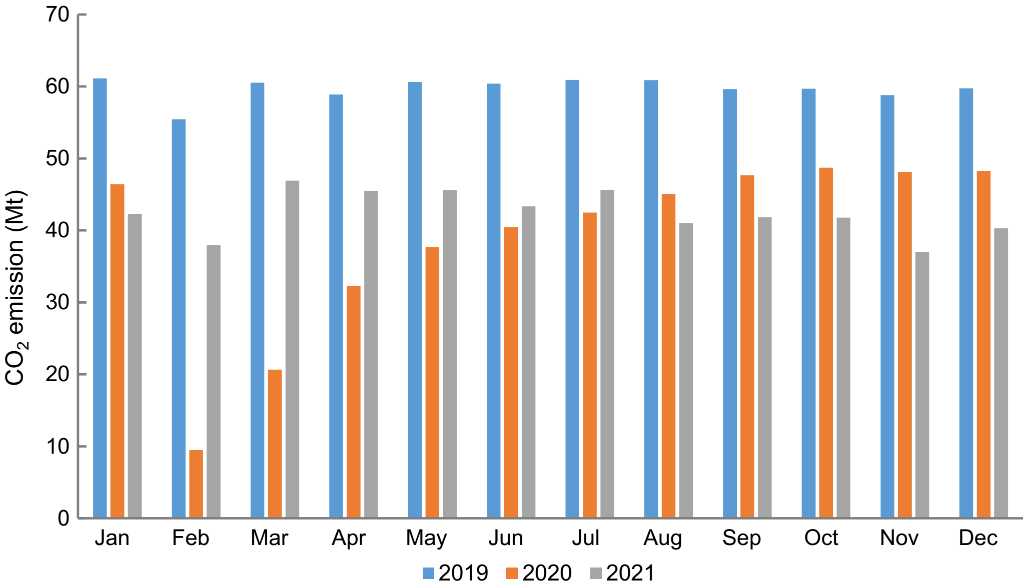

Fig. 4 Estimations of CO_2 emissions from urban passenger transport modes in China by month, 2019–2021

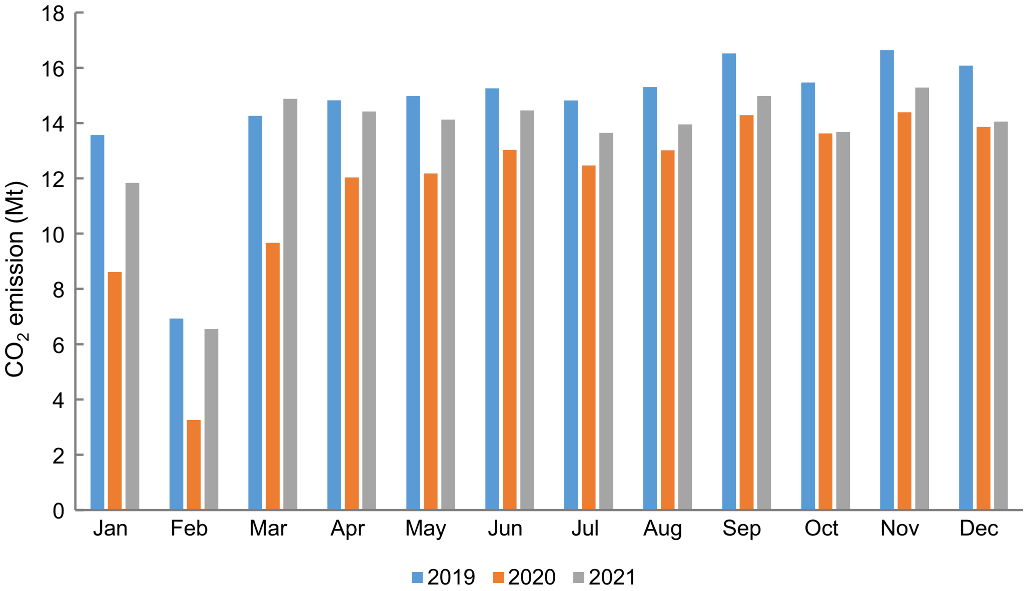

Fig. 5 Estimations of CO_2 emissions from private trucks and rural freight vehicles in China by month, 2019–2021

despite the adverse effects of COVID-19 on global economic development.

First, travel demand in China needs to be reduced and managed more carefully by optimising urban structure and integrating telecommunications and transportation to replace unnecessary travel. There is an increasing consensus that the growth of the total transport demand must be managed globally [73]. Specific strategies to reduce and manage travel demand include designing compact and mixed-use urban spaces, creating 15-min living circles, managing local traffic demand, optimizing the spatial layout of urban logistics systems, and encouraging remote and flexible work [74, 75]. To materialise a modal shift towards more environmentally-friendly transport modes, the encouragement of high-speed rail and urban public transit is crucial. This can be achieved by upgrading facilities, improving services, and fostering better integration with all

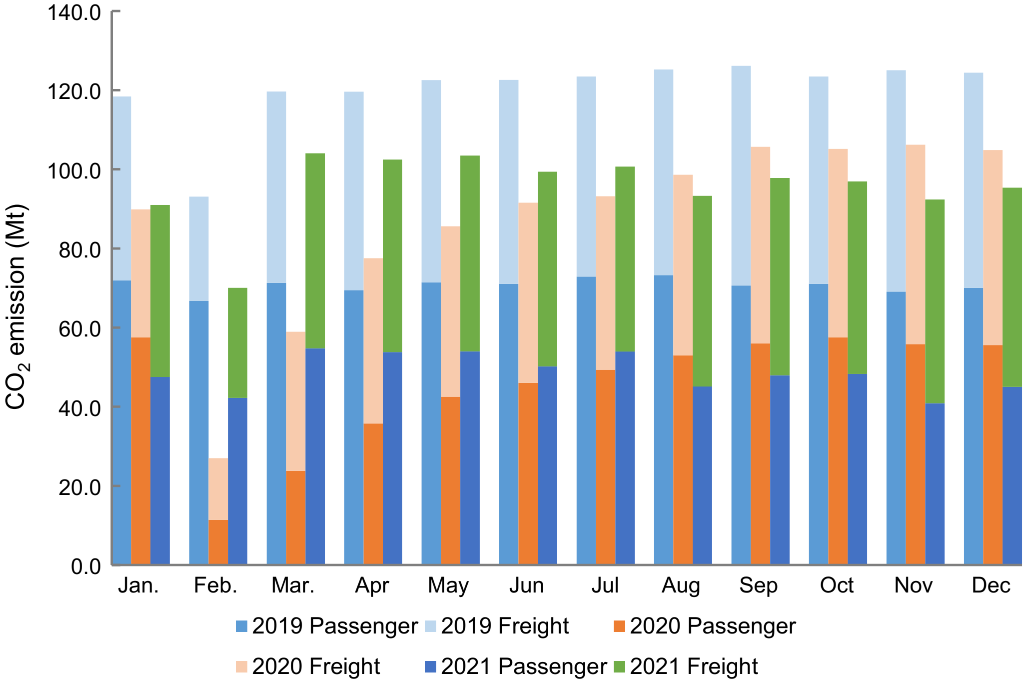

Fig. 6 Estimations of total passenger and freight transport CO_2 emissions in China by month, 2019–2021

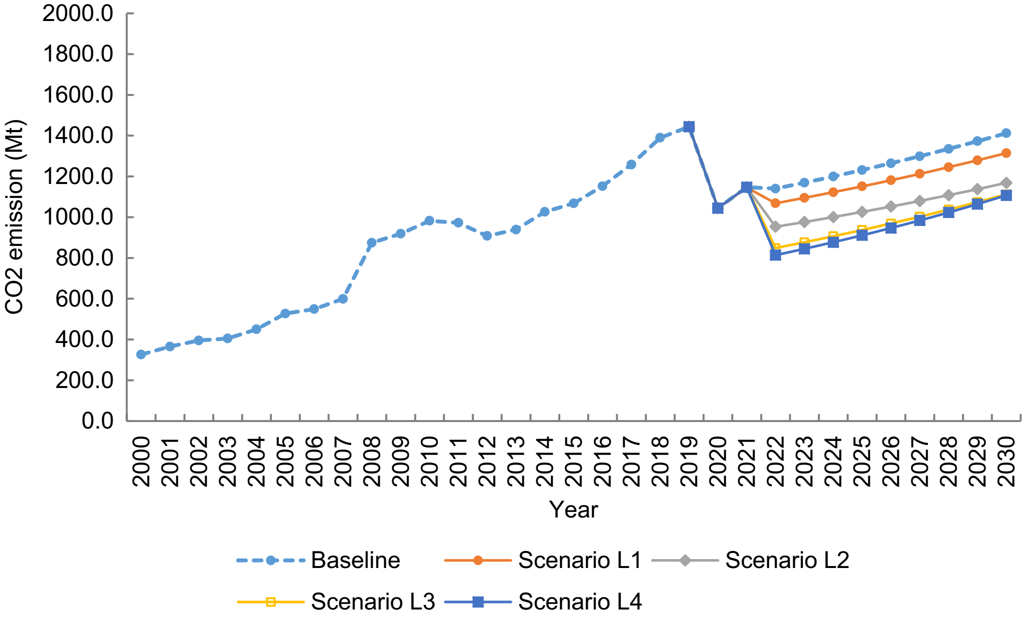

Fig. 7 The CO_2 emissions of passenger and freight transport in China in the medium-term under scenarios L1–L4

other transport modes [76, 77]. Measures to promote a shift in transport modes include encouraging shared mobility services, developing urban rail transit systems, enhancing pedestrian and cycling experience, promoting seamless multimodal transport, and encouraging individuals to use more environmentally-friendly modes of transport [78].

Second, the usage of electricity in both passenger and freight transport is necessary to reduce the reliance of the transport sector on fossil fuels. On roads, the primary approach will involve promoting electric vehicles and encouraging active transport [65, 79]. This includes the promotion of EVs with financial support, the construction of charging infrastructure, the development of electric public transport, R&D in EV technologies, and the establishment of relevant technical standards for EVs [80, 81]. However, due to carbon uncertainty, the transition to cleaner power systems must be ensured to realise and maximise the carbon reduction effects of EV adoption [70].

Third, the energy efficiency of all types of passenger and freight vehicles requires improvement through technological advancements and more stringent fuel economy standards. Concerning electricity generation, prioritizing a cleaner energy mix is essential. By further reducing the share of power generated from coal-fired stations and enhancing the efficiency of electricity for EVs, the CO_2 emission intensity of EVs could improve from being 38% lower than traditional fuel vehicles in 2020 to 69% lower by 2030 [81]. Nonetheless, it is important to reiterate that, given the scarcity of key minerals and other effects, there remains a need to limit the total transport volumes. In other words, the additional measures suggested are not alternative independent options. Only a holistic and synergetic bundle of measures for achieving transport decarbonisation will work. Improving energy efficiency involves enhancing energy technological innovations, establishing and enforcing energy efficiency standards, encouraging transport companies to adopt energy-saving equipment, promoting the purchase and use of vehicles with higher energy efficiency by citizens, and improving the efficiency of transport routes to reduce energy loss [82].

Currently, the Chinese government has made significant efforts in these directions. These efforts include supporting the development of new energy vehicles through subsidies, expanding charging infrastructure, extending the urban rail transit system, enacting energy conservation laws, and implementing goals for decreasing energy intensity [83]. For instance, China has adopted a multiprong approach to promote low-carbon transport. These measures include the extension of national subsidies for the purchase of new energy vehicles and tax exemptions. Meanwhile, the proportion of new energy vehicles in newly produced trucks is expected to reach around 10% by 2025, and the proportion of new energy vehicles in the urban bus fleet is projected to exceed 50% by 2025 [84]. Furthermore, the carbon emission factor in the power industry has been falling steadily.

However, industry-led measures are also necessary and may even be more effective in reducing carbon emissions in the transport sector [85]. For instance, transport industry associations could achieve decarbonization by promoting energy-efficient technologies, developing multimodal transport systems, researching and developing new energy technologies, and enhancing fuel quality. At an individual level, further raising environmental awareness, opting for the purchase and use of zero-emission vehicles, and choosing low-carbon transport modes are crucial in reducing transport carbon emissions. Reducing transport carbon emissions necessitates collaborative efforts from the government, industry, and individuals through policy support, technological innovations, and consumer choices to drive transport decarbonisation.

Based on the extra transport carbon reduction strategies above, we produce a set of additional scenarios (L1'-L4') that the collaborative efforts will lead to further behavioural changes—half of the air passenger transport would shift to rail by 2030, 50% of the vehicles on road would change to EVs, and 100% of city buses would change to EVs. Also, there will be cleaner electricity generation in China. In 2020, the percentage of EVs in taxis, private cars, and city buses was about 9%, 1%, and 55%, respectively. Figure 8 shows the resulting $L1'$-$L4'$ scenarios, combining the long-term effects of COVID-19 and the stronger transport carbon reduction strategies.

As shown in Fig. 8, transport CO_2 emissions are estimated to peak before 2030 across scenarios $L1'$-$L4'$ with both the impact of COVID-19 and intensified transport decarbonisation strategies. Under the minimal and low-impact scenarios of $L1'$ and $L2'$, where the effects of COVID-19 are less severe, the peak can potentially be reached earlier around 2025, when the lines start to flatten. However, in the severe-impact COVID-19 scenarios characterized by economic recession and sluggish R&D investment ($L3'$ and $L4'$), the peak cannot be reached until 2030. Therefore, combining the long-term effects of COVID-19 with robust transport decarbonisation measures, notably modal shift and new energy applications [86, 87], the transport sector in China would still have an opportunity to achieve the target of limiting temperature increase to within 1.5 °C before 2030.

Conclusions

In conclusion, the findings suggest that the impact triggered by COVID-19 alone will not be sufficient to meet the ambitious transport decarbonisation targets. With the short-term impact of COVID-19, the estimated carbon emissions from the transport system in China amounted to 1044.2 Mt in 2020, indicating a 28% decline compared to 2019. Over the medium- and long-term, various effects of COVID-19 are expected to be beneficial for transport decarbonisation. In comparison with the business-as-usual scenario, transport carbon emissions are projected to decrease by 6%, 15%, 21%, and 23% under the minimal-impact, low-impact, moderate-impact,

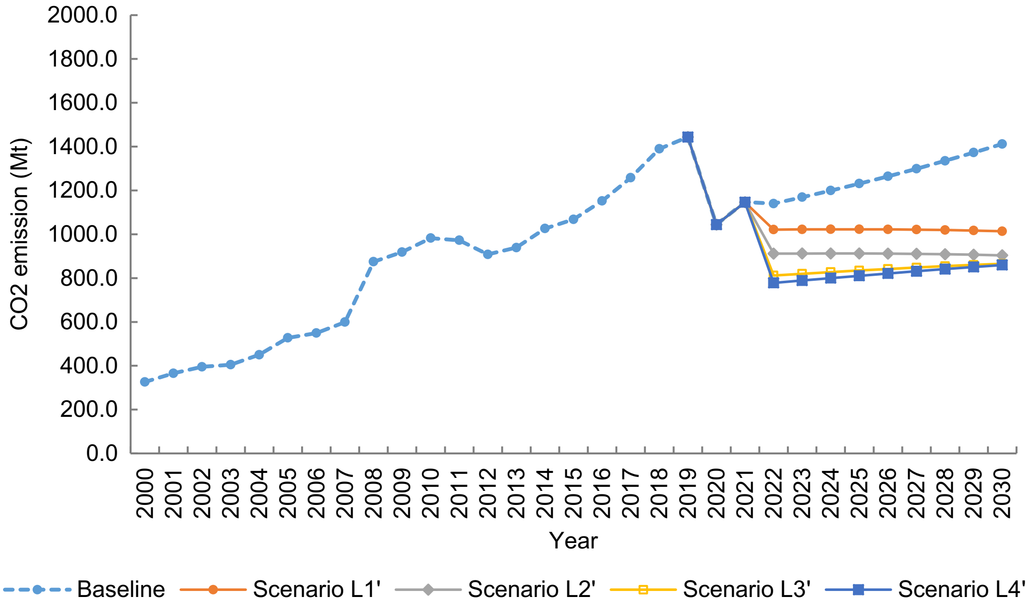

Fig. 8 The CO_2 emissions of passenger and freight transport in China in the medium-term under additional scenarios with strong transport carbon reduction measures

and severe-impact scenarios, respectively. Nevertheless, achieving China's commitments under the United Nations Framework on Climate Change necessitates combining the long-term effects of COVID-19 with robust transport decarbonisation measures like modal shift and the adoption of new energy applications. These lessons are also pertinent to other developing countries.

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Author contributions
Linna Li contributed to the methodology, visualization, and writing- original draft preparation; and Becky P.Y. Loo contributed to conceptualization, methodology, and writing—reviewing and editing.

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Declarations

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