Jiang, M, Wang, B, Hao, Y, Chen, S, Wen, Y and Yang, Z

Quantification of CO2 emissions in transportation: An empirical analysis by modal shift from road to waterway transport in Zhejiang, China

Transport Policy 145 (2024) 177–186

Contents lists available at ScienceDirect

Transport Policy

journal homepage: www.elsevier.com/locate/tranpol

Quantification of CO2 emissions in transportation: An empirical analysis by modal shift from road to waterway transport in Zhejiang, China

Meizhi Jiang [a,b], Benmei Wang [a], Yingjun Hao [a], Shijun Chen [a], Yuanqiao Wen [b], Zaili Yang [c,*]

[a] *Port and Navigation Research Institute, Zhejiang Scientific Research Institute of Transport, Hangzhou, China*
[b] *Intelligent Transportation System Research Center, Wuhan University of Technology, Wuhan, China*
[c] *Liverpool Logistics, Offshore and Marine Research Institute, Liverpool John Moores University, Liverpool, UK*

ARTICLE INFO

Keywords:
CO2 emissions
Road transport
Waterway transport
Reduction potential
Modal shift

ABSTRACT

In view of the huge contribution of transportation to global greenhouse gas emissions, it is imperative to embrace more carbon-efficient transportation modes to support our environmental goals. However, few studies offer empirical evidence to evaluate the potential of shifting transportation model for carbon emissions reduction. This paper, aiming at addressing this gap, conducts an empirical study to assess the CO2 emissions reduction through modal shift from road to waterway transport (MSRW). It utilizes primary data collected from more than 200 voyages of 92 enterprises through one national pilot project on CO2 emission reduction in the Quzhou region initiated by the Chinese central government. Specifically, it employs empirical analysis based on bottom-up methodologies to investigate the potential for CO2 emission reduction through MSRW. The results reveal that MSRW can aid to benefit 45,907 tons CO2 emission reduction from the modal shift within the study scope. When considering factors such as distance and voyage density, it provides new quantitative insights into the advantages of water transport over road transport in terms of CO2 emission reduction under different scenarios. Consequently, this study makes new contributions to the quantification of the benefits that an investigated region/city can derive from transport modal shift. It thereby lays the groundwork for effective cost-benefit analysis and policy implementation toward cleaner transportation.

1. Introduction

Transportation activities play a significant role in driving global economic growth. Given the fact that transportation activities produce approximately 20% of global greenhouse gas (GHG) emissions, particularly CO2 (IEA. International Energy Agency, 2014; 2016), the increasing use of transportation for economic development will unavoidably lead to a rise in global CO2 emissions. In recent years, it has become increasingly clear that CO2 emissions make a significant contribution to anthropogenic global warming, with their continuous growth resulting in numerous incalculable consequences for the ecosystem of the Earth and the human living environment. This concern for the sustainable development of Earth's ecological environment has stimulated research and policy developments aimed at reducing CO2 emissions from transportation (Hoang and Pham, 2020).

In light of the current global environmental situation, various governmental bodies have proposed measures aimed at the reduction of CO2 emissions across different transport models. For instance, the European Commission (EC) has mandated a speed limit rule for all ships entering European ports (Cariou and Cheaitou, 2012). Germany has proposed a series of measures and actions to reduce CO2 emissions from highways (German Government, 2019). It is also in line with an EU policy to prohibit the sale and production of new internal combustion engines by 2035 (European Commission, 2021). China has been actively fulfilling its commitments under the Paris Agreement and has undertaken strenuous efforts to combat carbon emissions by implementing strict rules and actions in pursuit of the goal to peak CO2 emissions by 2030 and achieve carbon neutrality by 2060.

In this context, the analysis of carbon emissions from various transport modes, including railways, highways, waterways, and civil aviation, under different policies and measures, has been widely conducted and documented in recent years (Song et al., 2019; Du et al., 2019, 2021; Trevisan and Bordignon, 2020). However, progress in reducing CO2 emission in the field of transportation sector has been still slower compared to other sectors (Peiseler and Serrenho, 2022), and hence it is of great importance to develop more efficient studies and policies for

* Corresponding author.
E-mail addresses: jiangmeizhi_zrit@163.com (M. Jiang), z.yang@ljmu.ac.uk (Z. Yang).

https://doi.org/10.1016/j.tranpol.2023.10.026
Received 7 June 2023; Received in revised form 9 October 2023; Accepted 30 October 2023
Available online 31 October 2023

carbon emission reduction. Current research in the field primarily focuses on individual transport sectors (e.g., waterways or highways) (e.g., Trozzi and Vaccaro, 1998; Dragović et al., 2015; Cariou et al., 2019; Lu et al., 2020; Duan et al., 2021; Hoang et al., 2022; Jimenez et al., 2022; Thaddaeus et al., 2022). The potential of exploring a carbon emission reduction solution by modal-shift studies across different transport modes are at large scanty, particularly from an empirical evidence perspective (Zhou et al., 2021; Ülker et al., 2021). This gap highlights the demands for new studies to investigate the effectiveness and efficiency of such solutions.

This paper aims to evaluate the CO2 emissions reduction by modal shift from road to water transportation (MSRW) and to generate empirical evidence demonstrating the effectiveness of MSRW in quantifying CO2 emission reduction. It conduces a case study by using a pilot on one of its most advanced manufacturing (i.e., Quzhou) in China. Recently, with the continuous growth of waterway transport turnover and CO2 emissions, studies on waterway transport has gained popularity in both academic and industrial fields (Gibbs et al., 2014; Jimenez et al., 2022). However, research on MSRW remains limited, which mainly focuses on the calculation of CO2 emissions and analysis of impact factors (Zhou et al., 2021; Wang et al., 2022; Alam et al., 2017; Xing et al., 2020). The quantification of CO2 emissions reduction from MSRW has predominantly concentrated on analysing the influencing factors of various measures and actions. To realize the peak CO2 emissions targets through the pathway of MSRW, it is crucial to analyse the transport links associated with CO2 emissions, so as to rationally inform and propose suitable policies and actions. This is an urgent need for research to evaluate CO2 emissions reduction by MSRW, which could offer guidance for making effective and appropriate measures and policies in large economic engines such as China, hence making new contributions from an applied research perspective.

The remaining part of this study is outlined as follows. Section 2 reviews the literature on CO2 emissions and their reduction within the field of transportation and its subdivision. Section 3 introduces the methodology and data source to support empirical analysis. Results of the empirical case in the Quzhou Region, together with comparative based on modal shift, as well as implications are presented in Section 4. Section 5 summarises the conclusions.

2. Literature review

Numerous studies have been carried out to examine CO2 emissions reduction from transportation over the past decades in respond to increasing environmental pressure. For instance, Ulrich and Karl (2022) proposed a method to estimate transport-CO2 emissions in European cities. Song et al. (2019) explored the CO2 emission reduction potential of China's transportation sector from 1991 to 2015. Wei et al. (2021) presented a novel approach to estimate the potential gains of CO2 emissions trading in the transport industry in China. Ağbulut (2022) employed three machine-learning algorithms to predict Turkey's CO2 emissions in the field of transportation. Wang et al. (2020) presented a project about the analysis of the CO2 emissions trends in transport for 29 Eurasian countries and explored the key influence of CO2 emissions decoupling using the logarithmic mean Divisia index (LMDI) method. Du et al. (2021) introduced a marginal abatement cost curve, using The Integrated MARKAL-EFOM1 System (TIMES) model, to identify the linkages among all transport modes, thus further estimating the potential for CO2 emissions reduction in China's transportation industry.

Investigation of the subdivision of transportation on CO2 emissions was also an increasing part of the research. The majority of research in the transportation industry focuses on emissions of CO2 from road transportation due to its high cargo turnover. According to Dong et al. (2022), who employed the bottom-up method to compute emissions of CO2 through road travel and the LMDI approach to examine the influence of influencing factors on the reduction of CO2 in road travel, China may have the potential to achieve carbon neutrality. Xu et al. (2022) incorporated highway mileage and CO2 emissions into the impact analysis of the increasing highway infrastructure on CO2 emissions. Xu et al. (2021) used a bottom-up approach to quantify the CO2 emissions from road vehicles and presented a national vehicular Carbon dioxide emission inventory that offered fresh information on China's vehicle CO2 emission controls. Alam et al. (2017) introduced a bottom-up data-based modelling technique to improve the accuracy of the GHG emissions estimation from the road transport sector in Irish. According to the analysis by Lu et al. (2020) on the potential for reducing CO2 emissions from road transportation in China, the short-term focus should be on increasing transportation equipment, while the long-term focus should be on updating technology. To gain a better understanding of the impact of engine warm-up states on vehicle CO2 emissions, Wang et al. (2022) devised a microscopic CO2 method to explore the link between ambient temperatures and CO2 emissions. Zhou et al. (2022) proposed a CO2 emission simulation model based on transport equipment trajectory to estimate CO2 emissions and employed a multi-dimensional geographical weight model to identify internal factors influencing road traffic CO2 emissions.

In terms of different transport modes, road transport is statistically the dominant source of transport carbon emissions. According to the Annual Report of China Mobile Source Environmental Management, GHG emissions from highways, waterways, civil aviation, and railways in China in 2020 amounted to approximately 6.9, 0.7, 0.5, and 0.1 million tons of CO2 equivalent, accounting for 84.1%, 8.5%, 6.1%, and 1.2%, respectively (MEE, 2020). Despite the rapid expansion of the waterway sector over the past few decades, it has also played a significant role in freight transport in terms of cargo turnover. In 2021, highway, waterway, civil aviation, and railway accounted for 30.7%, 53.6%, 0.1%, and 15.6% of cargo turnover, respectively in China (MEE, 2022).

Regarding adjustments to the transportation structure, various policies about CO2 emissions reduction have been introduced in a series of significant initiatives in recent years. For instance, in 2021, China issued the document "Opinions on the Complete, Accurate and Comprehensive Implementation of the New Development Concept and the Work of Carbon Peaking and Carbon Neutrality" (State Council of the PRC, 2021), followed by the "Work Plan for Promoting the Development of Multimodal Transport, Optimizing and Adjusting the Transport Structure" (State Council of the PRC, 2022), which highlights the advantages of waterways due to their low energy consumption and low emissions. China's waterway transport has experienced complex changes over the past decades. The Chinese Ministry of Transport released the 14th Five-Year Development Plan for Green Transport (MT, 2022), with a focus on shifting bulk cargo transport and medium and long-distance freight transport from roads to waterways. Since then, various cities have introduced related subsidies to support MSRW. It is therefore evident that more new building ships are entering the transport market (Zhou et al., 2021). On one hand, it may reduce the overall carbon emissions due to the energy-efficient and environmentally friendly nature of waterways compared to road transport. On the other hand, a significant increase in goods transported via water transport may impact the efficiency of water transport, potentially affecting CO2 emission reduction efforts.

The growing volume of global trade has a favourable impact on the levels of CO2 emissions produced by ships, as indicated by studies on CO2 emissions within maritime transport sector. Tran and Lam (2022) developed a model to simulate container flows by examining the influence of ship operations on CO2 emissions from a supply chain perspective. Mersin et al. (2019) analyzed the methods proposed by the IMO and discussed their advantages and disadvantages in the context of CO2 emissions reduction in maritime transportation. Zhu et al. (2018) developed a planning model based on random distribution to investigate the relationship between open Maritime Emissions Trading Systems (METS) and CO2 emission levels. Jimenez et al. (2022) proposed a comprehensive review of energy consumption and operational efficiency within the maritime industry, using a novel approach to offer valuable insights into CO2 emissions. The pathways for reducing CO2 emissions in the maritime sector were examined by Xing et al. (2020), who also established the agenda for future research and practical initiatives. By using the Automatic Identification System (AIS) data from Tianjin Port, China, Chen et al. (2016) proposed an energy-based method to analyse ship CO2 emissions. Chen et al. (2018) proposed a ship emission inventory for Bohai Rim Region, China, aiming to estimate the impact of ship emissions.

Apart from these studies analyzing the CO2 emissions reduction within different transportation sectors or subdivisions, there is a group of studies focusing on the comparative analysis of the impact of transport modal shift on CO2 emissions reduction across different subdivision sectors. The modal shift from road to sea transport has a beneficial effect on the reduction of GHG in terms of the analysis of CO2 emissions from short-distance waterway transport and road transport in Marmara conducted by Ülker et al. (2021). This finding provide a theoretical basis for the sustainable transportation development in the region. Zhou et al. (2021) used the LMDI approach to analyse the influencing factors behind CO2 emissions and the results confirmed that an effective structure change in transport would contribute to CO2 emissions reduction. Obviously, compared to the single mode analysis, studies on modal shift for CO2 emission reduction are limited and the MSRW poses a new research challenge. It is essential to conduct empirical studies to identify whether the MSRW has a positive impact on carbon emission reduction and if so, to quantitatively evaluate the extent to which the reduction can be maximized.

Top-down and bottom-up methodologies are predominantly employed in the literature on CO2 emission assessment in transportation (Miola and Ciuffo 2011; Chen et al., 2016; Alam et al., 2017; Dong et al., 2022; Xu et al., 2021). The bottom-up method involves calculating the CO2 emissions of specific ships or vehicles by analyzing their fuel consumption during transportation, while the top-down method is used to determine the overall carbon dioxide emissions in the maritime or road transport field by relying on tools such as energy balance sheets. The bottom-up method can yield reliable analysis results when the data on each involved specific vehicle can be accessed. In this paper, the bottom-up approach is used to determine the extent of CO2 emissions reduction achieved by MSRW in the Quzhou Region for its advantages in providing reliable modelling on specific ships/vehicles or lines.

It is also noteworthy that along with the studies focusing on CO2 emission evaluation, there is another cluster of studies on the uncertainty in carbon valuation which involve the cost benefit analysis or economic impact of carbon abatement. For instance, Meunier and Quinet (2015) reviewed critical projects that affect the accuracy of CO2 emission assessment and proposed a transport cost benefit analysis to value carbon emissions while considering associated uncertainty. Nocera et al. (2015) introduced a meta-analysis to analyse the economic implication of carbon abatement which could reduce the uncertainty through the investigation of the variation in emission costs. Nocera et al. (2018) believed that the value of carbon emission should be not uniform across sectors, advocating for a fair carbon evaluation specifically for the transportation sector. Nevertheless, the research scope of this manuscript is defined as the CO2 emission reduction through MSRW. It means that the cost-benefit of CO2 emission reduction and the associated uncertainty in valuations are beyond the main scope of this paper and will be a subject of consideration in future.

In view of the above, the contribution of this paper to the reduction of carbon emissions can be summarized as follows. 1) It offers a new analysis perspective to quantify the potential for carbon emission reduction by considering multidimensional MSRW, departing from the traditional approach of examining carbon emissions from single-dimensional transport modes or their subsectors as seen in previous studies. 2) It provides an effective technical solution for quantifying and evaluating the effect of the implementation of transport structural adjustment policies on carbon emissions. 3) It proposes a novel research method that addresses the uncertainty associated with both the top-down approach at a macro level (i.e. focusing on the whole transport system) and the bottom-up approach at a micro level (i.e. targeting single vehicles) simultaneously, to enable the detailed quantification of carbon emissions across an entire transport chain. It, therefore, makes significant contributions to the justification and implementation of newly introduced relevant policies.

3. Methodology and data source

3.1. Definition of carbon emission accounting boundary

Door-to-door transportation by road requires just three steps: loading, road transportation, and unloading, while water transportation must involve loading at the warehouse, road short barge to the port of departure, water transportation to the port of destination, and road short barge to the warehouse, and unloading. Door-to-door transportation by waterway can be described as three main links: road short barge at both ends, port loading and unloading operations, and water transport. As a result, when considering carbon emissions generated during transport, road transport only needs to account for the carbon emissions produced during the door-to-door journey of transport vehicles. Conversely, the estimation of CO2 emissions in water transport is relatively complicated, as it includes emissions from ships, port machinery, and ship locks, etc.

3.2. Approach to evaluating CO2 emission reduction of MSRW

3.2.1. CO2 emission reduction of a single voyage

The CO2 emission reduction of a single voyage of MSRW is defines as the CO2 emission reduction of water transportation compared with road transportation in the transportation demand of the same batch of goods (the same flow and direction), can be calculated as Eq (1):

$$S_{CER} = S_R - S_W - S_{SB} - S_P - S_L \tag{1}$$

where S_{CER} denotes the CO2 emission (tonnage) reduction of a single voyage, S_R and S_W represent the CO2 emission by road and waterway respectively that can be calculated by Eqs (2) and (3), S_{SB} represents the CO2 emission by short barge at the port of departure and destination, which can be calculated in the same way as S_R shown in Eq (3), S_P is the CO2 emission generated by the ship's operation at the origin and destination ports, and S_L represents the CO2 emission corresponding to the power consumed by the ship passing the lock in each voyage.

$$S_W = \sum e_{ij} \times K_{ij}^{s} \times C \tag{2}$$

where i represents the fuel type and j is the ship type, e_{ij} represents the CO2 emission (tCO2/t·km) per unit mile of a ton of goods transported by class j ship under the use of class i fuel, with its value shown in Table 1. K_{ij}^{s} denotes as the distance (km) of class j ship transported under the fuel of type i. C is the cargo weight of the ship for the voyage (t).

$$S_R = \sum FC_{ij}^{v} \times EF_i \times K_{ij}^{v} \times \frac{C}{N} \tag{3}$$

where FC_{ij}^{v} represents the fuel consumption per 100 km (tCO2/km) by class j vehicle under the use of class i fuel, and the value is shown in Table 2 EF_i is CO2 emission factors (tCO2/t) for class i fuel, and the value is shown in Table 3, N denotes the rated load (t) of different vehicles, assuming full load.

$$S_P = \frac{\sum FC_i^{p} \times EF_i}{T} \times C \times 2 \tag{4}$$

where FC_i^{p} refers to i kind of fuel that was used by the port in the previous year, and T is the port throughput of last year.

Table 1
Examples of the value of e_{ij}.

Ship types/Dead weight ton (t)		e_{ij} (10-6t/t·km)	Intensity of energy consumption	
			Diesel ((10^{-6}t/t·km)	Standard coal (10^{-6}t/t·km)
Bulk carrier	DWT≤500	13.839	3.789	5.521
	500<DWT≤1000	10.764	2.947	4.294
	1000<DWT≤1500	8.623	2.361	3.44
	DWT>1500	5.528	1.514	2.206
Dry cargo ship	DWT≤500	18.34	5.021	7.316
	500<DWT≤1000	11.585	3.172	4.622
	1000<DWT≤1500	7.198	1.971	2.872
	DWT>1500	4.462	1.222	1.781
Multiple purpose ship	DWT≤500	9.714	2.66	3.876
	500<DWT≤1000	6.353	1.739	2.534
	1000<DWT≤1500	4.711	1.29	1.88
	DWT>1500	5.243	1.435	2.091
Container ship	DWT≤500	/	/	/
	500<DWT≤1000	10.853	3.015	4.393
	1000<DWT≤1500	5.635	1.566	2.282
	DWT>1500	/	/	/

The data is calculated by Eqs (10) and (11) in Section 3.3 Data source.

Table 2
Examples of the value of FC_{ij}^{v}.

Ship types/Vehicle exhaust emission standards/weight (kg)		FC_{ij}^{v} (10^{-3}t/10^{2}km)	
		Diesel	Gasoline
Level III and below	weight≤1800 kg	8.084	7.811
	1800< weight ≤4500 kg	13.330	13.578
	4500< weight ≤12000 kg	19.178	19.491
	12000< weight ≤20000 kg	28.380	/
	20000< weigh≤31000 kg	37.840	/
	weight >31000 kg	43.000	/
Level IV	weight≤1800 kg	7.310	7.081
	1800< weight ≤4500 kg	11.180	11.388
	4500< weight ≤12000 kg	16.770	17.082
	12000< weight ≤20000 kg	25.800	/
	20000< weigh≤31000 kg	34.400	/
	weight >31000 kg	39.560	/
Level V	weight≤1800 kg	6.794	6.935
	1800< weight ≤4500 kg	9.890	10.074
	4500< weight ≤12000 kg	14.448	14.746
	12000< weight ≤20000 kg	22.360	/
	20000< weigh≤31000 kg	30.100	/
	weight >31000 kg	33.540	/
Level VI	weight≤1800 kg	6.622	6.716
	1800< weight ≤4500 kg	9.374	9.563
	4500< weight ≤12000 kg	13.674	13.943
	12000< weight ≤20000 kg	21.500	/
	20000< weigh≤31000 kg	25.800	/
	weight >31000 kg	31.820	/

Data are from the website of the Ministry of Industry and Information Technology, PRC.

$$S_L = \frac{\sum FC_{it}^{l} \times EF_i}{m_t} \times n \tag{5}$$

where FC_{it}^{l} refers to i kind of fuel that was used by the tth lock in the previous year; m_t is the total number of ships that passed through the tth lock last year; n is the number of locks required for the engaged voyage.

3.2.2. CO2 emission reduction of cargo owner enterprises

The calculation of CO2 emission reduction by cargo owner enterprises in a year includes two steps: 1) calculating the amount of MSRW undertaken by cargo owner enterprises and 2) quantifying the CO2 emission reduction of MSRW by cargo owner enterprises.

Table 3
Examples of the value of EF_i.

Fuel types	Standard coal coefficient (kg standard coal/kg)	Carbon emission factor (t CO2/t standard coal)	CO2 emission factors (tCO2/t)
The raw coal	0.7143	2.66	1.900038
Gasoline	1.4714	1.73	2.545522
Kerosene	1.4714		2.545522
Diesel	1.4571		2.520783
Fuel oil	1.4286		2.471478
Liquefied petroleum gas	1.7143		2.965739
Natural gas	1.33 (kg standard coal/m3)	1.56	2.0748kg/m3
The thermal	/	/	0.11 tCO2/million kilojoules
Electric power	/	2.85 tons/10,000 Kwh	Adopt the latest provincial average emission factor of the provincial power grid

The standard coal coefficient is derived from "General Principles for the Calculation of Comprehensive Energy Consumption" (GB/T 2589-2008); the Carbon emission factor, the thermal and electric power conversion carbon emission coefficient from the "Provincial Greenhouse Gas Inventory Compilation Guide" (Climate [2011]1041).

3.2.2.1. The calculation of the amount of MSRW by cargo owner enterprises. Based on the determination of CO2 emission reduction for a single voyage, the total CO2 emission reduction by cargo owner enterprises in a year is calculated by taking each owner enterprise as the research object. The accurate determination of the amount of MSRW is of paramount importance for assess the potential CO2 emissions reduction. In this study, cargo owner enterprises are divided into two types to more accurately identify the volume of MSRW. Using 2011 as baseline year, the first type of enterprises is defined as those that have not previously adopted water transportation but begun to do so since 2022 due to policies and other influences. The second category consists of businesses that, before 2022, utilized a variety of modes of transportation, including water transport and road transport. Following policy implementation, some of the road transport volumes have been shifted to water transport.

For the first type of enterprise, the MSRW volume for the current year is determined as the newly increased waterway transport volume. Starting from the next year, it will be identified based on the MSRW volume identification method of the second type of shippers. For the second type of enterprise, the MSRW amount for the current year is identified as the difference between the total increment of waterway transportation and the natural increment of cargo volume, which is calculated as Eq (6):

$$V_{ey} = V_{wey} - V_{we(y-1)} - \left(V_{we(y-1)} \times \frac{V_{sey} - V_{se(y-1)}}{V_{se(y-1)}} \right) \tag{6}$$

where y presents the year, V_{ey} is defined as the amount of MSRW of enterprise in the y year, V_{wey} is the cargo volume transported by the waterway of the enterprise in year y, V_{sey} is the total cargo transport volume of the region in yth year.

(2) CO2 emission reduction of MSRW by cargo owner enterprises

The CO2 emission reduction resulting from MSRW carried out by enterprises can be defined as the sum of the CO2 emission reduction generated by the completed voyage during the accounting period. For the first type of enterprise, the emission reduction of MSRW is determined to be the sum of the emission reduction of each voyage, which is calculated as Eq (7).

For the second type of enterprise, the emission reduction of MSRW is identified as the sum of the voyage emission reduction corresponding to its MSRW volume. For the enterprises with newly opened routes in the accounting year, the emission reduction for each voyage on the route is identified as the MSRW emission reduction; for the existing routes, it is determined that the emission reduction increased or decreased in the accounting year compared with the previous year, and the emission reduction of MSRW can be calculated as Eq (8).

$$E_{CER} = \sum S_{CERv} \tag{7}$$

$$E_{CER} = \sum S_{CERvn} + \sum S_{CERve} \times \left(\frac{V_{ey} - V_{eyn}}{V_{wey} - V_{we(y-1)} - V_{eyn}} \right) \tag{8}$$

where v denotes each voyage, E_{CER} is the amount by which CO2 emissions were reduced from MSRW during the accounting period, $\sum S_{CERv}$ refers to the amount by which CO2 emissions were reduced from MSRW in the accounting period of the first type of enterprise, $\sum S_{CERvn}$ is the amount by which CO2 emission were reduced from the newly added waterway transportation routes in the accounting period of the second type of enterprise, $\sum S_{CERve}$ is defined as the increased amount by which CO2 emission was reduced from the existing waterway transportation routes in the accounting period of the second type of enterprise compared with the previous year, V_{eyn} can be interpreted as the cargo transport volume of newly opened waterways routes of the second type of enterprise.

3.3. Computation of waterway advantage factor

It is obvious that waterway transport offers competitive environmental advantages over road transport. However, there is limited empirical evidence on how competitive the waterway transport could be, as it is influenced by multiple factors. Among them, distance is of great significance and deserves investigation. To measure the competitiveness, this paper introduces a waterway advantage factor (WAF), calculated as described in Eq. (9). It shows the distance superiority of waterway transport over the potential road distance between the investigated OD ports.

$$WAF(\%) = \frac{[d_r - (d_w \times s)] \times 100}{d_r} \tag{9}$$

where d_r represents the road transport distance between the OD ports (km), d_w means the waterway distance between the same OD ports (n mile), and s is the convertor between km and nautical miles, being 1.852km/n mile.

3.4. Data source

As one of the world's leading contributors to CO2 emissions (Zhou et al., 2020), China has also made great efforts in its transportation sector to achieve a carbon emissions peak and carbon neutrality through transport modal shifts (Cai et al., 2022). In 2022, the Office of the Zhejiang Provincial Transportation Leading Group issued the "Implementation Plan for Carbon Peak in the Transportation Field of Zhejiang Province", which proposes implementing modal shift from road to waterway transport (MSRW) for bulk goods and medium and long-distance goods. In addition, by the end of 2021, the total mileage of inland waterways in the Zhejiang province will be 9,771 km, and the mileage of high-grade waterways will reach 1,669 km. All 11 prefectures and cities will have access to the sea, which provides a good foundation for MSRW initiatives. The huge carbon emissions of road transport, combined with the ongoing policy support and infrastructure improvements for waterway transport, highlight the substantial potential of developing and implementing effective modal-shift measures to reduce transport CO2 emissions by moving freight from road to waterway transport.

Zhejiang Provincial Department of Transportation actively implements the national policy on transportation structure adjustment, and officially launches the online application digital platform of MSRW for bulk goods in Zhejiang Province in 2022, with Quzhou as a pilot. From the perspective of the carbon source structure of transportation in Zhejiang Province, the carbon emission of operating transportation accounts for about 70% of the total carbon emission of transportation, while the carbon emission of road transportation industry accounts for about 70% of the total carbon emission of operating transportation (Zhejiang provincial bureau of statistics, 2022). Therefore, the adjustments of transportation structure have a lot to do with the field of "carbon peak and carbon neutrality". While waterway transport is generally considered to be a clean and efficient mode of transport, and certain prerequisites for the transition from road to waterway transport are sometimes challenging to achieve (Gilbert and Bows, 2012).

Quzhou, as a city with developed waterway transportation, rapid economic development and a strong industrial foundation, is very suitable for being the first pilot city of the online application platform of MSRW. The mature waterway transport and strong industrial base in the region support multimodal transport within and outside Zhejiang province. Hence, the Quzhou Region is selected as the empirical case to investigate the CO2 emissions reduction potential of MSRW.

The ports in Quzhou are selected as the origin/destination ports, and the corresponding destination/origin ports include two categories: 1) in Zhejiang province and 2) outside the province. The ports outside Zhejiang province mainly include those from Shanghai, and Jiangsu provinces, while the ones inside Zhejiang province mainly are from the cities like Hangzhou and Jinhua, etc. They constitute the corresponding OD pairs shown in Fig. 1, namely (numbered), Anhui to/from Quzhou (1–11), Fujian to/from Quzhou (2–11), Henan to/from Quzhou (3–11), Jiangsu to/from Quzhou (4–11), Shanghai to/from Quzhou (5–11), Hangzhou to/from Quzhou (6–11), Jiaxing to/from Quzhou (7–11), Jinhua to/from Quzhou (8–11), Lishui to/from Quzhou (9–11), Wenzhou to/from Quzhou (10–11). Ninety-two enterprises account for most of the freight waterway transport in Quzhou. Therefore, more than 200 annual voyages involved in these 92 enterprises in the Quzhou Region are selected as the sample of this empirical case due to their advantages in industrial demands, infrastructure, and access to information.

The online application platform of MSRW developed by the Department of Transportation of Zhejiang Province issues yearly relevant statistics, including information on ships, vehicles, voyages, cargo owner enterprises and ports. Some specifications of vehicles were ob-

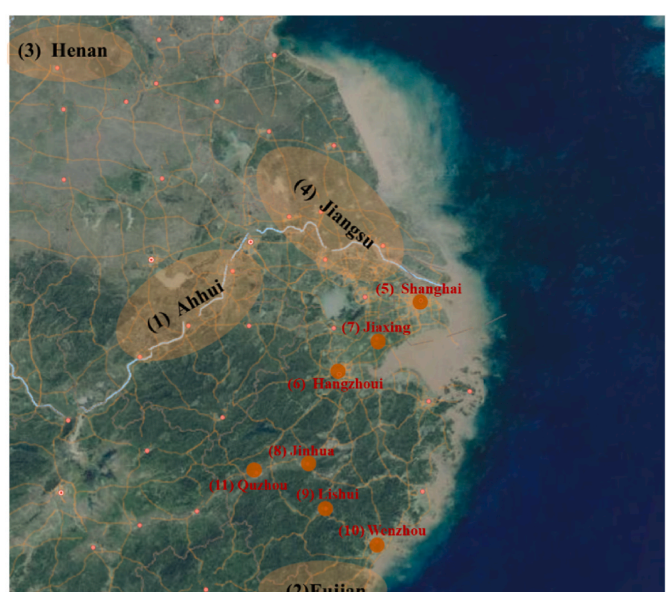

Fig. 1. The OD pairs selected in the empirical case.

tained from survey certificates issued by the Road Transport Comprehensive Supervision Platform, which include the type of vehicle, rated load capacity of the vehicle, and vehicle fuel type. Since individual CO2 emission (E) data for each ship are not available, the emissions of each ship are calculated using a bottom-up method based on AIS data. The following equation represents the general calculation method for a ship when travelling between sequentially reported locations (Chen et al., 2016, 2018; Goldsworthy and Goldsworthy, 2015).

$$E_{k,i,I} = P_k \times LF_{k,I} \times T_{k,i,I} \times EF_{k,i} / 10^6 \quad (10)$$

where $E_{k,i,I}$ represents CO2 emission from a kind k engine running on fuel kind i while in operating mode I (units: tonne); P_k is the rated power for engine kind k (units: kW); $LF_{k,I}$ means the fractional load factor for engine type k when operating in mode I; $T_{k,i,I}$ represents operating time for engine kind k, using fuel kind i when operating in mode I (units: h); $EF_{k,i}$ is the CO2 emissions factor, from engine kind k, using fuel type i (units: g/kWh). The rated power used in the calculation equation is derived from the China Classification Society (CCS) database. The calculation method of load factor is shown in Eq (10):

$$LF = (AS/MS)^3 \quad (11)$$

where LF defines as the load factor of the main engine; AS represents the actual ship speed that can be achieved from its AIS data (units: knots); MS means the maximum speed (units: knots) that can be achieved from the CCS database. The CO2 emission for each ship can be calculated by Eqs (10) and (11), and part of the results can be seen in Table 1.

4. Results and analysis

As seen from Table 4, there are a total of 92 enterprises involved in the Quzhou Region, and the freight volume of MSRW of the enterprises is 7 million tons. The corresponding CO2 emission reduction reaches 45,907 tons. Overall, the development of MSRW can hugely benefit the region to achieve carbon emission reduction in its transportation sector.

4.1. Comparing the waterway and highway routes in terms of distance

The WAF is defined in the study, which shows the distance advantage of waterway transport compared to road. As shown in Fig. 2, waterway distance compared with road transport distance between the OD ports and WAFs are obtained.

The results indicate that the WAF between the Quzhou port and the ports within Zhejiang province is generally higher than that bwtween QuZhou and the ports outside Zhejiang province. Among the ports outside Zhejiang province, those in Shanghai and Jiangsu region generally exhibit higher WAF values than those in other areas.

Table 4
The freight volume and CO2 emission reduction of MSRW.

Number	Enterprises	Freight volume (units: 10^4 tons)	CO2 emission reduction (units: tons)
1	Quzhou Yuanli Metal Products Co., LTD	15.97	686.98
2	Longyou Junan Logistics Co., LTD	0.44	18.53
3	Quzhou Leicheng Trading Co., LTD	5.42	262.47
4	Longyou Pengcheng Logistics Co., LTD	6.11	455.74
5	Nantong Guanhai Supply Chain Management Co. LTD	0.08	5.41
…	…	…	…
92	Quzhou Ruixin Logistics Co. LTD	4.26	294.40
Total		704.53	45907.18

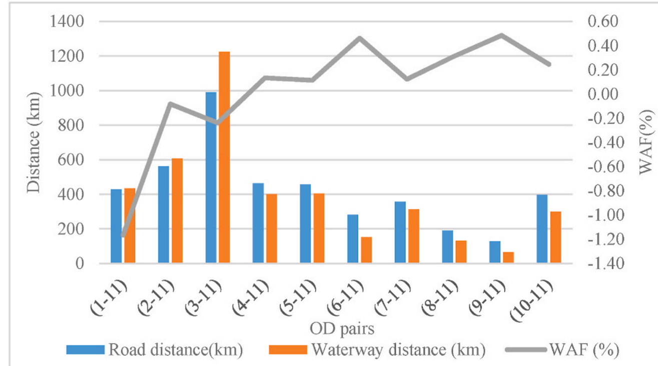

Fig. 2. waterway and road transport distance advantage factors of OD pairs.

The WAF is of significance importance for shipping companies to assess competitiveness and its environmental impact. Fig. 2 shows that the WAFs of shipping lines in Zhejiang province (6–11), (7–11), (8–11), (9–11) and (10–11) are higher. Ports in the Quzhou region are closely connected to other ports within Zhejiang Province. On the one hand, the ports in Zhejiang province have good water transportation infrastructure, while on the other hand, the industrial foundation behind it is strong, and there is a large demand for coal, iron ore, pulp and other bulk goods suitable for waterway transportation. The shipping lines outside Zhejiang province offer a lower WAF value, shipping lines (1–11), (2–11) and (3–11) even exhibit negative WAFs. Shipping lines (4–11) (5–11) in Jiangsu and Shanghai, which are leading water transport provinces, show their advantages over other provinces in infrastructure, industry and other aspects. The WAF of Jiangsu and Shanghai are higher than that of other provinces.

4.2. Comparing the waterway routes in terms of voyage density

As shown in Fig. 3, the busiest shipping lines of MSRW are shipping lines (4–11) and (7–11). Given their high values of WAF and a substantial number of voyages, they have played a pivotal role in reducing road transport around or inside the Quzhou region. Besides, the shipping lines (5–11) and (6–11) offer a relatively high number of voyages and are in relatively high demand. Meanwhile, their WAF values are also relatively higher than those of the other shipping lines, which can be seen in Fig. 2. Therefore, the port investment in these regions is particularly helpful to reduce road transport and thus reduce transportation-based CO2 emissions. Based on a comprehensive analysis considering environment, cost and benefit, increasing infrastructure investment in ports in the region, expanding industrial layout or establishing new lines can enhance water transport demand and further promote the associated MSRW initiatives.

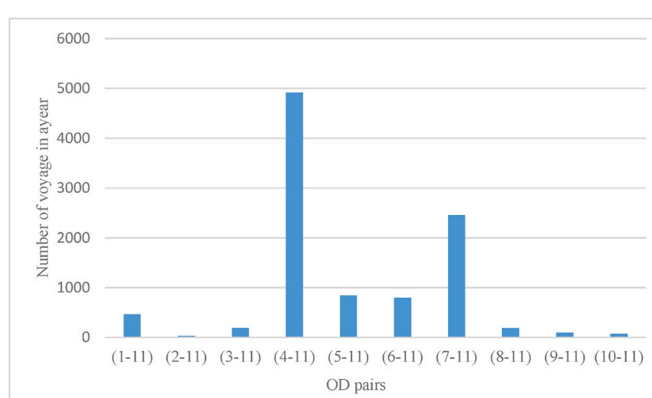

Fig. 3. Number of voyages of shipping lines.

4.3. Comparing the CO2 emission between waterway and road transport

The CO2 emissions from waterway are affected by such factors as distance, cargo volume, ship type, engine power, number of voyages, speed, and the way of computing the emissions. Meanwhile, the potential CO2 emissions from road transport are affected by factors such as distance, cargo capacity, vehicle type, number of vehicles and fuel. Given the commonality among the influential factors between the two modes, a comparative analysis on the emissions is conducted by using the approach in Section 3. The analysis results are presented in Fig. 4. In Fig. 4, the OD pairs of (6-11), (7-11), (8-11), (9-11), and (10-11) are combined into the OD pair of (6/7/8/9/10–11) due to the fact that the ports of 6,7,8,9, and 10 are all located in Zhejiang Province.

Shipping line (4–11) shows its best performance in terms of road transport's CO2 emission reduction potential. As the carrier truck of road transportation is a high-emission vehicle, the WAF of the line (4–11) is also at a high level, and the road transport demand of this line is the largest compared with other lines, resulting in the shipping line (4–11) having the highest potential for MSRW. This conclusion reflects the environmental advantages of multimodal transport instead of road transport as proposed by Liao et al. (2009).

The shipping lines (6–11), (7–11), (8–11), (9–11), and (10–11) serve the waterway transport in Zhejiang province, the demand of which is only the second to the shipping line (4–11), and its WAF is also at a high level. Therefore, the CO2 emission reduction of MSRW also has great potential. As for the shipping line (3–11), its WAF value is the highest among all the lines. However, the CO2 emission reduction of MSRW is also relatively small because its transport demand is less than other routes. On the other hand, the development of highway transportation along the route is advanced, which also has an impact on the potential of MSRW.

In view of this, this paper suggests that the value of WAF, the type of carrier vehicles and the type of ships should be carefully evaluated to realize the sustainable development of Quzhou in terms of both economy and environment. Increasing investment in environmentally friendly lines is crucial for Quzhou's long-term development. Transferring the transportation of containerized goods from road to waterway can reduce the transportation-based CO2 emissions, as well as alleviate road traffic congestion, and enhance residents' satisfaction with their living environment.

Future efforts to reduce CO2 emissions will be more effective thanks to the continued development and use of clean energy source as well as the promotion of shore power technologies. Waterway transport can take the first step of decarbonization by adopting these technologies. It will be beneficial to conduct future studies on the impact of using new clean energy/technologies on the MSRW in general and the Quzhou case in specific.

4.4. Scenario analysis

The comparison analysis results between road and waterway transport in terms of distance, voyage density and CO2 emissions have revealed the necessity of MSRW. In order to further analyse the impact of MSRW on CO2 emissions for policy implications, scenario analysis is conducted by adjusting the original data in this section.

Three scenarios are set up in this paper to investigate the MSRW effect on CO2 emissions including: **I-cargo volume scenario**-increasing the cargo volume of MSRW; **II-lock scenario**-optimizing the waiting time of the ship; **III-port handling scenario**-changing fuels to clean oil and/or electricity for port handling machinery. These scenarios were chosen based on the analysis's findings regarding the areas of the entire transport chain that could most readily benefit from potential policies in the near future.

Under the scenario I, we assume that the cargo volume of MSRW of 92 enterprises increases by 10% compared to the original volume. The result of the optimization measure is a 6.5% increase in CO2 emission reduction for the corresponding MSRW. Therefore, increasing transport capacity and infrastructure of waterway transport is an effective way to increase waterway freight volume and thus reduce carbon emissions.

Under the scenario II, 16 ship locks in Zhejiang province are investigated, which mainly located in the JingHang Canal, Hangyong Canal, and Qiantang River. Generally, the average waiting time of the lock is about 2 days. For the Sambo lock, a core hub, the average waiting time for the lock is about 5 days, and it even can extend to 15 days. Although the main engine of the ship is turned off while waiting in a lock, the auxiliary engine is still needed to generate essential energy to meet the living needs of the crew and thus produce a large amount of carbon dioxide. Thus, it is advantageous to shorten the ships' lock wait times. In scenario 2, we analyse the impact of the reduced time of ships passing the gate to half of the original time. The results show a 1.5% reduction in overall CO2 emissions, which provide evidence to support the opinion that improved operational efficiency can reduce the CO2 emission.

Under the scenario III, the main types of energy directly used for loading and unloading operations and auxiliary products in the port are electricity and diesel. By applying electric power and clean energy to fuel-consuming machineries such as cars, single-bucket loaders, front cranes, vehicles, and excavators, diesel consumption can be reduced and carbon emissions of port operating machinery can be also reduced accordingly. According to the previous investigation and analysis conducted by the Zhejiang Provincial Department of Transport, under strict control of the energy structure of the port, the use of diesel oil in the associated ports connecting Quzhou can be reduced by approximately 3%–5%. Assuming a 5% reduction, the results show that the use of clean energy can also reduce overall CO2 emissions at a level of 0.4%. The application and promotion of clean energy represent one of the main

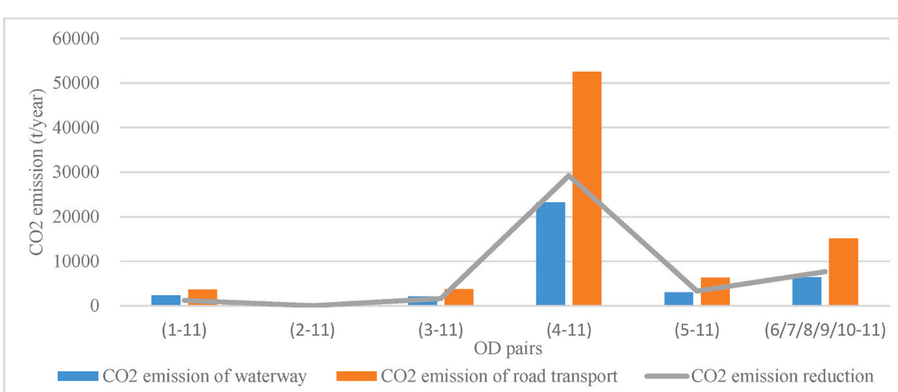

Fig. 4. Comparative analysis of CO2 emission results for waterway and road transport.

directions for future carbon emission reduction efforts.

4.5. Policy implication

The scenarios analysis based on the changes highlights the following policy implication.

First, the empirical study demonstrates that an increase in the cargo volume of MSRW leads to a higher CO_2 reduction. This exhibits the need to enhance the transport capacity and infrastructure of waterway transport. It is necessary to assess CO_2 emissions for both the new-opened and existing shipping lines that can increase the volume of MSRW to sustain the development of environmentally friendly transport. The large-scale development of ships serving shipping lines of MSRW is also one of the beneficial measures to increase transport capacity. For instance, future development trends include the application and popularization of 64 TEU double-deck container ships, the development and application of the sea-inland river direct ship and the sea-Yangtze River combined transport container ship. On the other hand, new investments in waterway transport infrastructure needs to be strengthened. The reconstruction and expansion of provincial waterways should be accelerated to form the main framework of Y-shaped thousand-ton waterway, especially replying on the Jinghang Canal, Hangyong Canal, and Qiantang River.

Second, empirical study shows that the CO_2 emission can be reduced by increasing the efficiency of ship crossing locks. This confirms that the operational efficiency involving waterway transport is necessary. The government should continue to formulate policies and guide relevant parties to improve operational efficiency. Many approaches could be adopted to improve operational efficiency. For instance, by optimizing and improving the scheduling scheme of locks, we can guide the locks in the middle and upper reaches of the Qiantang River and Hangyong Canal to reasonably extend the operation time according to the needs of locks, so as to optimize the scheduling of the locks and ensure smooth waterway transport. Priority should be given to the transport of cargo in containers in the key areas of MSRW for its advantages in efficient transportation. In addition, priority in investment also should be given to the road networks and approach channels around key port areas for MSRW to solve the last kilometre problem of door-to-door transportation. It is also necessary to assess shipping lines to provide useful information about ship speed, ship energy consumption and cargo volume for energy efficiency, which can offer more economic and the environmental advantages.

Third, the empirical study highlights that the application of clean energy makes a difference. The government should continue to introduce the corresponding energy conservation and emission reduction policies while strengthening management practices. It is particularly urgent to enforce CO_2 emission limits and standards for all new operating vessels and speed up the phasing out of old ships. On the other hand, the government should intensify efforts to promote the application of new energy, clean energy and renewable synthetic fuel in ships. It should also guide and encourage enterprises to carry out pilot projects of hydrogen (internal combustion engine), ammonia, non-food biomass liquid fuel and renewable synthetic fuel in the main line of the Yangtze River, Jinghang Canal and the coastal waters of the Yangtze River Delta under the premise of safety and control. Meanwhile, the construction of LNG and hydrogen refueling stations and charging and changing power stations along the waterway should be accelerated. In terms of port energy usage, the government should expedite the construction and renovation of shore power facilities. For example, it is necessary to promote the standardization of port and port power facilities, investigate and issue technical guidelines for the construction of marine shore power facilities, technical standards for shore power connectors and other standards and norms, and strengthen cooperation with the development and reform departments and the State Grid to achieve unified standards for land use, equipment configuration and operation of shore power.

5. Conclusions

Considering the increasing CO_2 emissions from the transportation sector at present, it is imperative to transfer road transport with high energy consumption to waterway transport with relatively low energy consumption in appropriate areas. Environmental assessment and economic cost-benefit analysis should be taken before making decisions and investments, as well as environment-friendly measures to reduce transport CO_2 emissions and improve the sustainability of transportation by policymakers, shipowners, and shipping enterprises. Within this scope, this paper proposes a new generic method enabling the quantification of CO_2 emission reduction by MSRW, applies it to investigate Quzhou region transport systems and provides empirical evidence to support the development of cost-effective policies. Because of its generality, the new method can also be applied in other regions to promote the development and application of MSRW.

In the meantime, the following is a summary of the findings from the case study on MSRW in the Quzhou Region:

(1) Although compared with other modes of transportation, the CO_2 emissions per ton of goods per kilometre of waterway transportation are generally the lowest, the CO_2 reduction potential of MSRW is affected by many factors. Therefore, any new investment in waterway transport should be justified by a reasonable evaluation of the economy, adaptability, and environmentally sustainable development of the MSRW, particularly in a quantitative manner for effective cost-benefit analysis.
(2) WAF is of great significance in the evaluation of shipping lines' benefits. In general, the MSRW lines in Quzhou have a rather high WAF value, which provides advantages in transportation distance, transportation time, reducing road transport and CO_2 emissions.
(3) Although the analysis method presented in this paper can be applied to the assessment of the CO_2 emission reduction potential of MSRW in other regions, not all the shipping lines have the applicability of the implementation of the MSRW scheme. Therefore, line optimization, cost-benefit analysis and assessment of CO_2 emission reduction potential are very important for decision-makers to make investment decisions.
(4) The implementation of the MSRW will lead to the rising demand for waterway transport. Therefore, it is beneficial to test and apply cleaner new energy to new ships to reduce CO_2 emissions generated by waterway transportation.
(5) There are main limitations that need to be addressed in the future. On the one hand, in terms of model data acquisition, the carbon emission coefficient per ton-kilometre of transport equipment in this paper is mainly obtained from the calculation of the model and the standard data provided by the Ministry of Industry and Information Technology. In the future, obtaining region-specific data will further improve the empirical analysis and results. Within this context, the transport authority in the Quzhou region plans to install energy consumption flowmeters on the transportation equipment to accurately calculate the model parameters. On the other hand, regarding the application scenarios, the approach proposed in this paper is only applied in the Quzhou area at present, and a set of standards or norms has not been formed and promoted to a wider context. Conducting more demonstration applications could improve the generality of the proposed method and develop a reproducible standard to guide the MSRW development in regions of high similarity.

The research scope of this study is constrained on CO_2 emission from transport model shift. The relevant economic analysis and incorporation of the uncertainty in such analysis will be conducted in future work. For instance, it can be conducted from the perspectives of cost benefit analysis or economic impact to further investigate how to formulate the most appropriate carbon reduction measures when considering the uncertainty associated with them.

Funding

This research was supported by the independent research and development project of Zhejiang Science Research Institute of Transport [grant number ZK202322; ZK202323]; Science and technology plan project of Zhejiang Provincial Department of Transportation [grant number 202205]; Zhejiang Provincial Science and Technology Plan Project [grant number 2022C35068]; European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme [Grant Agreement No. 864724].

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the independent research and development project of Zhejiang Science Research Institute of Transport [ZK202322, ZK202323], Science and technology plan project of Zhejiang Provincial Department of Transportation [202205], Zhejiang Provincial Science and Technology Plan Project [grant number 2022C35068] and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant Agreement No. 864724). Also, with special thanks to the Zhejiang Provincial Department of Transportation and Zhejiang Port and Channel Management Center for the data sources and their valuable information sharing.

References

Ağbulut, Ü., 2022. Forecasting of transportation-related energy demand and CO2 emissions in Turkey with different machine learning algorithms. Sustain. Prod. Consum. 29, 144–157.

Alam, M.S., Duffy, P., Hyde, B., McNabola, A., 2017. Improvement in the estimation and back-extrapolation of CO2 emissions from the Irish road transport sector using a bottom-up data modelling approach. Transport. Res. Transport Environ. 56, 18–32.

Cai, L., Luo, J., Wang, M., Guo, J., Duan, J., Li, J., Li, S., Liu, L., Ren, D., 2022. Pathways for municipalities to achieve carbon emission peak and carbon neutrality: a study based on the LEAP mode. Energy 262 (Part B), 125435.

Cariou, P., Cheaitou, A., 2012. The effectiveness of a European speed limit versus an International bunker-levy to reduce CO2 emissions from container shipping. Transport. Res. Transport Environ. 17 (2), 116–123.

Cariou, P., Parola, F., Notteboom, T., 2019. Towards low carbon global supply chains: a multi-trade analysis of CO2 emission reductions in container shipping. Int. J. Prod. Econ. 208, 17–28.

Chen, D., Zhao, Y., Nelson, P., Li, Y., Wang, X., Zhou, Y., Lang, J., Guo, X., 2016. Estimating ship emissions based on AIS data for port of Tianjin, China. Atmos. Environ. 145, 10–18.

Chen, D., Zhao, N., Lang, J., Zhou, Y., Wang, X., Li, Y., Zhao, Y., Guo, X., 2018. Contribution of ship emissions to the concentration of PM2.5: a comprehensive study using AIS data and WRF/Chem model in Bohai Rim Region, China. Sci. Total Environ. 610–611, 1476–1478.

Dong, J., Li, Y., Li, W., Liu, S., 2022. CO2 emission reduction potential of road transport to achieve carbon neutrality in China. Sustainability 14, 5454.

Dragović, B., Tzannatos, E., Tselentis, V., Meštrović, R., Škurić, M., 2015. Ship emissions and their externalities in cruise ports. Transport. Res. Part D 61, 289–300.

Du, H., Chen, Z., Peng, B., Southworth, F., Ma, S., Wang, Y., 2019. What drives CO2 emissions from the transport sector? A linkage analysis. Energy 175, 195–204.

Du, H., Li, Q., Liu, X., Peng, B., Southworth, F., 2021. Costs and potentials of reducing CO2 emissions in China's transport sector: findings from an energy system analysis. Energy 234, 121163.

Duan, L., Hu, W., Deng, D., Fang, W., Xiong, M., Lu, P., Li, Z., Zhai, C., 2021. Impacts of reducing air pollutants and CO2 emissions in urban road transport through 2035 in Chongqing, China. Environmental Science and Ecotechnology 8, 100125.

European Commission, E.C., 2021. European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions. Available at: https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541.

German Government, 2019. Bundesregierung will CO2-Ausstoß senken. Available at: https://www.bundesregierung.de/breg-de/themen/klimaschutz/kimaschutzgesetz beschlossen-1679886. (Accessed 20 October 2022).

Gibbs, D., Rigot-Muller, P., Mangan, J., Lalwani, C., 2014. The role of sea ports in end-to-end maritime transport chain emissions. Energy Pol. 64, 337–348.

Gilbert, P., Bows, A., 2012. Exploring the scope for complementary sub-global policy to mitigate CO2 from shipping. Energy Pol. 50, 613–622.

Goldsworthy, L., Goldsworthy, B., 2015. Modelling of ship engine exhaust emissions in ports and extensive coastal waters based on terrestrial AIS data – an Australian case study. Environ. Model. Software 63, 45–60.

Hoang, 2022. Energy-related approach for reduction of CO2 emissions: a critical strategy on the port-to-ship pathway. et al. J. Clean. Prod. 355, 131772.

Hoang, A.T., Pham, V.V., 2020. A study on a solution to reduce emissions by using hydrogen as an alternative fuel for a diesel engine integrated exhaust gas recirculation. In: AIP Conference Proceedings. AIP Publishing LLC, 20035.

IEA. International Energy Agency, 2014, 2016. CO2 emissions from fuel combustion: highlights, 2016. http://www.iea.org/publications/freepublications/.

Jimenez, V.J., Kim, H., Munim, Z.H., 2022. A review of ship energy efficiency research and directions towards emission reduction in the maritime industry. J. Clean. Prod. 366, 132888.

Liao, C.H., Tseng, P.H., Lu, C.S., 2009. Comparing carbon dioxide emissions of trucking and intermodal container transport in Taiwan. Transport. Res. Transport Environ. 14 (7), 493–496. https://doi.org/10.1016/j.trd.2009.05.002.

Lu, Q., Chai, J., Wang, S., Zhang, Z.G., Sun, X.C., 2020. Potential energy conservation and CO2 emissions reduction related to China's road transportation. J. Clean. Prod. 245, 118892.

MEE, 2020. Ministry of Ecology and Environment of the People's Republic of China. China Mobile Source Environmental Management Annual Report. https://www.mee.gov.cn/hjzl/sthjzk/ydyhjgl/202008/P020200811521365906550.pdf.

MEE, 2022. Ministry of Ecology and Environment of the People's Republic of China. China Mobile Source Environmental Management Annual Report. https://www.mee.gov.cn/hjzl/sthjzk/ydyhjgl/202212/W020221207387013521948.pdf.

Mersin, K., Bayirhan, I., Gazioglu, C., 2019. Review of CO2 emissions and reducing methods in maritime transportation. Therm. Sci. 23 (6), 2073–2079.

Meunier, D., Quinet, E., 2015. Valuing greenhouse gases emissions and uncertainty in transport cost benefit analysis. Transport. Res. Procedia 8, 80–88.

Miola, A., Ciuffo, B., 2011. Estimating air emissions from ships: meta-analysis of modelling approaches and available data sources. Atmos. Environ. 45, 2242–2251.

MT, 2022. Ministry of transport of the People's Republic of China. The 14th Five-Year Development Plan for Green Transport. https://xxgk.mot.gov.cn/2020/jigou/zhghs/202201/t20220121_3637584.html.

Nocera, S., Tonin, S., Cavallaro, F., 2015. The economic impact of greenhouse gas abatement through a meta-analysis: valuation, consequences and implications in terms of transport policy. Transport Pol. 37, 31–43.

Nocera, S., Galati, O.I., Cavallaro, F., 2018. On the uncertainty in the economic valuation of carbon emissions from transport. J. Transport Econ. Pol. 52 (1), 68–94.

Peiseler, L., Serrenho, A.C., 2022. How can current German and EU policies be improved to enhance the reduction of CO2 emissions of road transport? Revising policies on electric vehicles informed by stakeholder and technical assessments. Energy Pol. 168, 113124.

Song, Y., Zhang, M., Shan, C., 2019. Research on the decoupling trend and mitigation potential of CO2 emissions from China's transport sector. Energy 183, 837–843.

State Council of the, P.R.C., 2022. Work plan for promoting the development of multimodal transport, optimizing and adjusting the transport structure (2021-2015). http://www.gov.cn/xinwen/2022-01/07/content_5666976.htm.

State Council of the PRC, 2021. Opinions on the Complete, accurate and comprehensive implementation of the new development Concept and the work of carbon peaking and carbon neutrality. http://www.gov.cn/zhengce/2021-10/24/content_5644613.htm.

Thaddaeus, J., Asukwo, E.O., Ibrahim, T.K., Iroka, J., Iwokette, U.J., 2022. Quantifying energy-related CO2 emissions reduction potential of a proposed organic ranking cycle system for exhaust heat recovery application in commercial trucks. Energy and Climate Change 3, 100083.

Tran, N.K., Lam, J.S.L., 2022. Effects of container ship speed on CO2 emission, cargo lead time and supply chain costs. Research in Transportation Business & Management 43, 100723.

Trevisan, L., Bordignon, M., 2020. Screening Life Cycle Assessment to compare CO 2 and Greenhouse Gases emissions of air, road, and rail transport: an exploratory study. Procedia CIRP 90, 303–309.

Trozzi, C., Vaccaro, R., 1998. Methodologies for estimating air pollutant emissions from transport, 1998 European Commission. https://trimis.ec.europa.eu/sites/default/files/project/documents/meet.pdf.

Ülker, D., Bayırhan, i., Mersin, K., Gazioğlu, C., 2021. A comparative CO2 emissions analysis and mitigation strategies of short-sea shipping and road transport in the Marmara Region. Carbon Manag. 12 (1), 1–12.

Ulrich, G., Karl, W., 2022. Estimating transportation-related CO2 emissions of European city tourism. J. Sustain. Tourism 30 (1), 145–168. https://doi.org/10.1080/09669582.2021.1939708.

Wang, C., Zhao, Y., Wang, Y., Wood, J., Kim, C., Li, Y., 2020. Transportation CO2 emission decoupling: an assessment of the Eurasian logistics corridor. Transport. Res. Transport Environ. 86, 102586.

Wang, Y., Zhao, H., Yin, H., Yang, Z., Hao, L., Tan, et al., 2022. Quantitative study of vehicle CO2 emission at various temperatures and road loads. Fuel 320, 123911.

Wei, X., Chang, Y., Kwon, O., Zhang, N., 2021. Potential gains of trading CO2 emissions in the Chinese transportation sector. Transport. Res. Transport Environ. 90, 102639.
Xing, H., Spence, S., Chen, H., 2020. A comprehensive review on countermeasures for CO2 emissions from ships. Renew. Sustain. Energy Rev. 134, 110222.
Xu, Y., Liu, Z., Xue, W., Yan, G., Shi, X., Zhao, D., Zhang, Y., Lei, Y., Wang, J., 2021. Identification of on-road vehicle CO2 emission pattern in China: a study based on a high-resolution emission inventory. Resour. Conserv. Recycl. 175, 105891.
Xu, H., Cao, S., Xu, X., 2022. The development of highway infrastructure and CO2 emissions: the mediating role of agglomeration. J. Clean. Prod. 337, 130501.
Zhejiang provincial bureau of statistics, 2022. Zhejiang statistical Yearbook 2022. http://tjj.zj.gov.cn/col/col1525563/index.html.
Zhou, X., Zhou, D., Wang, Q., Su, B., 2020. Who shapes China's carbon intensity and how? A demand-side decomposition analysis. Energy Econ. 85, 104600. http://refhub.elsevier.com/S0921-3449(21)00236-6/sbref0051.
Zhou, D., Huang, F., Wang, Q., Liu, X., 2021. The role of structure change in driving CO2 emissions from China's waterway transport sector. Resour. Conserv. Recycl. 171, 105627.
Zhou, X., Wang, H., Huang, Z., Bao, Y., Zhou, G., Liu, Y., 2022. Identifying spatiotemporal characteristics and driving factors for road traffic CO2 emissions. Sci. Total Environ. 834, 155270.
Zhu, M., Yuen, K.F., Ge, J.W., Li, K.X., 2018. Impact of maritime emissions trading system on fleet deployment and mitigation of CO2 emission. Transport. Res. Transport Environ. 62, 474–488.