Supplementary materials
for
Round-trip multimodal transportation routes planning for foldable vehicle racks

Mengru Shen [a], ***Zhongbin Zhao*** [a,*], ***Hao Wang*** [b], ***Xifu Wang*** [a], ***Kai Yang*** [c], ***Zheng Wan*** [d], ***Wei Liu*** [d]

[a] *School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China*
[b] *Ocean College, Zhejiang University, Zhoushan 316021, China*
[c] *School of System Sciences, Beijing Jiaotong University, Beijing 100044, China*
[d] *College of Transport & Communications, Shanghai Maritime University, Shanghai 201306, China*

1. Supplementary introduction and figures

1.1. Commodity vehicle and pulp trading

Since the conclusion of the economic and financial crisis in 2009, the global automotive market has exhibited a sustained recovery. Despite setbacks caused by the Covid-19 pandemic and the Ukraine war, a discernible resurgence has been evident since 2021, as illustrated in Annex Fig. 1a. Currently, the automotive sector is undergoing a profound energy transition, marked by a significant surge in market demand for new energy vehicles and a simultaneous decline in the traditional internal combustion engine market, as depicted in Annex Fig. 2a-d. At the forefront of this transformation are domestically manufactured new energy vehicles in China, assuming a pivotal role, as highlighted in Annex Fig. 1a-b. Concurrently, the robust demand for automobile shipments has precipitated an unprecedented escalation in freight rates for conventional Pure Car and Truck Carriers (PCTC). These specialized vessels, designed for the transport of automobiles, trucks, or roll-on/roll-off (ro-ro) cargo, have experienced a notable surge. According to data from Clarksons Shipping Research as of October 2022, PCTC charter rates have surpassed $100,000 per day, a threshold that skyrocketed to an astonishing $110,000 per day just two months later. Presently, the market comprises 759 PCTCs, totaling 4,011,314 Car Equivalent Units (CEUs). Notably, PCTCs with a capacity exceeding 6,000 CEUs contribute to over 70% of this figure, as demonstrated in Annex Fig. 3.

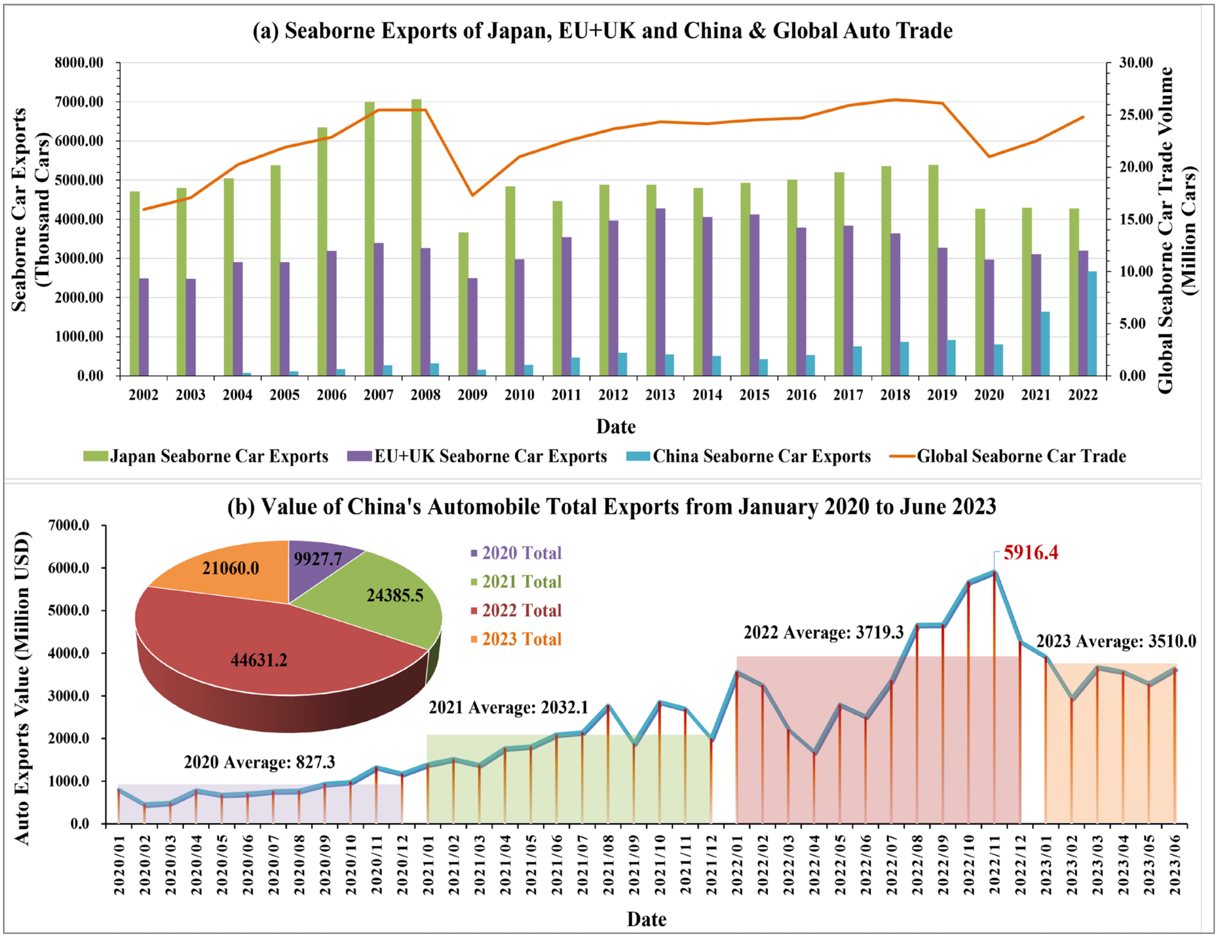
Meanwhile, China also has consistently maintained a heightened importation of pulp, with an unvarying intake of approximately 30 million tons over the past three years. Concurrently meeting the demands of the domestic paper consumption, the export of diverse paper products has exhibited a steady annual growth trend, as illustrated in Annex Fig. 4. Pulp, as a fundamental bulk raw material commodity, is conventionally transported across borders via maritime shipping. To streamline the export of Chinese automobiles and the importation of pulp, COSCO Shipping Specialized Carriers Corporation introduced an innovative service paradigm in August 2022. This pioneering approach involves the transportation of Foldable Vehicle Racks (FVRs) utilizing the Multipurpose Pulp Carrier (MPPC) for the outbound journey and transporting both pulp cargo and empty FVRs on the return voyage. The primary focus of this research is on this groundbreaking service pattern.

1.2. Conveyances of automobiles and pulp

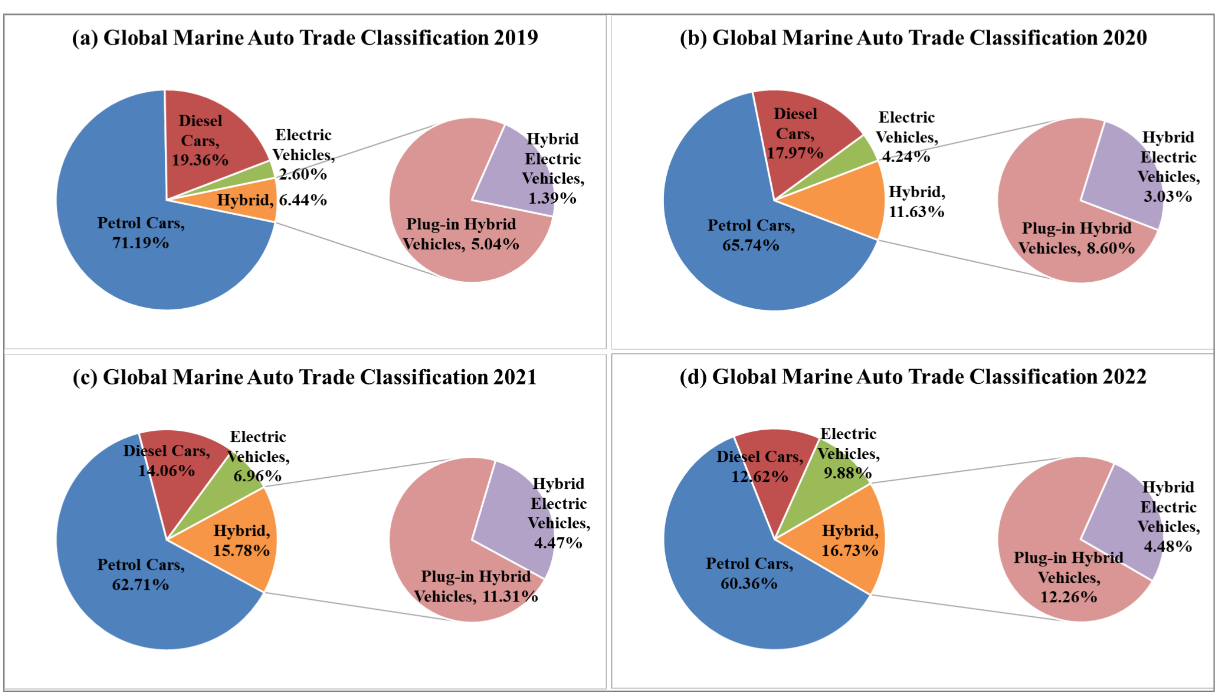
Currently, international commodity vehicle transportation encompasses three primary categories: automotive container shipment, PCTC roro shipping, and FVR transportation.

- In the realm of automotive container transportation, a prevalent practice involves loading three automobiles within either a standard 40ft container or a 40ft high container (40ft HC). Proximate overland conveyance is achieved through container trucks or a ‘trailer + semi-trailer’ combination treated as a singular unit. Presently, short-distance rail transit employs articulated container cars alongside traction locomotives. Within China, X6A-type articulated cars predominantly facilitate the conveyance of 40-foot containers. On dedicated rail lines in China and North America, additional cargo can be transported using double-stacked container trains (Zhao et al., 2022). For short-distance inland waterway transportation, river container ships or versatile vessels are employed. Long-distance conveyance relies primarily on maritime container liners or the China-Europe Railway Express (CERE), as illustrated in Annex Fig. 5.
- In the PCTC ro-ro transportation mode, six autos are typically contained in a specialized truck for highway transport or a specialized articulated car for railway shipping (JSQ6-type rail scaffolding cars are available in China for loading two tiers of automobiles). Short-distance river transportation is conducted by inland PCTCs, and long-distance carriage is performed by the PCTC or the CERE, as depicted in Annex Fig. 6. Each commodity car needs to occupy at least one CEU on the PCTC based on its size. Notably, PCTC carriers usually assess freight charges based on the CEU and the volumetric value of the automobile.
- In the context of FVR transportation, highway transit is facilitated by container trucks, railway transport employs X4K-type 48ft container articulated cars, and inland waterway conveyance continues to rely on inland container ships or multipurpose vessels, albeit requiring more space and Twenty-feet Equivalent Unit (TEU). For long-distance travel, the seaway MPPC or the CERE is engaged, as exemplified in Main Text Fig. 1.
- Additionally, pulp is considered a type of bulk clean general cargo. Short-distance shipping is primarily accomplished by highway trucks, railway dry cargo flatcars, or river general cargo ships, while long-distance transmission relies on MPPC or CERE; see Main Text Fig. 1 and Annex Fig. 7. While FVR and automotive container transportation fall under multimodal transport, pulp shipping and PCTC automobile shipment are categorized as combined transport.

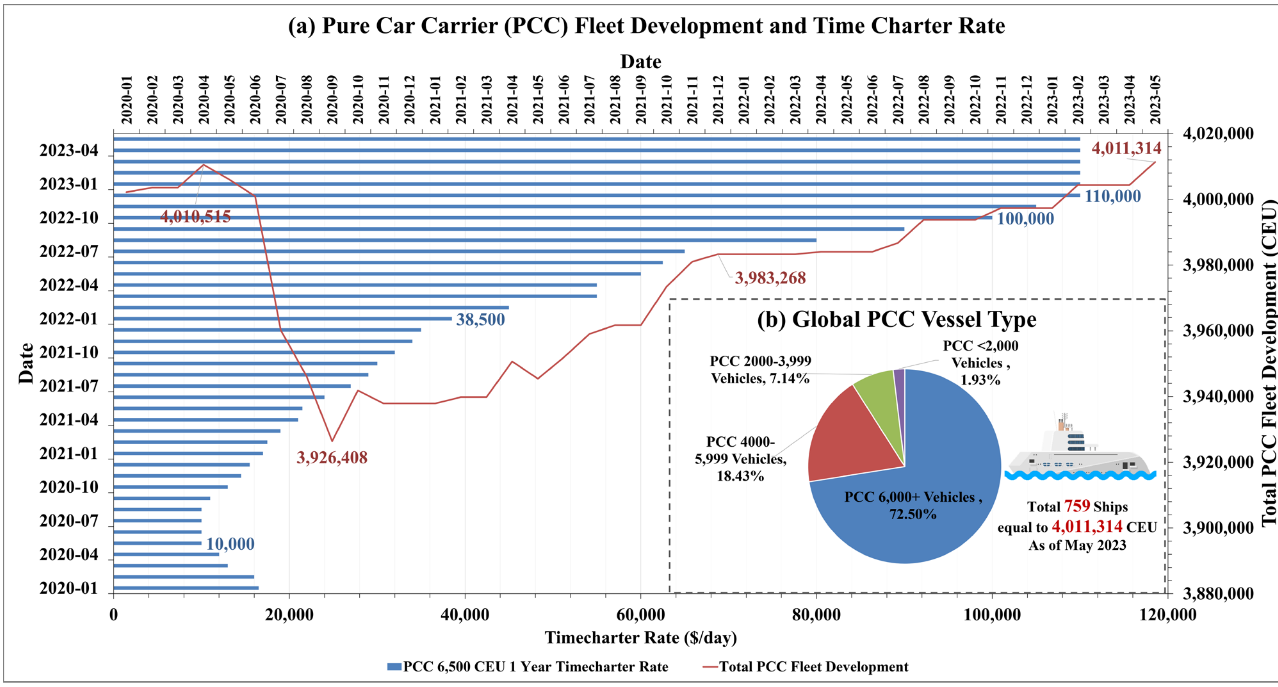
* Corresponding author: Zhongbin Zhao (zhongbinwork@163.com // 22110288@bjtu.edu.cn)



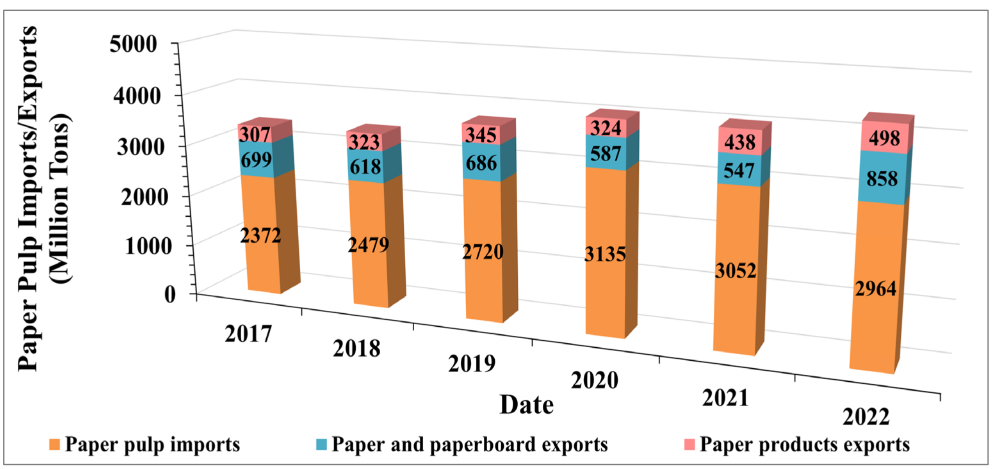
Annex Fig. 1. China's commercial vehicle exports



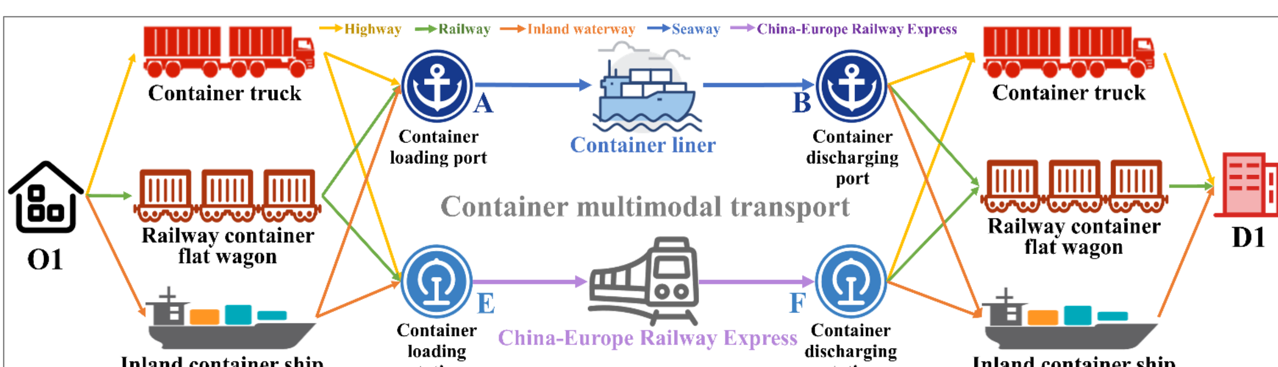
Annex Fig. 2. Classification and volume of global seaborne automobile trade



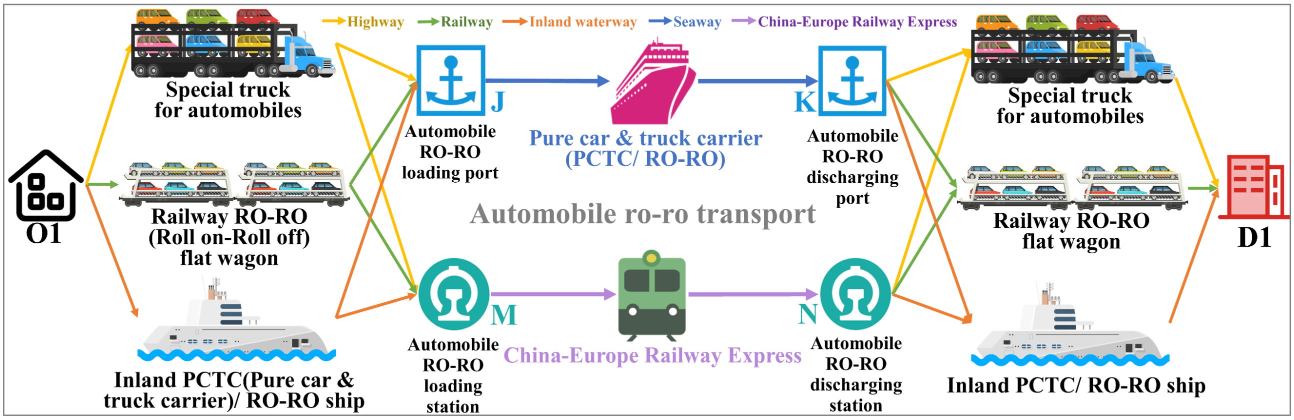
Annex Fig. 3. Global Pure Car and Truck Carrier (PCTC) market analysis



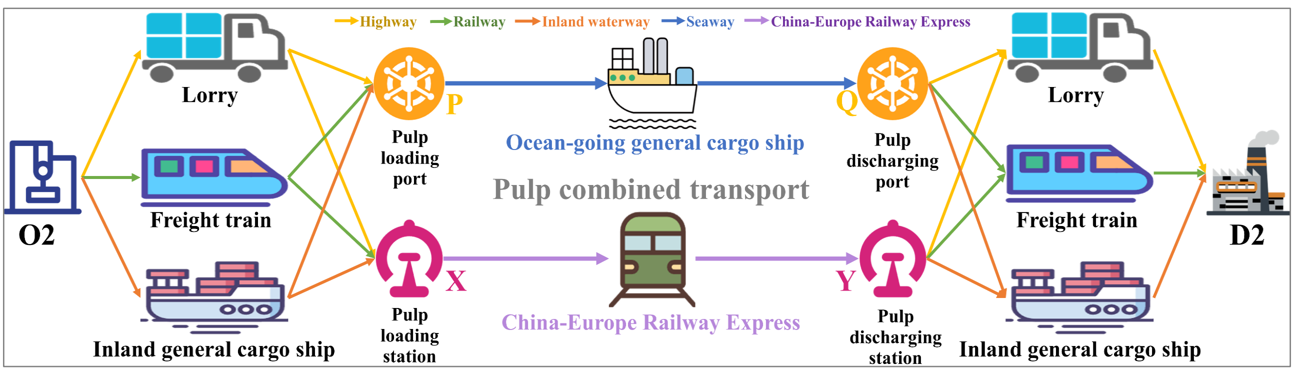
Annex Fig. 4. China's pulp imports and various exports of paper products, 2017~2022



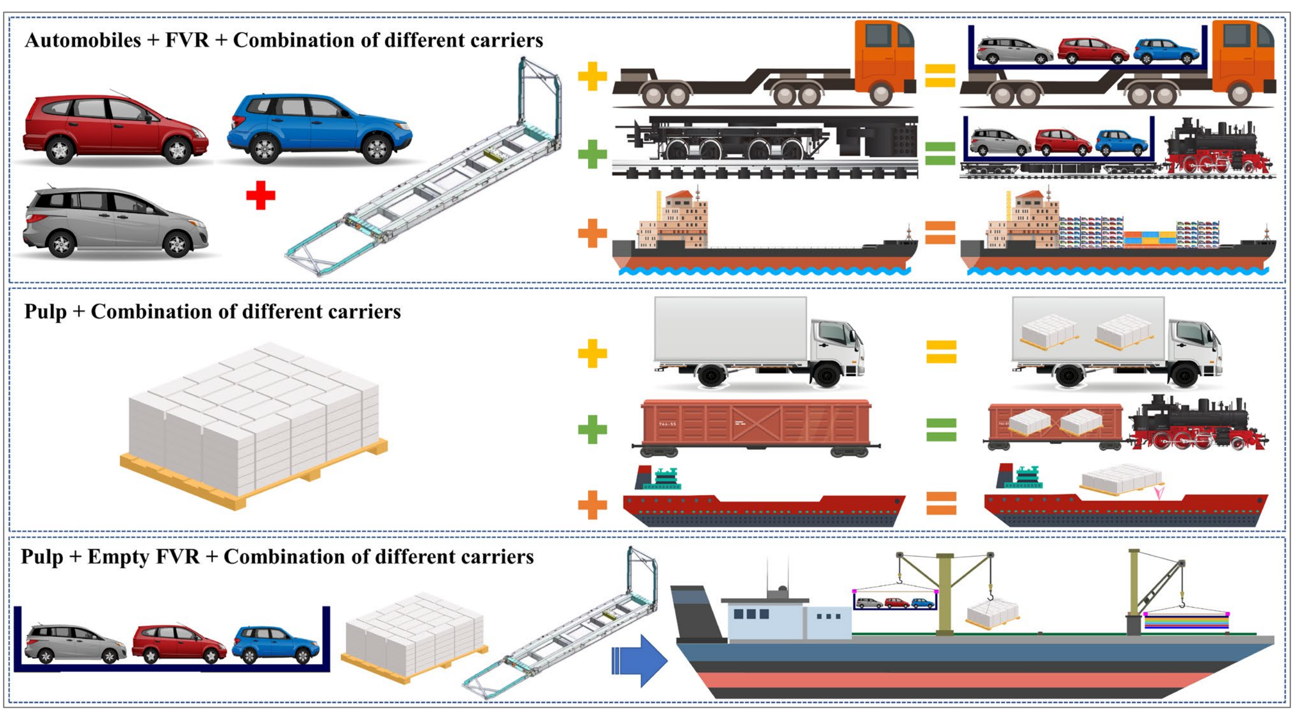
Annex Fig. 5. Schematic diagram of multimodal auto container transportation



Annex Fig. 6. Schematic diagram of combined vehicle roll-on/roll-off (ro-ro) transportation



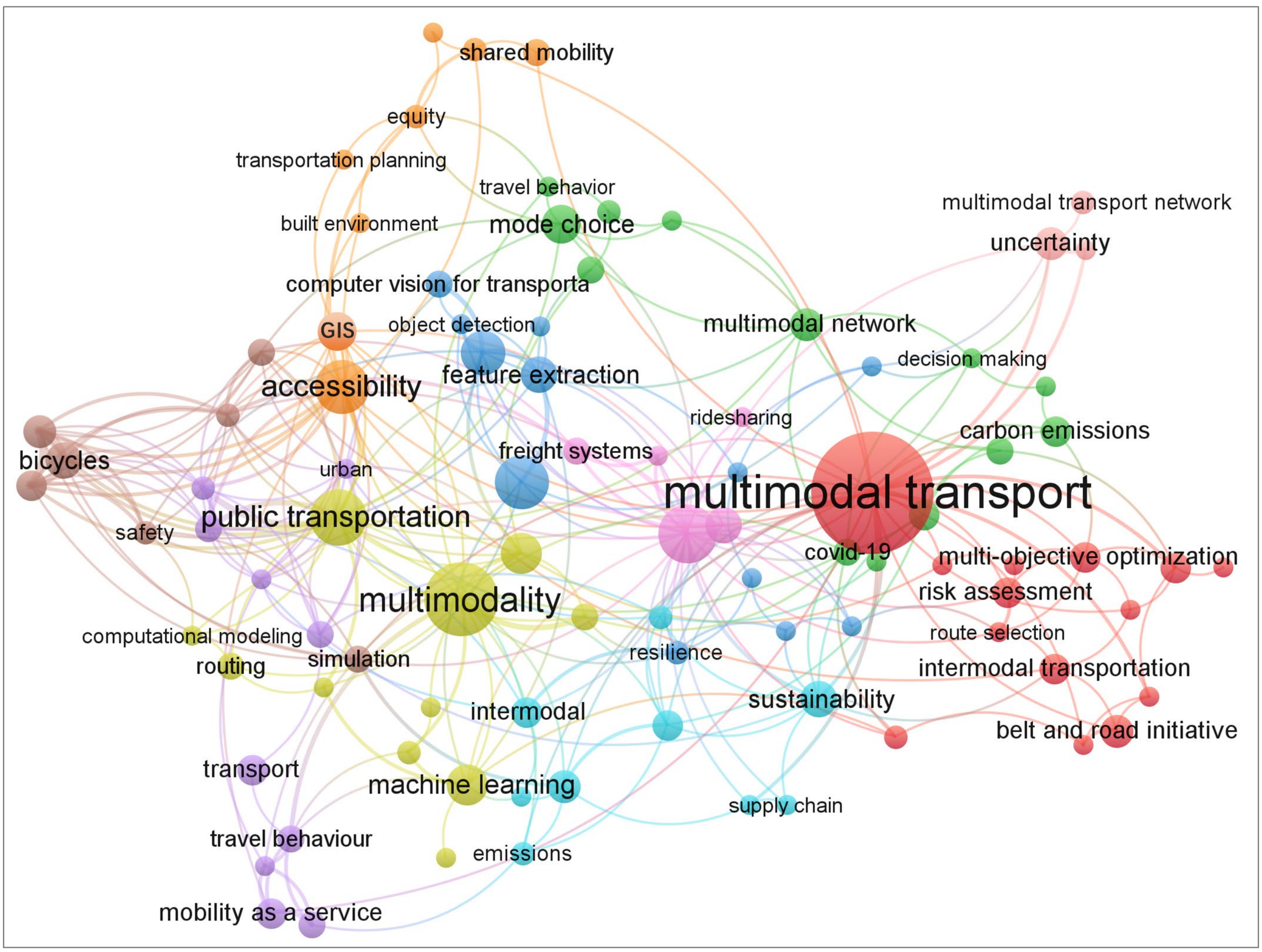
Annex Fig. 7. Schematic diagram of pulp combined transportation



Main Text Fig. 1 Conveyance tools related to Foldable Vehicle Rack (FVR)

1.3. Bibliometric analysis on multimodal transport

Searching with [‘multimodal transport’ OR ‘intermodal transport’] as the subject terms yielded 1183 publications of the type ‘Paper’ in the core collection of Web of Science. Applying a minimum occurrence threshold of 5 with the support of VOSviewer led to the refinement of 89 keywords. Subsequently, we computed the co-occurrence intensity among these keywords, as illustrated in Annex Fig. 8. Prominent keywords clustered in the initial red category include ‘multimodal transport, multiobjective optimization, intermodal transportation, risk assessment, route selection, Belt and Road Initiative.’ These keywords collectively relate to research on multimodal transport and risk assessment. The central keywords in the subsequent yellow cluster encompass ‘multimodality, public transportation, machine learning, computational modeling, simulation, and routing.’ This lexicon collectively suggests a discernible inclination towards leveraging machine learning and sophisticated computer-aided methodologies to intricately optimize routes within the complex framework of multimodal transportation networks. The paramount keywords within the third blue cluster include ‘sustainability, resilience, emissions, supply chain, intermodal, COVID-19.’ Taken together, these descriptors underscore a pronounced emphasis on emissions regulation, the establishment of sustainability benchmarks, and the fortification of resilience within multifaceted supply chain architectures. All of this is done while navigating the challenges posed by the intermodal paradigm and the transformative impact of the global pandemic.



Annex Fig. 8. Visual mapping of multimodal transport

2. Supplementary tables

Annex Table 1 Revenue items and parameters for 5 transport modes

Transport mode	Revenue items	Parameter 1		Parameter 2		Parameter 3		Parameter 4	
1-Highway	Freight revenue [2]	Base freight rate 1 (USD[1]/ FVR)	1.1281	Base freight rate 2 (USD/ FVR-KM)	0.7897	Heavy FVRs for the outbound trip (No.)	1200	Trcuks required for the outbound trip (No.)	1200
	Empty return fee revenue [2]	Base freight rate 1 (USD/ truck)	1.1281	Base freight rate 2 (USD/ truck-KM)	0.7897	Pulp quantity for return trip (ton)	55000	Trcuks required for the return trip (No.)	2200
2-Railway	Freight revenue [3]	Base freight rate 1 (USD/ FVR)	74.095	Base freight rate 2 (USD/ FVR-KM)	0.4675	Base freight rate 1 (USD/ ton)	3.6212	Base freight rate 2 (USD/ ton-KM)	0.0192
	FVR usage fee [3]	Per FVR usage charge	30.000	-	-	-	-	-	-
3-Inland waterway	Inclusive freight [4]	Base freight rate 1 (USD/ FVR-KM)	0.2702	Base freight rate 2 (USD/ FVR-KM)	0.0084	-	-	-	-
4-Seaway	Basic freight revenue [5]	Outbound trip freight (USD/ FVR-KM)	0.0835	Return trip freight (USD/ FVR-KM)	0.0030	-	-	-	-
	Various surcharges [5]	Outbound trip port surcharges (USD/ FVR)	675.412	Carrier-related surcharges per FVR for the outbound trip (USD/ FVR)	748.741	Port-related surcharges per FVR for the return trip (USD/ FVR)	710.96	Liner-related surcharges per FVR for the return trip (USD/ FVR)	209.50
5-CERE	Freight revenue [6]	Base freight rate 1 (USD/ FVR)	88.914	Base freight rate 2 (USD/ FVR-KM)	0.5611	Base freight rate 1 (USD/ ton)	4.3454	Base freight rate 2 (USD/ ton-KM)	0.0231
	Outbound FVR royalties [6]	Outbound trip usage charge (USD/ FVR)	960	-	-	-	-	-	-
	Outbound FVR relocation revenue [6]	Outbound trip single FVR transfer fee (USD/ FVR)	320	-	-	-	-	-	-
	Subsidies for return eastbound heavy FVR [6]	Single FVR return subsidy deduction (USD/ FVR)	300	-	-	-	-	-	-

Notes: **(1)** As of August 1, 2023, the Bank of China's exchange rate for the U.S. dollar to the Chinese yuan was 1:7.18 and the exchange rate for the euro to the US dollar was 1:1.10. (https://www.boc.cn/sourcedb/whpj/). **(2)** Data source: Express Logistics Technology Group Limited. **(3)** Data source: China Railway 95306 Online Platform. **(4)** Data source: Yangtze River Shipping Development Research Center of the Ministry of Transport of the People's Republic of China. **(5)** Data source: COSCO Shipping Lines. **(6)** Data source: China Railway Container Shipping Corporation. **(7)** Data source: China-Europe Railway Express Information Platform.

Annex Table 2 Breakdown of seaway surcharges per FVR

Surcharge type	Surcharge breakdown [1]	Outbound trip surcharges (USD/FVR) [2]	Return trip surcharges (USD/FVR) [2]
Port-related surcharges	Origin Terminal Handling Charge (OTHC)	132.31	231.00
	Destination Terminal Handling Charge (DTHC)	231.00	170.61
	Port Security Surcharge (PSS)	12.10	9.35
	Port Congestion Surcharge (PCS)	300.00	300.00
	Aggregation	675.41	710.96
Carrier-related surcharges	Fuel Adjustment Factor (FAF)	416.00	104.00
	Carrier Security Surcharge (CSS)	4.40	5.50
	Peak Season Surcharge (PSS)	222.84	0.00
	Currency Adjustment Surcharge (CAS)	5.50	0.00
	War Risk Surcharge (WRS)	100.00	100.00
	Aggregation	748.74	209.50

Remarks: **(1)** Data source: COSCO Shipping Lines. **(2)** Surcharge for 48 ft FVR at the standard of the 40 ft HC.

Annex Table 3 Cost items and parameters for 5 transport modes

Transport mode	Cost items	Parameter 1		Parameter 2		Parameter 3		Parameter 4		Parameter 5	
1-Highway	Diesel fuel cost	Fuel cost (USD/FVR-day)	900	Fuel cost per (USD/ton-day)	18	Unit fuel consumption (ton/day)	0.75	Unit diesel price (USD/ton) [1]	1200	Carrying tonnage per truck (ton)	50
	Trailer usage cost	Trailer usage cost (USD/truck-day)	111.42	Shipping speed (KM/day)	2040	Required trucks for 5500 tons of pulp (No.)	1100	Required trucks for 1200 FVRs (No.)	1200	Outbound FVR (No.)	1200
	Various additional costs [2]	Total additional cost (USD/FVR-day)	172.01	Lifting and dropping fee per FVR (USD)	53.62	Sealing and weighing fee per FVR (USD)	48.747	Surcharge per 48ft FVR (USD)	69.64	Return pulp (ton)	55000
2-Railway	Articulated car usage service cost [3]	Articulated car service cost (USD/car-day)	424.79	Outbound articulated cars (No.)	1200	Return articulated cars (No.)	1976	Average speed (KM/day)	2160	-	-
	Locomotive operation cost [3]	Locomotive operating cost (USD/day)	601.67	Outbound locomotives (No.)	24	Return locomotives (No.)	40	FVRs carried per train (No.)	50	Carrying tons per train (ton)	1524
	Railroad facility access service cost [3]	Rail facility usage cost (USD/KM)	76.316	Handling efficiency per 3 cranes (natural FVRs/day)	2160	Pulp handling efficiency (ton/day)	40000	-	-	-	-
3-Inland waterway	VLSFO cost for voyage days	VLSFO cost (USD/FVR-day)	42.667	VLSFO cost (USD/ton-day)	0.931	Unit VLSFO consumption (ton/day)	80	VLSFO price (USD/ton) [1]	640	Shipping speed (KM/day)	800.06
4-Seaway	LSFO cost for voyage days	LSFO cost (USD/FVR-day)	42.500	LSFO cost (USD/ton-day)	0.927	Unit LSFO consumption (ton/day)	100	LSFO price (USD/ton) [1]	510	Shipping speed (KM/day)	844.51
	IFO380 cost for voyage days	IFO380 cost (USD/FVR-day)	41.250	IFO380 cost (USD/ton-day)	0.900	Unit IFO380 consumption (ton/day)	110	IFO380 price (USD/ton) [1]	450	Shipping speed (KM/day)	888.96
	Empty FVR relocation cost on return trip [4]	Total relocation cost (USD/FVR-day)	260	Port commission (USD/port)	20000	Canal pass fee (USD/trip)	150000	Return empty FVR (Unit)	1200	-	-
5-CERE	Articulated car usage service cost [5]	Articulated car service cost (USD/car-day)	509.75	Outbound articulated cars (No.)	1200	Return articulated cars (No.)	1976	Average speed (KM/day)	1200	Rail track switching time (day/train)	0.1667
	Locomotive operation cost [5]	Locomotive operating cost (USD/day)	722.01	Outbound locomotives (No.)	24	Return locomotives (No.)	40	FVRs carried per CERE (No.)	50	Carrying tons per CERE (ton)	1524
	Railroad facility access service cost [5]	Rail facility usage cost (USD/KM)	91.579	-	-	-	-	-	-	-	-
	Empty FVR relocation cost on return trip [5]	Total relocation cost (USD/FVR)	300	-	-	-	-	-	-	-	-

Notes: **(1)** Fuel oil price information updated on August 2, 2023 from Maritime Online. **(2)** Data source: Express Logistics Technology Group Limited. **(3)** Data source: China Railway 95306 online platform. **(4)** Data source: COSCO Shipping Lines. **(5)** Data source: China-Europe Railway Express Information Platform.

Annex Table 4 Classification and summary of shipping nodes

Node	Node	Classification	Special node	Region	Node cost (USD)	Stopover time (Day)
1	Wuhan	Departure origin/Loading station	-	China	12000	0.5556
2	Taicang	Loading port	Cargo replacement node	China	12000	0.5556
3	Nansha	Loading port	Cargo replacement node	China	12000	0.5556
4	Jeddah	Midway port	Stopover node	Offshore	-	-
5	Naples	Midway port	Stopover node	Offshore	-	-
6	Zeebrugge	Unloading port	Cargo replacement node	Europe	12000	0.5556
7	Antwerpe	Unloading port	Cargo replacement node	Europe	12000	0.5556
8	Brussels	Delivery destination	-	Europe	12000	0.5556
9	Alashankou-Dostek	Railroad entry and exit border crossing	CERE gauge switching node	Offshore	30000 | 49397 [1]	2.004 | 3.2938 [2]
10	Brest-Malashevich	Railroad entry and exit border crossing	CERE gauge switching node	Offshore	30000 | 49397	2.004 | 3. 2938
11	Zamyn Ude-Erenhot	Railroad entry and exit border crossing	CERE gauge switching node	Offshore	30000 | 49397	2.004 | 3. 2938
12	Duisburg	Unloading station	Cargo replacement node	Europe	12000	0.5556
13	Hamburg	Empty container loading port/ station	Empty container loading node	Europe	1714.29	0.0794
14	Tampere	Departure origin/Loading station	-	Europe	27500	1.3750
15	Rauma	Loading port	Cargo replacement node	Europe	27500	1.3750
16	Helsinki	Loading port	Cargo replacement node	Europe	27500	1.3750
17	Motril	Midway port	Stopover node	Offshore	-	-
18	Mersin	Midway port	Stopover node	Offshore	-	-
19	Changshu	Unloading port	Cargo replacement node	China	29214.29	1.4544
20	Qingdao	Unloading port	Cargo replacement node	China	29214.29	1.4544
21	Moscow	Loading station	Cargo replacement node	Europe	29214.29	1.4544
22	Zhengzhou	Unloading station	Cargo replacement node	China	29214.29	1.4544
23	Jining	Delivery destination	-	China	29214.29	1.4544

Notes: **(1)** The transhipment cost at this node for CERE to carry 1,200 FVRs on the outbound trip is 30,000 USD, and the transhipment cost on the return trip to carry 1,200 empty FVRs and 55,000 tons of pulp is 49640 USD. **(2)** The layover time at this node for CERE to carry 1200 FVRs on the outbound trip is 2.004 days, and the stopover time on the return trip to carry 1200 empty FVRs and 55,000 tons of pulp is 3.334 days.

Annex Table 5 Division and distance of transport sections (Unit: KM)

Node i	Node j	1-Highway distance	2-Railway distance	3-Inland waterway distance	4-Seaway distance	5-CERE distance
1	2	787	650	1009	-	-
1	3	1031	1060	-	-	-
2	4	-	-	-	12227	-
3	4	-	-	-	10879	-
4	5	-	-	-	3434	-
5	6	-	-	-	4328	-
5	7	-	-	-	4417	-
6	8	112	94	115	-	-
7	8	45	45	109	-	-
6	13	-	-	-	646	-
7	13	-	-	-	709	-
13	15	-	-	-	1983	-
13	16	-	-	-	2000	-
14	15	142	135	-	-	-
14	16	179	180	-	-	-
15	17	-	-	-	4828	-
16	17	-	-	-	4845	-
17	18	-	-	-	3524	-
18	19	-	-	-	14234	-
18	20	-	-	-	14712	-
19	23	683	398	695	-	-
20	23	428	307	-	-	-
1	9	-	-	-	-	4015
1	11	-	-	-	-	1928
9	10	-	-	-	-	5692
11	10	-	-	-	-	7594
10	12	-	-	-	-	1717
12	8	218	190	463	-	-
12	13	-	-	-	-	462
13	10	-	-	-	-	1460
10	21	-	-	-	-	1637
14	21	1172	575	-	-	-
21	9	-	-	-	-	4055
21	11	-	-	-	-	6966
9	22	-	-	-	-	3669
11	22	-	-	-	-	1403
22	23	314	430	-	-	-

Annex Table 6 Notation definition and description

	Notation	Explanation
1	Q_g^h	Freight volume from China to Europe on the outbound trip by transport mode h, $h \in \{1,2,3,4,5\}$.
2	Q_r^h	Freight volume from Europe to China on the return trip by transport mode h, $h \in \{1,2,3,4,5\}$.
3	$p_{i,j}^h$	Harmonized freight rate per unit of cargo by transport mode h, $h \in \{1,2,3,4,5\}$.
4	$\mu_{i,j}^h$	Uniform shipping cost per unit of cargo by transport mode h, $h \in \{1,2,3,4,5\}$.
5	δ_h	Per-unit empty FVR relocation cost from Europe to China by transport mode h, $h \in \{4,5\}$.
6	$d_{i,j}^h$	Denotes the shipping distance between nodes i and j by transport mode h, $h \in \{1,2,3,4,5\}$.
7	v_h	Denotes the average shipping speed between nodes i and j by transport mode h, $h \in \{1,2,3,4,5\}$.
8	Ω	Add a factor to the transit time between different transport modes to measure the waiting time for transhipment.
9	$\mho$	Add a factor to the cargo handling time at node i for a given transport mode to measure node congestion situation.
10	$e_i^{h,k}$	Denotes the conversion efficiency at node i from transport mode h to mode k, $h,k \in \{1,2,3,4,5\}$.
11	e_i^h	Denotes the handling efficiency at node i in transport mode h, $h \in \{1,2,3,4,5\}$.
12	p_1^h	Base freight rate 1 in short-distance highway or railway transport mode, $h \in \{1,2\}$.
13	p_2^h	Base freight rate 2 in short-distance highway or railway transport mode, $h \in \{1,2\}$.
14	ω	Empty return fee when applying short-distance highway transport mode, h=1.
15	I_c^r	FVR royalty when applying short-distance railway transport mode, h=2.
16	I_c^c	Outbound FVR royalty when applying long-distance CERE transport mode, h=5.
17	α	Return FVR transfer fee when applying long-distance CERE transport mode, h=5.
18	β	Subsidies for return eastbound heavy FVRs when applying long-distance CERE transport mode, h=5.
19	s_p	Port-related surcharges per FVR.
20	s_l	Carrier-related surcharges per FVR.
21	U_d	Trailer usage cost when applying short-distance highway transport mode, h=1.
22	φ	Other additional costs that may be incurred when applying highway shipping, such as FVR lifting-dropping fee and weighing fee.
23	U_l	Articulated car usage service cost by days and articulated cars number when applying railway or CERE transport mode, $h \in \{2,5\}$.
24	O_l	Locomotive operation cost by days and locomotives number when applying railway or CERE transport mode, $h \in \{2,5\}$.
25	U_r	Railroad facility service cost charged according to the transportation mileage.
26	g_d	The diesel fuel price for trailer truck.
27	g_v	The price of Very Low Sulfur Oil (VLSFO) consumed by vessels navigating within the inland waterway Emission Control Area (ECA).
28	g_l	The price of Low Sulfur Fuel Oil (LSFO) consumed by vessels navigating within the coastal ECA designated by the sovereign state.
29	g_f	The IFO 380 price for ships sailing beyond the ECA.
30	θ_d^h	Unit diesel fuel consumption per kilometer of trailer, h=1.
31	θ_v^h	VLSFO consumption per sailing day of the vessel when applying inland waterway transport mode, h = 3.
32	θ_l^h	LSFO consumption per sailing day of the vessel when applying seaway transport mode, h = 4.
33	θ_f^h	IFO 380 consumption per sailing day of the vessel when applying seaway transport mode, h = 4.
34	c_i^g	Cargo switching cost at the CERE gauge switching node, h = 4.
35	$c_i^{h,k}$	Cargo replacement cost at the transport mode changeover node.
36	c_i^s	Cargo loading cost at the origin and unloading costs at the destination.

Annex Table 7 Abbreviations in this paper

Abbreviations	**Description**
FVR	Foldable Vehicle Rack
MPPC	Multipurpose Pulp Carrier
CERE	China-Europe Railway Express
COSCO	China Ocean Shipping (Group) Company
CCS	China Classification Society
MTO	Multimodal Transport Operator
PCTC	Pure Car and Truck Carrier
O-D	Origin-Destination
ECA	Emission Control Areas
FHVR	Foldable Heavy Vehicle Rack
40ft HC	40ft High Container
RORO	Roll on/ Roll off
COA	Contract of Affreightment
MGO	Marine Gas Oil
VLSFO	Very Low Sulfur Fuel Oil
LSFO	Low Sulfur Fuel Oil
EWM	Entropy Weighting Method
GSBN	Global Shipping Business Network
NSGA-II	Non-dominated Sorting Genetic Algorithm II