Road, rail and waterway freight traffic interactions at German trimodal hubs

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Abstract

Intermodal freight transport is an essential and growing part of the whole transportation system. However, traffic relationships between transport modes along intermodal hubs have seldom been studied. This paper investigates the dynamic relationships of freight traffic on road, rail, and waterways. We derive daily incoming and outgoing traffic for inland waterway vessels, freight trains, and trucks, and compile a dataset for German trimodal ports along the river Rhine for 2023. Correlations and OLS regression analysis reveal the concurrent and lagged interactions between the three modes of transport. Incoming trucks are correlated with more outgoing trains and ships, and vice versa. This holds true for both contemporaneous and one-day lag effects. Incoming ships have a concurrent correlation with outgoing trains, but no lagged effects. This is the first study to provide a longitudinal cross-modal dataset of trimodal hubs and empirically investigate dynamic relationships between transport modes. This paper contributes to the quantification of intermodal shifts and thus enables a better understanding of traffic flows in the freight transport network.

Keywords: Freight transport, Waterways, Railways, Road traffic, Intermodal transport, Inland waterway vessels, Freight trains, Trucks, Container terminals

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1. Introduction

The last decade has witnessed a rising trend of intermodal freight transport in Europe. Between 2013 and 2023, the proportion of all European rail freight transported in intermodal transport units (ITU) have increased by close to 33 percent (Eurostat, 2025d). In Germany, the amount of freight transported in ITUs on road and rail increased by 13 percent and on inland waterways by 10 percent between 2013 and 2023 (Eurostat, 2025c,b,a).

This trend comes with a growing need for a comprehensive understanding of freight traffic flows at multimodal hubs. However, traffic around these hubs have seldom been studied. On the one hand, much research has been made about the basic principles of intermodal transportation, its system and its potential improvements (see Agamez-Arias and Moyano-Fuentes (2017) for a comprehensive review and Abu-Aisha et al. (2024) for a review of intermodal rail-sea transport). Bhattacharya et al. (2014) examine how intermodal freight transport can reduce costs and increase the profitability of the entire logistics chain. Koritarov and Dimitrakiev (2025) emphasize the potential of digitalizing multimodal logistics to increase capacity without physical expansion. On the other hand, many papers tackle intermodal systems modeling and planning optimization. SteadieSeifi et al. (2014) provides an extensive review of this, and more recent contributions have been made by Chang et al. (2019) and Krylatov and Raevskaya (2023). Most of these papers, however, only deal with intermodal transport in two modes and no paper to our knowledge has empirically investigated actual traffic flows in intermodal hubs over time and for three transport modes.

This paper takes a step in this direction by compiling and analyzing the traffic flows around German multimodal hubs for road, rail and waterway. A mode-specific approach is developed that calculates incoming and outgoing traffic around multimodal hubs. Road traffic is calculated from toll data; railway traffic is approximated from train counts provided by the Deutsche Bahn (DB); and waterway traffic is derived from Automatic Identification System (AIS) data.

We apply the developed approaches to a sample of German trimodal ports along the Rhine, the most important waterway for freight transport in Europe. We then use the generated dataset for 2023 to investigate correlations and dynamic interactions between the three transport modes. The aim is to answer the following questions: (1) To what extent do road, rail and waterway freight traffic correlate with each other at trimodal hubs? (2) Do these relationships display lagged effects?

2. Data

We use data on intermodal terminals from the Intermodal Map (The Association for Combined Transport, 2022) to determine which ports have the infrastructure for intermodal transshipment.

Figure 1 shows that the Rhine region has the highest density of trimodal hubs in Germany, with the exception of Hamburg. The paper focuses on 22 ports with trimodal terminals along the Rhine (in red). For traffic calculations in all three transport modes, we use the geo-coordinates of the trimodal terminal located inside the port. For ports with several trimodal terminal, an arbitrary terminal is selected.

The following sections discuss the data and calculations of traffic flows round the selected trimodal ports by transport mode.

2.1. Road traffic

Toll data from the Federal Office for Logistics and Mobility was used to estimate truck traffic at the selected trimodal ports. Entry and exit points of toll segments are identified as *port-relevant* if:

1. They fall within a five-kilometer radius from a trimodal port, and
2. They are on the same side of the Rhine as the port.

All toll-paying trucks that enter or leave the toll network through port-relevant entry or exit points are considered for the traffic calculation. Truck *arrivals* at the port are defined as the number of trucks *leaving* the toll network, and truck *departures* from the port as the number of trucks *entering* it. Truck arrivals and departures are then aggregated per day and port.

We make the assumption that all toll-leaving trucks are heading directly to the port and that all toll-entering trucks just came from the port. Since we do not have data outside the toll network, actual truck origin and destination are unknown. However, it can be assumed that truck traffic at the port-relevant entry and exit points are strongly related to the ports, given that adjacent warehouses, factories or production facilities often associate with intermodal hubs.

The port of Duisburg-Rheinhausen represents a special case in terms of road freight transport. Using the above approach, only one segment of the highway is located in the port-relevant area. However, Duisburg is Germany's

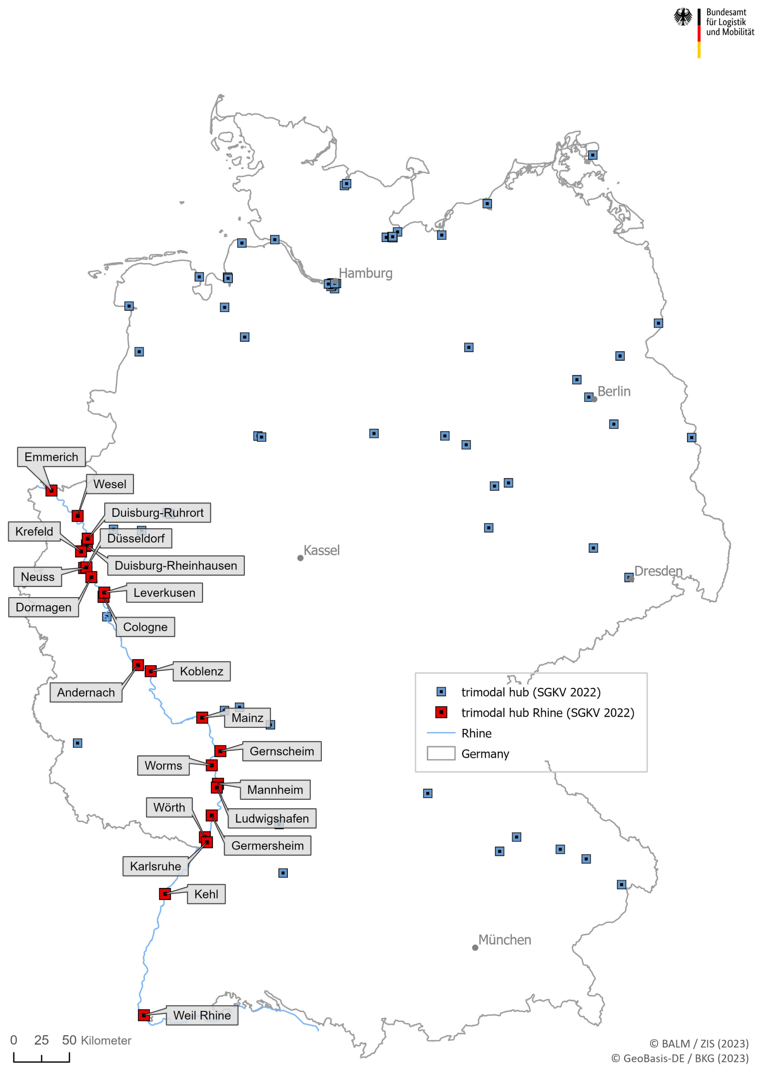

Figure 1: Trimodal terminals in Germany (blue) and the trimodal ports along the Rhine (red).

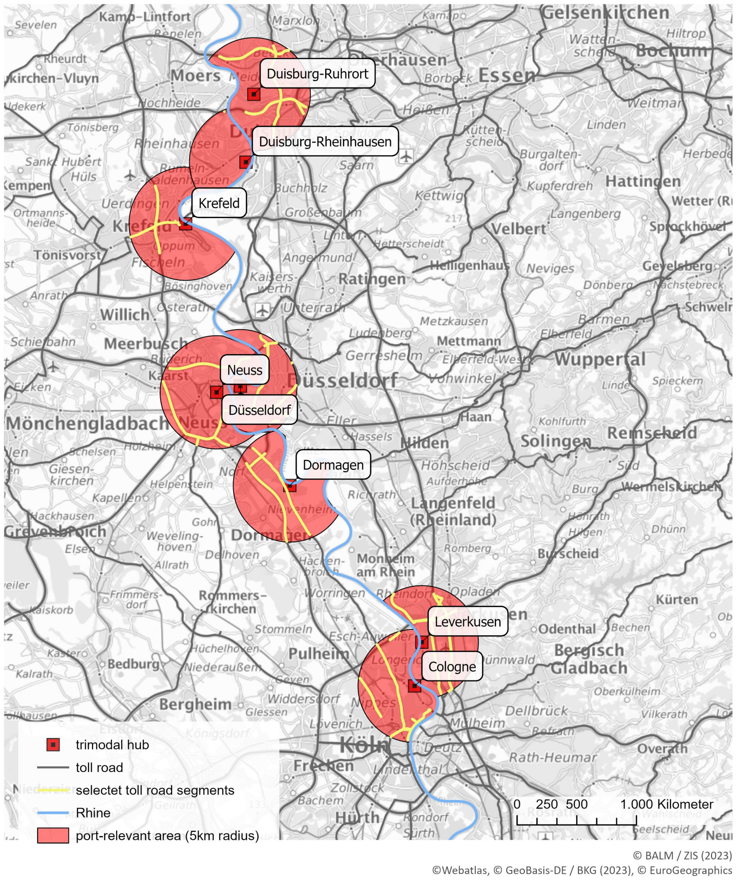

Figure 2: Identification of toll segments (yellow) in port-relevant areas (red).

largest inland port and is therefore of interest for the analysis. For this reason, nearby sections with a toll connection to Duisburg-Rheinhausen have been added manually to supplement the data for this port.

It is important to note that the number of toll segments taken into account plays a significant role in determining the number of trucks to and from the ports. The more included segments, the higher the number of possible counted trucks arriving or leaving the port. It is therefore important to control for the number of segments associated with every port in the empirical analysis.

2.2. Rail traffic

We use daily train counts from DB InfraGO AG to estimate railway traffic at the trimodal ports. The data covers all segments of the railway network operated by the DB from 2018-2025. For each segment of the network between two DB operating points (OP), there is information on the number of passing trains per day categorized into passenger or freight train. We use only freight train counts for the year 2023 to calculate train traffic flows around intermodal ports. Unlike roads, which offer many possible routes to the port, the public railway has only one access point to the port: the port's private railway siding connected to an OP, which is only accessible by one connecting switch. Since sidings are often privately owned, they are not included in the DB data. Therefore, train traffic flows can only be estimated from the port-connected OP.

As an estimate for the train traffic counts around intermodal ports, the OP with a clear access to the port via a rail siding is manually determined for each port. Train arrivals (or departures) are then defined as the number of incoming (or outgoing) freight trains at the port-connected OP.

The port-connected OP can either be an end station or an intermediate station. An end station is the last station in a route, and is typically a station built specifically to serve the port. An intermediate station is between two other stations within a route. A limitation the raw DB data is that it only contains *daily* counts and cannot distinguish between passing trains that do not enter the port, and trains that enter and leave the port *on the same day*. This applies in particular to intermediate stations, where passing trains that do not necessarily go to the port are included in the counts of train arrivals and departures. It is assumed that trains arriving and departing at the port-connected OP correspond approximately to the trains traveling to and from the port. The consequence of this assumption is that the standard errors in the statistical analyses are higher due to the greater uncertainty in the train counts at intermediate stations. To mitigate this issue, intermediate stations must be controlled for in the statistical analyses.

2.3. Inland waterway traffic

We base our waterway-traffic flow calculations on AIS data from inland waterway vessels in the year 2023 (Amt für Binnen-Verkehrstechnik, 2023). This data is received by 117 land stations with a reach of up to 100 km, depending on the topology of the surrounding area. All ports along the

Rhine except Weil am Rhein are within range of a land station, enabling AIS-derived traffic calculations for 21 out of the 22 selected ports.

The AIS data is available as individual files for each day, containing all ship movements on that day. Ships are first identified using their Maritime Mobile Service Identity numbers. Data points across all files are then consolidated for every ship resulting in one dataset per ship. A data point in each file corresponds the ship's location at a point in time. Points are grouped into *tracks* such that, within each track:

1. The ship direction is unchanged,
2. The speed of the ship does not fall below two km/h,
3. There are no changes in the reported trip status (underway or moored), and
4. The manually provided ship dimensions are unchanged (e. g. for push or coupled barges).

When a ship's track begins (or ends) within a 1.5-kilometer radius from the port, it is counted as departure from the port (or an arrival into the port, respectively).[1] The 1.5-kilometer radius was selected because it is the smallest radius that spatially encompasses the full areas of all the ports in the study.

Arrivals and departures are then aggregated per day and per port. With the exception of the two nationwide AIS service interruptions in 2023 (November 18-19, and November 27 to December 7), all days of 2023 have information on waterway traffic flow.

This approach works well for most ports in the study. A special case is the trimodal port in Wesel, called the Emmelsum Port, whose 1.5 km radius encompasses two other areas that are also relevant for arrivals and departures: the moorings and waiting areas of the Friedrichsfeld lock and the bimodal Rhein-Lippe port. Both areas are on the same side of the Rhine as the Emmelsum port, but the ship movements taking place in these two areas are not associated with the Emmelsum port. Similar to the toll data, ship traffic derived through the 1.5-km radius method cannot differentiate between the traffic around the Emmelsum port and the Rhein-Lippe port. However, this issue is less of a limitation due to the fact that both the truck

[1] The KD-tree algorithm is used to efficiently determine whether a data point lies within one of the port radii.

and the ship traffic from the port of Rhein-Lippe will be captured by both toll and AIS data, respectively. Given that the Rhein-Lippe port does not have railroad infrastructure, the traffic values calculated in Wesel effectively takes into account the same area for all three modes of transport.

2.4. Combined data

The processed datasets from the three transport modes are matched using port and date to obtain a cross-modal dataset of daily traffic flows for Rhine ports in 2023. For this study, we are interested primarily in within-port traffic interactions. But since traffic magnitudes differ substantially across ports and modes, we standardize the values at the port level:

$$Z_{it} = \frac{X_{it} - \phi_i}{\sigma_i} \tag{1}$$

where Z_{it} is the standardized value for port i at day t; X_{it} is the original value of traffic counts; and ϕ_i and σ_i are the mean and standard deviation of daily traffic in port i for the year 2023.

This standardization removes level-differences in traffic counts across ports and modes, allowing the focus on the traffic fluctuations around port-specific means. Figure 3 shows the incoming traffic of all three modes for a sample month in March 2023. Positive values indicate above average fluctuations, and negative values indicate below-average fluctuations. For trucks and trains, there is an evident regular pattern of fewer traffic on the weekends. Weekly fluctuations must therefore be controlled for in the empirical analysis.

3. Empirical strategy

To investigate the correlations and dynamic interactions between transport modes at trimodal ports, we need to analyze whether traffic in one transport mode has contemporaneous as well as lagged effects on other modes. To keep it simple, we run three ordinary least squares (OLS) regressions, one for each transport mode j, following the form

$$D_{it,j} = \alpha + \beta A_{it,-j} + \boldsymbol{\gamma' A_{it-1,-j}} + \boldsymbol{\delta' X_{it,j}} + \epsilon_{it,j} \tag{2}$$

where $j \in \{\text{Truck, Ship, Freight train}\}$; $D_{it,j}$ is the standardized departing vehicle count at port i on day t; $A_{it,-j}$ is a vector of standardized arriving

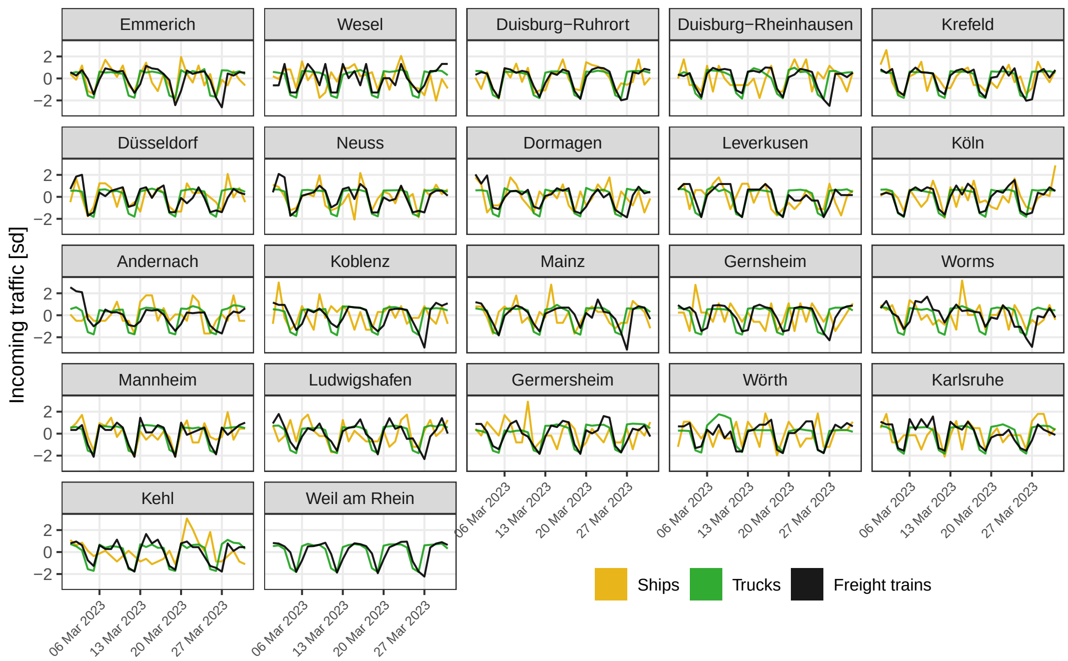

Figure 3: Daily incoming ship, truck, and train traffic around Rhine ports; standardized; March 2023.

vehicle counts for the non-j transport modes and $A_{it-1,-j}$ is its one-day lag; $X_{it,j}$ is a vector of control variables for weekend and holiday effects, and transport mode-specific controls; and $\epsilon_{it,j}$ is an error term. The transport mode-specific controls take account of factors that mitigate the limitations of the data: the number of highway segments in the port-relevant area when j = Truck; whether a port-connected OP is an intermediate or end station when j = Freight train. Also included are dummy control variables for ports with special cases like the port of Wesel when j = Ship.

We hypothesize a positive correlation between incoming traffic from one mode and outgoing traffic from other modes, i.e., that $\beta > 0$.

We also hypothesize some lagged effects, i.e. $\boldsymbol{\gamma} > 0$, due to the discrepancies in the capacities of the three transport modes. An inland vessel in the form of a push boat with two barges can transport a total of 2,800 tons, corresponding to the load of 112 trucks each carrying 25 net tons (Federal Waterways and Shipping Agency , GDWS). Similarly, a 740-meter long freight train can transport around 1,400 tons, corresponding to the load of 52 trucks (pro Schiene, 2016). Capacity discrepancies are bound to cause some goods to be warehoused for a day, before being loaded to another mode.

4. Results

Table 1 presents the results of the regressions. The coefficients of *Incoming trucks* and *Incoming trucks, t-1* are positive and significant in all regressions, showing that incoming trucks have both a same-day and one-day lagged effect on outgoing trains (column 2) and ships (column 3). The variable *Incoming ships* also has positive and significant coefficients, revealing contemporaneous effects of incoming ships on outgoing trucks (column 1) and trains (column 2). The variable *Incoming ships, t-1* has positive coefficients, but is only significant for outgoing trucks (column 1), suggesting that ship traffic has a one-day lagged effect on truck counts but not on train counts. The coefficients of *Incoming freight trains* and *Incoming freight trains, t-1* are only positive and significant for outgoing trucks (column 1). The data finds no effect of trains on ships.

The significant coefficients greater than zero support our first hypothesis that there is a positive correlation between modes of transport. For ships and freight trains, however, the direction of the effect is not symmetric. Whereas an incoming ship is associated with more outgoing trains on the same day, an incoming train does not affect the number of outgoing ships.

Table 1: Regression Results

	Outgoing vehicles		
	Trucks	Freight trains	Ships
	(1)	(2)	(3)
Incoming trucks		0.309^{***}	0.193^{***}
		(0.030)	(0.044)
Incoming trucks, t-1		0.285^{***}	0.123^{***}
		(0.009)	(0.017)
Incoming ships	0.020^{***}	0.018^{*}	
	(0.003)	(0.008)	
Incoming ships, t-1	0.012^{***}	0.002	
	(0.003)	(0.008)	
Incoming freight trains	0.071^{***}		0.032
	(0.005)		(0.018)
Incoming freight trains, t-1	0.009^{*}		-0.012
	(0.004)		(0.017)
Weekday = 1	1.929^{***}	0.724^{***}	0.357^{***}
	(0.011)	(0.061)	(0.090)
Holiday = 1	-1.988^{***}	-0.787^{***}	-0.471^{***}
	(0.020)	(0.075)	(0.110)
Constant	-1.323^{***}	-0.487^{***}	-0.240^{***}
	(0.009)	(0.043)	(0.063)
Mode-specific controls	Yes	Yes	Yes
Observations	7350	7350	7392
R^2	0.930	0.619	0.192

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

When it comes to our second hypothesis on lagged effects, yesterday's incoming trucks are correlated with more outgoing freight trains and ships today. Conversely, yesterday's incoming ships and trains also positively correlate with today's outgoing trucks. This suggests that some of the cargo brought by trucks may be stored for a day before being transferred to a ship or train, and vice versa. Between ships and trains, no lagged effects were found, supporting our hypothesis that dynamic lagged effects exist for transport modes with very large capacity differences.

On the whole, our results reveal that road traffic, being the most flexible mode of transport, correlates both contemporaneously and lagged with the two other modes, while the less-flexible modes correlate only contemporaneously with each other.

5. Conclusion

This is the first paper that provides a systematic method to calculate cross-modal, longitudinal traffic flows at trimodal hubs and generates insights into the empirical relationships between them. Using toll data, AIS-Data and train count data, we find positive contemporaneous correlations between trucks, ships and trains. Results also suggest one-day lagged relationships between trucks and ships, and trucks and trains. Given that this is the first study to statistically test these relationships, work could be further developed to validate the traffic calculation approaches and extend them to all intermodal hubs in Germany. The findings of this paper can contribute to the integration of intermodal hubs in modeling freight traffic, allowing us to build a more complete picture of the freight transport network.

References

Abu-Aisha, T., Audy, J.F., Ouhimmou, M., 2024. Toward an efficient sea-rail intermodal transportation system: a systematic literature review. Journal of Shipping and Trade 9. doi:https://doi.org/10.1186/s41072-024-00182-z.

Agamez-Arias, A.d.M., Moyano-Fuentes, J., 2017. Intermodal transport in freight distribution: a literature review. Transport Reviews 37, 782–807. doi:10.1080/01441647.2017.1297868.

Amt für Binnen-Verkehrstechnik, 2023. AIS-Dienst: Automatic Identification System. URL: https://www.abvt.wsv.de/webcode/1032678.

Bhattacharya, A., Kumar, S., Tiwari, M., Talluri, S., 2014. An intermodal freight transport system for optimal supply chain logistics. Transportation Research Part C: Emerging Technologies 38, 73–84. doi:10.1016/j.trc.2013.10.012.

Chang, Y., Zhu, X., Haghani, A., 2019. Modeling and solution of joint storage space allocation and handling operation for outbound containers in rail-water intermodal container terminals. IEEE Access 7, 55142–55158. doi:10.1109/ACCESS.2019.2913019.

Eurostat, 2025a. Unitisation in inland waterways freight transport - tonne-kilometre for gross-gross weight of goods. tran_im_uiww. European Commission. URL: https://doi.org/10.2908/TRAN_IM_UIWW.

Eurostat, 2025b. Unitisation in rail freight transport- tonne-kilometre for gross-gross weight of goods. tran_im_urail. European Commission. URL: https://doi.org/10.2908/TRAN_IM_URAIL.

Eurostat, 2025c. Unitisation in road freight transport - tonne-kilometre for gross weight of goods. tran_im_uroad. European Commission. URL: https://doi.org/10.2908/TRAN_IM_UROAD.

Eurostat, 2025d. Unitisation in the different modes of transport - tonne-kilometre for gross weight of goods. tran_im_umod. European Commission. URL: https://doi.org/10.2908/TRAN_IM_UMOD.

Koritarov, T., Dimitrakiev, R., 2025. Intermodal and multimodal integration in eu maritime logistics: Challenges and strategic implications. International Journal of Innovative Science and Research Technology 10, 3658–3669. doi:10.38124/ijisrt/25may2193.

Krylatov, A., Raevskaya, A., 2023. Freight flow assignment in the intermodal logistics network. Transportation Research Procedia 68, 492–498. doi:10.1016/j.trpro.2023.02.066.

pro Schiene, A., 2016. Überblick: Wie der güterzug länger werden kann. https://www.allianz-pro-schiene.de/themen/aktuell/740-meter-gueterzug. Accessed: 2025-09-30.

SteadieSeifi, M., Dellaert, N., Nuijten, W., Van Woensel, T., Raoufi, R., 2014. Multimodal freight transportation planning: A literature review. European Journal of Operational Research 233, 1–15. doi:https://doi.org/10.1016/j.ejor.2013.06.055.

The Association for Combined Transport, 2022. Intermodal map. URL: https://www.intermodal-map.com/.

Federal Waterways, Shipping Agency (GDWS), 2025. Klassifizierung der binnenwasserstraßen. URL: https://www.gdws.wsv.bund.de/DE/wasserstrassen/01_bundeswasserstrassen/Klassifizierung/Klassifizierung_node.html.