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Smart & Resilient Logistics Corridors Future Gateway to the Green Trade

DEVELOPMENT OF THE 'INLAND SHIPPING MILEAGE INDEX' USING AIS DATA FOR HINTERLAND

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ABSTRACT

Due to growing transport volumes that can no longer be handled by road and rail alone, and the environmental advantages of inland waterway transport (IWT), a modal shift to waterways can be expected. Traffic on German waterways is closely linked to the ARA-seaports of Antwerp (Belgium), Rotterdam (Netherlands) and Amsterdam (Netherlands), which are among the largest in the world. Understanding transport characteristics is vital for the growth of the IWT sector. Germany's main IWT transport statistics are in the annual traffic report by the Federal Waterways and Shipping Agency, based on 35 counting points. Some points provide details like vessel type, direction or load. Others only give the total number of vessels. This limits the report's ability to make specific statements. To close these gaps, the processing of data from the Automatic Identification System (AIS) will be presented, which enables more comprehensive findings on traffic to be computed. Artificial cross-sections from AIS data employed by this study are used to compare the passages of vessels with the 35 counting points from the traffic report. To enable comparison with the dominant mode of transport, road transport, the "truck toll mileage index" developed by the Federal Office for Goods Transport is applied to IWT and leads to the introduction of the "inland shipping mileage index". Due to erroneous and incomplete AIS data, a systematic processing methodology is introduced. A strong correlation between the processed AIS data and the traffic reports has revealed the quality of the data and the effectiveness of the processing method. The daily mileage is an example of an application that shows weekly and seasonal patterns. Finally, the inland shipping mileage index enables a comparative analysis with road transport and provides a solid database for future challenges in the development of hinterland connections for the most important European seaports.

1. INTRODUCTION

For European supply chains, the ARA-seaports of Antwerp (Belgium), Rotterdam (Netherlands) and Amsterdam (Netherlands) fulfil an important role in overseas shipments. International transport therefore has a direct impact on regional hinterland connections. An analysis of the modal split at the Port of Rotterdam [1] illustrates the strong interdependence between maritime shipping and inland waterway transport (IWT). In 2024, 27,617 seagoing and 91,356 inland waterway vessels called the port. IWT accounted for 34% of the modal split in the container segment [2], with even higher proportions anticipated for dry and liquid bulk.

Waterborne cargo is transported from these ports via the Rhine, one of the world's most intensively used inland waterways [3], and distributed throughout the European IWT network, facilitating access to key hinterland markets. Given the lower greenhouse gas emissions of IWT (34 grams/tonne-kilometer) compared to modal split dominating trucks (119g/tkm) [4], the European Commission has set the target to shift a significant proportion of the 75% of domestic freight currently transported by road to rail and inland waterways as part of the European Green Deal [5]. Consequently, a solid understanding of transport characteristics is becoming even more important for the aimed increase in the IWT sector and for establishing reliable supply chains in general.

Although the Automatic Identification System (AIS) was originally developed for collision avoidance between ships, it has been recorded for several years, first at sea and then on inland waterways, and analyzed for various purposes. Emmens et al. [6] provide a good overview to start with by revealing the promises and perils of AIS data. Various possible applications ranging from supply chain management and infrastructure to environmental aspects are presented. On the other hand, potential sources of error due to gaps in the data caused by reception problems resulting from large buildings or excessive traffic density are shown. It is concluded that AIS data contains insightful information, but that this can only be made visible through precise data processing. In their comprehensive survey, Tu et al. [7] categorize the capabilities of AIS into the areas of traffic anomaly detection, route estimation, collision prediction and path planning. A systematic literature review of Industry 4.0 technologies for IWT is provided by Branch et al. [8], containing helpful background information on AIS data applications. With traffic monitoring, smart navigation, emission reduction, analytics with big data and cybersecurity, five domains of scientific literature are identified. As AIS data originates in the maritime sector, the majority of research in the field of waterway performance monitoring focuses on maritime issues: While Mitchell and Scully [9] analyze the influence of tidal currents on waterway transit time, Meyers et al. [10] characterize vessel traffic by analyzing ship sizes and types, draught, and speed and Yan et al. [11] use weighted origin-destination matrices for traffic routes to estimate global oil trade. This demonstrates that AIS data makes a valuable contribution to understanding transport characteristics, particularly in the maritime sector.

In Germany, the standard source for IWT statistic is the annual traffic report published by the Federal Waterways and Shipping Agency, which is based on 35 counting points [12]. For some points, information on the type of vessel, direction of travel or load status is available, while in others only the total number of vessels is given. It is only capable of making general statements about traffic, not specific ones. Similarly, it is not possible to compare different modes of transport using the same key figures. Aiming to provide a better understanding of traffic, this project contains the following contribution: (1) By comparing traffic at artificial cross-sections from AIS data at the counting points of the annual traffic report with the traffic volumes in the report, it is demonstrated that AIS data is suitable for expressing traffic. (2) In order to compare traffic across different modes of transport, the "truck toll mileage index" developed by the Federal Office for Goods Transport is presented and methodically transferred to IWT, and the "inland shipping mileage index" is calculated and its results analyzed. As will become apparent from the literature study below, each research question requires individual processing of the AIS data, which is why two different data processing methods are presented for these two topics.

The paper is structured as follows: Section 3 begins with an introduction to AIS data within the regional context of Germany. This is followed by a description of the method used to prepare the data for correlation analysis with the annual traffic report, which is employed to validate the data and its processing. In order to facilitate a comparison between IWT and road freight transport, Section 4 introduces the truck toll mileage index. The ensuing discourse will provide a detailed exposition on the processing of AIS data to calculate and evaluate the inland shipping mileage index. Section 5 provides a final conclusion.

2. APPLICATION OF AIS DATA FOR TRAFFIC STATISTICS

To present the applicability of AIS data for traffic statistics, correlations between the traffic data of the annual traffic report and its counting points with processed AIS data are presented. The data processing developed for this purpose is described following a thematic introduction to AIS, its original purpose, functionality, advantages, and limitations.

2. 1 The Automatic Identification System (AIS)

Depending on the ship's speed and other factors, every ship longer than 20 meters transmits static, dynamic and voyage-related data at intervals ranging from three seconds to a few minutes. This includes, for example, the ship's name, size and identification number, position details, heading and speed, as well as the port of destination and expected time of arrival. The raw AIS data contains position data as longitude and latitude, as well as a timestamp for each ship, and can be assigned to individual ships via their unique call sign (Maritime Mobile Service Identity (MMSI)). The data transmitted by ships via VHF (very high frequency, similar to radio communication) is received by other ships in the vicinity for the original purpose of collision avoidance. It is also received by land stations and is centrally archived and analyzed by the Federal Waterways Engineering and Research Institute since 2019.

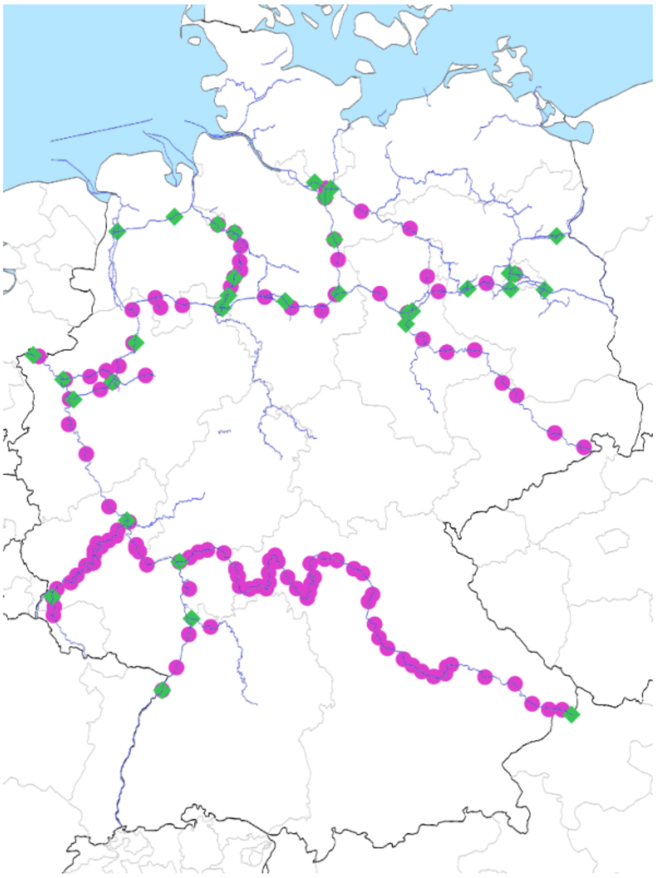

Figure 1: The 119 land stations for receiving AIS data (magenta dots) and the 35 counting points of the annual traffic report of the Federal Waterways and Shipping Agency (green squares).

Particularly important for the spatial distribution of AIS data is their availability. The range is determined by the height of the transmitter and receiver antennas and the terrain between them, in addition to the transmission power and other interference signals. The maximum extendable height of the wheelhouse, on whose roof the ship's antenna is usually mounted, limits its height. This is usually between 4.5 and 7 meters. Radio masts on land are generally between 10 and 25 meters high. In an open area, a land station can thus receive AIS signals from ships within a radius of up to 50 kilometers. Since rivers in their upper and middle segments often lie in winding valleys, the range is significantly reduced by the topography. Buildings in cities have a similar, albeit not quite as intense, effect. Even though such approaches do not allow for exact calculations of network coverage, when applied to the 119 German land stations [13], which are shown in Figure 1, they provide a sufficiently accurate basis for estimating sections of waterways with and without the ability to receive AIS data.

2.2 Data processing

In order to validate the AIS data, the correlations between traffic volumes and official statistics are examined. In Germany, this source is the annual traffic report published by the Federal Waterways and Shipping Agency [12]. Figure 1 shows the distribution of the 35 counting points on which the report is based. A comparison of the counting points with AIS land stations clearly illustrates the difference in network coverage. It reveals that ships can navigate the Rhine between Duisburg and Mannheim, for example, or the entire Main-Danube Canal, without being registered in the traffic report.

As mentioned in almost all sources, quality issues in AIS data often lead to analysts misunderstanding ship behavior. A major challenge for each research question is correcting errors in the AIS data and processing it. He et al. [14] and Chen et al. [15] examine the sources of error in more detail, presenting denoising and interpolation methods. However, they also demonstrate that data processing in the literature is always adapted to the specific research question. Nevertheless, many methods share similarities in the following four steps: Data pre-processing; time interval distribution analysis; abnormal data detection and removal; and kinematic interpolation.

As ships can move freely on waterways, the comparison is made using the one-dimensional reference system of waterway kilometers in order to be capable of detecting all ships. For each waterway, a centerline is uniformly specified and georeferenced by the German Federal Waterways and Shipping Administration, which is usually located in the middle of the waterway. The respective waterway kilometer is calculated based on the minimum distance of each AIS data point from the nearest axis. For the counting points from the reports, identification number of the waterway and the kilometer are determined. In order to compare this with the AIS data, all AIS data points are converted from its original position format with longitude and latitude coordinates (GPS) to waterway kilometers. Since data is not sent continuously but at intervals, information is not available for every vessel for every kilometer of waterway. For this reason, all data is interpolated in a standardized manner on artificial cross-sections at each hectometer. These passages can then be aggregated as needed, in this case annually.

Since many counting points are located at locks, potential sources of error must be taken into account: while waiting to pass through the locks, ships often moor in the approach area, which means that they may pass through a cross-section several times when docking or undocking. The accuracy of GPS signals is also a problem given the slow speed of the ships: As entering and exiting locks is challenging due to the very limited space for maneuvering, ships navigate these areas with extreme caution and at low speed. If a ship is travelling at 5 km/h, for example, and sends a data set every 3 seconds, the distance between two positions is only 4.8 meters. However, the accuracy of GPS is usually specified as up to 15 meters for 95% of measurements.

For an accurate position, an unobstructed environment is essential, and as many satellites as possible must be received from as many different angles as possible. If the water level in the lock chamber is at the level of the lower-water, the chamber walls and the lock gates massively restrict the reception of satellite signals at the usual heights of ten meters. It can therefore be assumed that the signal from a stationary ship in the chamber passes through a cross-section several times. The example of the Koblenz lock, where more than twice as many ships were detected in the chamber than before and after, illustrates this phenomenon. Since ships do not usually turn back after an interruption to their journey at waiting points at locks, but continue on their way through the lock, it can be assumed that the vast majority of these ships will also pass through the lock and are therefore relevant for the correlation studies. However, there are often transshipment points in the wider vicinity of the locks where ships change direction without passing through the lock. In order to calculate a representative value for the ships passing through the lock, outliers are eliminated and the average of three cross-sections of the chamber center in each direction is calculated.

To record low values for ship passages due to data reception disruptions, it is sensible to record these separately. If no AIS data is received in a section on a given day, a disruption is assumed. The results from the days without disruptions are then extrapolated to the full year. However, this was only the case in very isolated instances in 2022 (2023), meaning that data is available for an average of 363 (362) days per year for waterways equipped with counting points, with a lower limit of 336 (348) days.

2.3 Correlation study

Pearson's correlation shows a high positive linear relationship between the AIS data and the traffic report data for both 2022 (r = 0.914) and 2023 (r = 0.926). There is no apparent relation between the absolute number of ships at a counting point and the relative variation of the data. Even if there is no constant relationship between the absolute number of ships at a counting point and the relative variation of the data, looking at size categories reveals commonalities within them. Examining the correlations of the counting points, which were passed by fewer than 3,000 ships in the 2022 (2023) traffic report, there is only a moderate correlation of r=0.501 (r=0.608). The remaining stations with more than 3,000 ships have a much higher correlation of r=0.885 (r=0.891).

It is also notable that the variations are not consistent over time: The top three counting points with the largest variations in lower ship numbers in the AIS data compared to the traffic reports in 2022 (Dörpen -73%, Oldenburg -71%, Duisburg-Meiderich -43%) are, with one exception, different from those in 2023 (Kleinmachnow -83%, Dörpen -36%, Geesthacht -32%). The top 3 counting points with the largest variations in higher ship numbers in the AIS data compared to the traffic reports from 2022 (Rothensee +77%, Bremen +51%, Lauenburg +34%) are again different from those in 2023 (Lauenburg +79%, Koblenz +53%, Friedrichsfeld +41%).

It is noticeable that traffic reports tend to count more ships than are recorded in the AIS data: in 2022, the values from 22 of the counting counting points are higher than those from the AIS data, and in 2023, the value from 16 counting points. As expected, a small percentage variation at the heaviest traffic counting point in Emmerich has a major impact on the total variation in absolute ship numbers, accounting for 67%.

When looking at the sum of the percentage of deviations between the AIS data and the traffic report data, it is noticeable that the year 2022 deviates by 1,012%, which is more than the year 2023 with 756%. However, the counting point at the Jochenstein lock on the German-Austrian border on the Danube River stands out with a deviation of 167% in 2022 and 96% in 2023. Excluding this outlier, the median percentage deviation is 16% in 2022 and 13% in 2023. In 2022, 64% of counting points have an absolute deviation of less than 20%, compared to 53% in 2023.

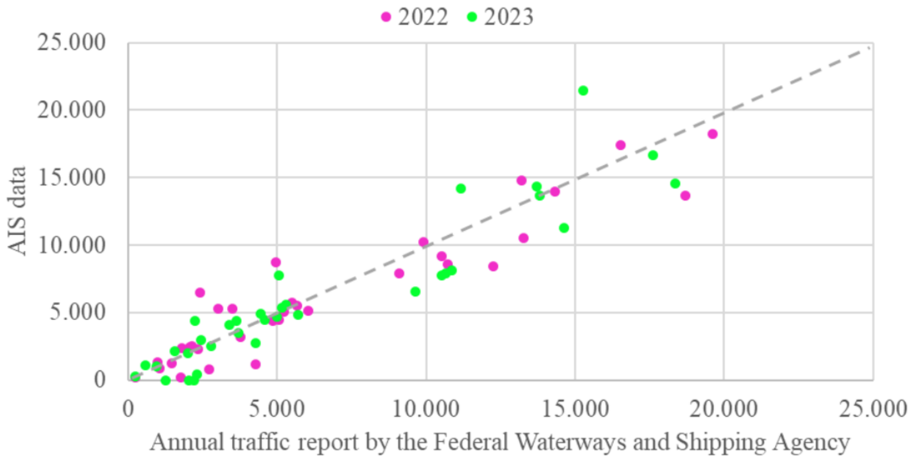

Figure 2: Comparison of AIS data on 35 artificial cross-sections of the counting points from the annual traffic report by the Federal Waterways and Shipping Agency for the years 2022 and 2023.

3. MODAL COMPARISON

3.1 The truck toll mileage index

In order to enable a modal shift in freight transport, a standardized cross-modal database is crucial. The annual traffic report does not provide such a database, meaning it is not possible to compare different modes of transport using the one set of key figures. To enable comparison with the dominant mode of transport, road transport, the truck toll mileage index developed by the Federal Office for Goods Transport [16] is used. It was developed in 2018 from digital process data generated in the course of truck toll collection. Mileage is the total number of kilometers travelled. The magnitude and development of freight transport can only be determined by comparing the absolute figures with a reference period. Development trends can be identified by examining a time series. To eliminate seasonal effects, calendar and seasonal weight adjustments are also made. The non-adjusted index is calculated as follows, where MI is the mileage index, m is the month, M is the mileage (total kilometers driven per month), and jo is the base year. This is followed by calendar and seasonal corrections.

$$MI_m = \frac{M_m}{\frac{1}{12} \cdot \sum_{i=1}^{12} (M_i)_{j0}} \cdot 100 \tag{1}$$

The delivery of materials for production and the distribution of manufactured products generates freight transport, which is why it is closely linked to economic developments. While company data for analyzing the economy can only be collected time-consuming at considerable effort, this transport data is available at an early stage and, when anonymized and aggregated, provides a valuable basis for analyzing economic developments. During the coronavirus pandemic in particular, they played a special role in assessing the impact of political decisions on the economy and have since become established. Compared to other indices, this index is available much earlier and is a reliable indicator of industrial production and economic activity.

3.2 Data processing

The mileage index is calculated based on the distance driven in the waterway kilometers reference system. For this purpose, the raw AIS data is grouped by ship using MMSI and sorted by time. The distance between two data points is calculated based on the difference in waterway kilometers between these two points. Due to the geometry of the waterways, this distance is not the same as the actual distance driven, which is longer on outer curves and shorter on inner curves. However, these effects balance each other and result in negligible deviations. In order to avoid erroneous values when changing between waterways, the data is grouped by waterway before the difference is calculated and then regrouped afterwards. The kilometers driven are aggregated on a daily basis or, for the mileage index, on a monthly basis. An initial evaluation of this data has revealed implausible variations: for the year 2023, data is available for 347 out of 365 days, with a median of (plausible) 129,525 driven kilometers per day. However, the standard deviation is 50,274 kilometers. Even though weekly and seasonal fluctuations are known from previous studies, this figure is unusually high. The cause of these variations is assumed to be data gaps due to failures of parts of the AIS land infrastructure. If all 119 land stations fail simultaneously and for the entire day, no data is received on that day, which is directly visible in the daily data. However, this occurs rarely. If only individual land stations fail temporarily, it is not possible to directly determine from the data which land stations are affected. In order to detect failures of individual land stations, the longitude and latitude data available for the land stations are converted into position data in waterway and kilometer. In a next step, each AIS data point is checked whether it is located within a radius of +- 10 driven waterway-km around a land station. In order to identify implausible outliers, the moving average of the sum of kilometers driven in the adjacent two months (30 adjacent values on both sides) is calculated for each station. A tolerance range of +- 25% for plausibility is defined. Outside the tolerance, values are considered implausible and replaced by the moving average. Data gaps are also filled in using the moving average described above.

However, the data analyzed in this way only covers the kilometers traveled within a 10 driven waterway km radius of the respective stations. With 119 stations, each covering 20 driven waterway km, this means that 2,380 km are recorded. The network of federal waterways in Germany comprises approximately 7,300 km of inland waterways. So only about one third of the network is covered. This makes it necessary to project the kilometers driven within a 10-kilometer radius of the respective stations onto the entire network. Since the kilometers driven at the individual stations vary greatly and stations fail independently of one another, it is necessary to project the kilometers driven for each station specifically. To establish this relationship, the median of the total kilometers driven per day in Germany was calculated. On the other hand, the median was calculated based on the total kilometers driven within a 10-km radius of all stations. Putting these in relation to each other gives a factor of 2.23. This means that the adjusted total of kilometers driven within a 10-kilometer radius of each land station must be multiplied by a factor of 2.23 to determine the total kilometers driven in Germany. For clarification, an example for the Kaub land station on the Rhine is given in Table 1.

For further processing, the prepared data from all land stations is first aggregated on a daily basis and then on a monthly basis for the mileage index. The inland shipping mileage index is then calculated using formula (1) in analogy. The monthly mileage is finally adjusted for German public holidays and seasonal factors using the open-source programming language R and a method based on the US Census Bureau's standard X13 ARIMA SEATS method.

Table 1. Example for a short-term data failure at AIS land station Kaub (Rhine) and its adjustment

Date	Driven Kilometers	Rolling mean	Value outside tolerance and to be replaced	Factored value
01.06.2024	1.453	1.286	No	3.240
02.06.2024	1.115	1.287	No	2.486
03.06.2024	856	1.290	Yes	2.877
04.06.2024	76	1.287	Yes	2.870
05.06.2024	80	1.289	Yes	2.874
06.06.2024	1.506	1.302	No	3.358
07.06.2024	1.489	1.304	No	3.320
08.06.2024	1.595	1.299	No	3.557
09.06.2024	1.215	1.298	No	2.709

In order to validate the presented data and processing method, the newly developed index is compared with the transport index inland shipping of the Federal Statistical Office of Germany [17]. The transport index was published as experimental statistic between 2016 and 2023 in order to meet the high political and social interest in rapidly available economic indicators. The data is based on the number of cargo ships calling at nine high-volume inland ports, which already account for approximately 40 per cent of the total throughput of German inland ports. When interpreting the data, the different base years of the transport index (2019) and the inland shipping mileage index (first 12 months available from 07/2021 to 06/2022) must be taken into account. During the period when the two indices overlap, a similar trend can be observed: an increase from mid-2021 to the end of the year, followed by a slight decline at the beginning of 2022, which leads to a stable level in the second half of the year. At the end of 2023, both indices fall to a low point, after which they rise at a similar rate. Although there are two peaks in the transport index in March and August 2022 that are not visible in the inland shipping mileage index, these can be considered isolated outliers (see Figure 3).

3.3 Interpretation of results

IWT is subject to a complex variety of dependencies, but broad trends can often be explained, at least in part, by individual events. The increase in the second half of 2021 is explained by the robust recovery of the economy after the coronavirus pandemic. Supply chains, some of which had collapsed significantly, are recovering, and transport volumes in some segments are reaching levels above those seen before the coronavirus pandemic, while in others they remain slightly below. The drop in water levels at the turn of the year led to an increase in transport prices, which was reflected in a decline in traffic volume [18]. In 2022, the impact of high inflation and a slowdown in GDP growth also come into consideration [19]. Due to the phase-out of coal in electricity generation in Germany, a decline in coal, which is the leading dry bulk commodity in terms of volume, is to be expected from 2021 onwards [20]. The outbreak of armed conflict between Russia and Ukraine in February 2022 led to an increase in gas prices due to sanctions on gas imports from Russia. However, this has made coal, as a than cheaper alternative, more attractive again. As coal is transported by waterway, the decline in total transport volumes is visible, but not as pronounced as expected, particularly in the first half of 2022 [21]. The decline at the beginning of the second half of the year can be explained by a period of low water levels in July and August 2022. The decline in the compensatory effects of coal and the economic recession in the inland waterway freight transport sector is apparent in the second half of the year.

A look at maritime transport shows the close interaction between inland and maritime shipping, as reflected in the decline in the volume of goods handled by the ports of Rotterdam (-4.1%) and Antwerp (-7.5%) in inland waterway transport for 2022 [19]. In 2023, the global economy proved resilient and inflation fell almost as quickly as it had risen in 2022, which stabilized IWT. Similarly, there were no major low-water periods that affected transport. The attacks by Yemeni rebels on merchant ships in the Bab-el-Mandeb Strait from October 2023 onwards also had an impact on fluctuations in inland waterway transport volumes, as 75% of European exports are usually handled via this strait [22]. Stability is maintained in the first half of 2024, but the long-term trend of declining transport on waterways remains visible.

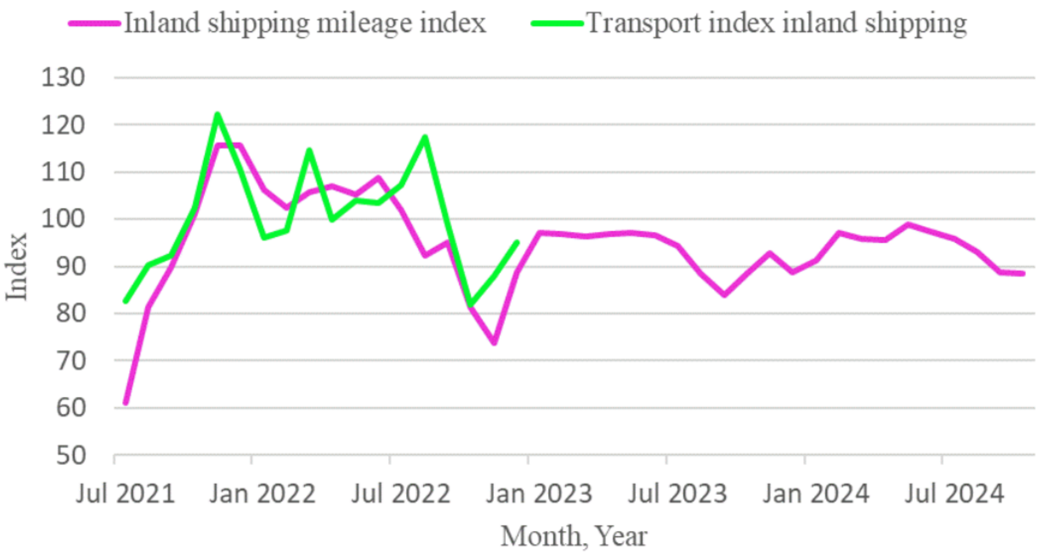

Figure 3: The inland shipping mileage index over time and it's comparison with the transport index of the Federal Statistical Office

An analysis of the mileage of inland waterway vessels without calendar and seasonal adjustment reveals seasonal effects, with a maximum of over 4.5 million kilometers driven in the summer months of June, July and August and a decline in the winter months to around 3 million kilometers driven per month. A daily analysis reveals a weekly cycle with minimum values of approximately 125,000 kilometers per day on Sundays and an increase to just over 150,000 kilometers per day by the end of the working week, followed by a sharp decline on Sundays.

4. CONCLUSIONS

Due to the current challenge of phasing out coal for electricity generation and the associated decline in the most commonly transported bulk goods, as well as the politically induced modal shift due to the ecological advantages of IWT over road transport and the infrastructure and capacity constraints on the roads, the freight transport sector is facing a transformation. To be able to do so, a detailed and comprehensive knowledge is required, which cannot currently be derived from the existing databases.

By using artificial cross-sections in AIS data to demonstrate the applicability of AIS data for traffic statistics, hectometer-based interpolation has been shown to be successful. Correlations of 0.91 and 0.93 for comparison data sets from 2022 and 2023 demonstrate the high quality of the data and the presented processing method. Since comparable figures for all modes of transport are absolutely essential for a modal shift in freight transport, the truck toll mileage index developed by the Federal Office for Goods Transport was presented and applied to IWT. In order to calculate the inland shipping mileage index, it was demonstrated how the necessary mileage can be derived from AIS data. The quality of the database and the processing methodology was confirmed by comparison with the inland shipping transport index of the Federal Statistical Office for the period in which the two indices overlapped. Within the discussion of the index presented, national and global influences on IWT in Germany were revealed. During the discussion of the index presented, national and global influences on IWT in Germany were demonstrated. It could also be proven how closely maritime shipping and European hinterland connections are linked and how events that are a considerable distance away are reflected in German IWT data. This enables the inland shipping mileage index to be used as a foundation for quantifying future potential modal shifts, as well as for measuring the success of government initiatives.

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6. DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this work, the author used DeepL in order to translate and improve scientific writing. After using this tool, the author reviewed and edited the content as necessary and takes full responsibility for the content of the publication.

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