International Journal of Transport Development and Integration
Vol. 9, No. 2, June, 2025, pp. 217-225
Journal homepage: http://iieta.org/journals/ijtdi

Comparing Intermodal and Synchromodal Transport Systems to Enhance Efficiency and Sustainability at the Port of Aktau, Kazakhstan

Yun Chen[1], Olga Kisselyova[2], Ainur Abzhapbarova[3], Dana Aliakbarkyzy[1], Yerzhan Karsybayev[1*]

[1] Department of Transport Services and Business, ALT University named after Mukhametzhan Tynyshbayev, Almaty 050012, Kazakhstan
[2] School of Transport Engineering and Logistics named after M. Tynyshpayev, Satbayev University, Almaty 050013, Kazakhstan
[3] Department of Organization of Air Transportation and Logistics, Academy of Civil Aviation, Almaty 050039, Kazakhstan

Corresponding Author Email: karsybayev3@onmail.com

https://doi.org/10.18280/ijtdi.090201

Received: 12 November 2024
Revised: 29 January 2025
Accepted: 11 February 2025
Available online: 30 June 2025

Keywords:
synchromodal logistics systems, intermodal transport optimization, Port of Aktau, container transport modeling, GIS-based transport analysis, CO_2 emissions, real-time transport planning

ABSTRACT

The Port of Aktau, Kazakhstan, is a vital logistics hub within the Trans-Caspian Transport Route. Synchromodal logistics emphasizes synchronized operations and real-time modal shifts to improve sustainability and efficiency. However, its comparative advantages over intermodal systems remain underexplored, particularly in emerging logistics markets like Kazakhstan. The research evaluates transport costs, times, and environmental impacts using data on container flows from the Port of Aktau. GIS-based modeling and Monte Carlo simulations were employed to assess dynamic demand and optimize transport modes and routes. Key performance metrics included transportation distances, terminal waiting times, and CO_2 emissions. Synchromodal systems demonstrated substantial advantages: a 35.5% reduction in road transport costs, 37.7% shorter terminal waiting times, and a 33.3% decrease in CO_2 emissions compared to intermodal systems. Despite higher rail transport and cargo handling costs, synchromodal logistics significantly improved overall efficiency. Road usage was reduced by 40.7%, while rail usage increased by 250%, optimizing transport distances and enhancing environmental sustainability. Synchromodal systems outperform intermodal logistics in cost-efficiency, environmental impact, and operational resilience at the Port of Aktau. These findings highlight the potential of synchromodal logistics to enhance freight transport sustainability and competitiveness in regional and global contexts. Future research should focus on broader applications and empirical validation of these systems.

1. INTRODUCTION

In the contemporary world, where socio-economic development and the improvement of living standards are increasingly evident, there is a steady growth in demand for freight transportation. This, in turn, leads to the flourishing of the transportation and logistics industry. In this context, multimodal transport emerges as a modern alternative to single-mode transportation methods [1]. In China and Kazakhstan, in particular, multimodal transport is gaining importance due to initiatives like the “Belt and Road” and the rapid development of road, waterway, railway, aviation, and pipeline infrastructures. The railway network of Kazakhstan ranks among the largest in the world, with a total length of over 16,000 kilometers. The country's railway system operates approximately 2,500 stations and junctions. Kazakhstan is also advancing its high-speed rail connections, enhancing transport accessibility, and promoting economic integration across regions [2-6]. The road network of Kazakhstan spans approximately 97,000 kilometers in total length, with over 25,000 kilometers designated as republican-level public roads. Key highways include the west-east corridor “Western Europe - Western China,” integral to a major international transport corridor linking Europe with China.

Roads play a crucial role in providing internal transport connectivity between cities and regions of Kazakhstan. Major urban centers such as Nur-Sultan, Almaty, Shymkent, and Karaganda are interconnected by modern highways, facilitating fast and safe transport [7, 8].

Multimodal transport encounters several challenges associated with uncertainties such as weather changes, road conditions, and unforeseen vehicle breakdowns, which can lead to delays and disruptions in supply chains. These factors pose complexities for decision-makers in planning and organizing multimodal transport, thereby hindering its further development [1]. For multimodal transport operators, this necessitates managing complex logistics involving multiple modes of transport, while cargo owners prioritize timely and cost-effective transportation. Given these uncertainties, effective management is critically important for decision-makers in transport, ensuring cost-efficient transport services and successful goods delivery.

Therefore, the development of transport plans must be rational and efficient to minimize the impact of uncertainties on decision-making regarding multimodal transport routes. Optimizing multimodal transport routes involves combinatorial optimization tasks, encompassing route and mode selection. The first optimization model for multimodal transport routes was proposed in 1995 [9], where the assumption was made that total costs include intercity transport expenses and intracity transit costs. A planning model was developed with minimizing total costs as the optimization goal for vehicle transit between cities. In subsequent years, research in this field evolved into an international scientific direction. Researchers have developed various models and algorithms to address optimization problems considering factors such as cost, time, and risks [10-14].

With increased emphasis on the environmental sustainability of transportation, studies have begun incorporating concepts of "green" and "low-carbon" transport. Optimization models now include not only traditional time and cost metrics but also carbon dioxide emissions. Researchers have proposed new approaches to organizing multimodal transport that enable the selection of transportation plans considering energy conservation and emission reduction [15-17].

Uncertainties in multimodal transport refer to unpredictable and probabilistic aspects that may arise during transportation due to inclement weather, changes in road conditions, vehicle failures, epidemics, and natural disasters. Research in this field often focuses on stochastic demand and transportation times, while vehicle failures and cost uncertainties are less frequently studied. Methods such as fuzzy logic, robust optimization, as well as various algorithms including metaheuristics, taboo search, simulated annealing, and ant colony optimization, are employed to address uncertainties. These approaches aim to mitigate the impacts of uncertainty and enhance decision-making in multimodal transport planning [18-21].

In recent years, the concept of synchromodality has gained new significance within the context of multimodal transport [22-24]. Research on synchromodality has attracted international attention in recent years, shifting focus towards this concept [25, 26]. van Riessen et al. [27] conducted a study covering integrated network planning, real-time network planning, and planning flexibility, which has made a significant contribution to synchromodality research. Other researchers have analyzed critical success factors and technologies necessary for synchronous logistics, emphasizing that such an approach enhances service quality and meets customer needs. Expert opinions have also been analyzed, identifying key criteria influencing synchromodality such as service quality, efficiency, adequacy of infrastructure, technical characteristics of terminals, and technology integration.

Researchers have also investigated the dynamic problem of matching freight shipments in internal synchromodality, proposing methods for processing real-time information on new cargo dispatch requests and developing heuristic algorithms for decision-making [28-31]. Multi-objective optimization models have been devised that take into account decision-makers' preferences, addressing transshipment collection and distribution problems, for which adaptive large neighborhood search algorithms have been developed [32-34].

Despite the growing importance of efficient freight transportation systems, intermodal systems face challenges such as limited flexibility, higher environmental impact, and inefficiencies in resource utilization. These limitations hinder their ability to adapt to dynamic market demands and sustainable logistics practices. Synchromodal systems, which integrate real-time synchronization and modal shifts, have emerged as a potential solution, but their comparative advantages over intermodal systems remain underexplored, particularly in regions like Kazakhstan.

This study aims to evaluate and compare the performance of intermodal and synchromodal transport systems at the Port of Aktau, focusing on cost-effectiveness, environmental sustainability, and operational efficiency. Specific objectives include: analyzing transportation costs, terminal waiting times, and CO_2 emissions for both systems; assessing the potential for synchromodal systems to optimize resource utilization and reduce environmental impact; and identifying the practical implications for logistics operations in Kazakhstan and similar contexts.

By highlighting the comparative strengths and weaknesses of these systems, this research provides valuable insights for policymakers, logistics providers, and environmental advocates. The findings can guide the development of more efficient and sustainable freight transportation strategies, enhancing the competitiveness of transport hubs like the Port of Aktau on regional and international scales.

2. METHODS AND MATERIALS

2.1 Sea Port of Aktau, Kazakhstan

The Sea Port of Aktau, officially known as JSC "NC 'Aktau Sea Commercial Port,'" is located in the city of Aktau, Kazakhstan, on the northeastern coast of the Caspian Sea [35]. It serves as a crucial transportation hub, playing a key role in the international freight transport system. Port Aktau is part of the Trans-Caspian Transport Route and is integral to the Silk Road initiative, facilitating cargo transport from China to Kazakhstan, Azerbaijan, Georgia, Turkey, and Europe. The port handles both dry cargo and crude oil, with an annual transshipment capacity exceeding 15 million tons.

Port Aktau comprises several terminals, including a container terminal, a dry cargo terminal, and a liquid cargo terminal. It is equipped to handle a wide range of commodities, including oil, metals, grain, and containerized goods. Modern warehousing and logistics facilities within the port enable efficient cargo handling and storage.

Port Aktau is connected to the railway network extending to Mangyshlak station. This provides direct rail connections to major industrial and commercial centers in Kazakhstan, as well as neighboring countries. Aktau is linked to the national road network, facilitating easy access to the port from various regions of the country. These road connections also link the port to international transport corridors, thereby contributing to increased volumes of international trade. Overall, Port Aktau and its transport infrastructure play a crucial role in the economy of Kazakhstan and the region, ensuring efficient movement of goods and fostering the development of international trade, as shown in Figure 1.

Figure 1. Map of Port Aktau, Kazakhstan. a) Satellite view; b) Topography

For our study, key regions of Kazakhstan have been selected as primary destinations for domestic container transport, based on historical flows where these regions constitute approximately 90% of the total volume. Container transport is of particular interest due to its standardized size and suitability for intermodal handling. This facilitates overcoming constraints related to size and equipment, thus facilitating mode selection for transportation.

Container shipments from the Port of Aktau are directed to eight key regions of Kazakhstan, thereby fostering both domestic and international trade connections. The principal regions include:

(1) Akmola Region: A region housing significant agricultural and industrial enterprises that receive container shipments through the Port of Aktau.

(2) Almaty Region: One of Kazakhstan's largest economic regions, where container shipments support diverse manufacturing and consumer needs.

(3) Atyrau Region: An important region for the oil and gas industry, frequently receiving container shipments via the Port of Aktau, particularly equipment and materials for oil and gas extraction.

(4) East Kazakhstan Region: A region known for its developed mining and metallurgical industries, receiving container shipments of equipment and raw materials.

(5) Zhambyl Region: A crucial agricultural and industrial region receiving container shipments of agricultural machinery and fertilizers.

(6) Karaganda Region: An industrial hub of the country receiving container shipments of equipment, raw materials, and finished products for its metallurgical and engineering enterprises.

(7) Kostanay Region: An agricultural region where container shipments of agricultural machinery and products are directed.

(8) Mangystau Region: Encompassing the Port of Aktau and other industrial areas actively involved in the processing and transportation of oil and gas.

These regions play a pivotal role in the economy of Kazakhstan and actively utilize container transport to maintain and develop their infrastructure and industry.

While the port boasts significant capabilities, including container terminals and connectivity to national rail and road networks, it faces several logistical challenges. Key issues include infrastructure limitations, such as outdated equipment and insufficient terminal capacities, which hinder efficient cargo handling. Additionally, demand variability, driven by seasonal and economic factors, complicates the planning and allocation of resources. These challenges exacerbate delays, increase costs, and impact the reliability of transport services.

Addressing these issues is vital for optimizing the port's operations and leveraging its strategic position within the Trans-Caspian Transport Route.

2.2 Real-time synchromodal system with joint planning of container routes and transport vehicles

The real-time synchromodal system is an advanced logistics concept that integrates various modes of transport to optimize and enhance flexibility in managing container shipments (Figure 2). This system facilitates joint planning of container and transport vehicle routes, thereby improving efficiency and reducing costs in the supply chain.

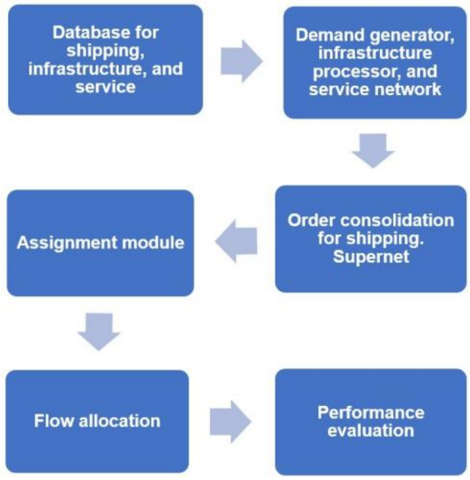

Figure 2. Synchromodal model

The system is based on the principles of synchronization and modal switching, enabling responsive adaptation to changes in demand and delivery conditions. The real-time synchromodal system components interact seamlessly to optimize logistics operations. The Request Generator captures dynamic transport demands, while the Network Processor maps the transport network, facilitating flow management. The Flow Assignment Module allocates resources based on operational decisions, and the Performance Evaluation Tool assesses economic and social impacts. Together, these components enable adaptive routing and mode selection, enhancing efficiency and responsiveness to changing conditions in the supply chain. This integration fosters improved service quality, reduced costs, and increased resilience in logistics operations.

The demand for transport can be modelled as a stochastic process. Let $D(t)$ represent the dynamic demand profile at time t, which includes variables such as destination d_i; departure time t_d; type of goods g_j; hazard categories h_k. This demand can be captured through a probability distribution that reflects uncertainties in logistics operations (e.g., weather conditions, and vehicle availability).

The flow of goods through the network can be represented by a flow assignment function f_{ij}, which indicates the flow from node i to node j. The total flow must satisfy:

$$\sum_{j \in N} f_{ij} = D(t), \forall_i \in N$$

This ensures that the total flow into each node equals the demand at that node.

The optimization problem can be framed as follows: $\min_f \sum_{l \in L} c_l f_l$ subject to: demand constraints ($f_{ij} \leq D(t)$); capacity constraints (each link has a maximum capacity that cannot be exceeded); and modal switching constraints (allowing for transitions between different modes of transport based on real-time data).

To implement real-time adaptations, we can use Monte Carlo simulations to model uncertainties in demand and transport times. The simulation generates multiple scenarios based on probability distributions for: demand patterns; transport times; and costs. The performance evaluation tool computes metrics such as total costs, loading/unloading times, and emissions reductions:

$$Total\ cost = C_{transport} + C_{loading} + C_{emissions}$$

Incorporating environmental considerations into synchromodality involves multi-objective optimization where objectives may include minimizing costs while maximizing service quality and minimizing CO_2 emissions:

$$min: C_{total} = f_1(x) + f_2(y) + f_3(z)$$
$$s.t.:\ g_i(x, y, z) \leq 0$$

where, f_1, f_2, f_3 represent different objectives (costs, service quality, emissions), and g_i are constraints related to capacity and demand satisfaction.

This study utilized Monte Carlo simulation to model stochastic demand and freight flows. Monte Carlo simulation was chosen due to its ability to handle uncertainty and variability in complex systems, making it ideal for dynamic demand scenarios in logistics. The method generates multiple scenarios by sampling from probability distributions representing demand patterns, transport times, and costs.

The system is evaluated in terms of transportation costs, loading and unloading operations, freight and vehicle value losses, as well as overall time expenditures. Social impacts include reductions in road traffic and consequently, reductions in CO_2 emissions.

The synchromodal system enables significant cost savings by optimizing vehicle utilization and reducing delivery times. It also enhances customer service quality and improves the resilience of logistics operations. A real-time synchromodal system with joint planning of container and transport routes represents a powerful tool for modern logistics. It provides the necessary flexibility to adapt to changing market conditions and facilitates the creation of more efficient and resilient transport networks. This system can serve as a model for developing integrated transport solutions that consider both economic and environmental aspects of global logistics.

The real-time synchromodal system with joint planning of container and transport routes is implemented in transportation planning software based on local GIS. This software utilizes a comprehensive database that includes shipment details, transport modes, and cargo types, allowing for precise route planning and resource allocation. By leveraging GIS capabilities, the software visualizes transport networks and analyzes spatial data to optimize container flows from the Port of Aktau to various regions. The integration facilitates real-time updates on demand fluctuations and transport conditions, enabling adaptive routing and efficient management of multimodal transport operations, ultimately improving service quality and reducing costs. Information on container shipments throughout the year was sourced from open literature and publications [8, 36-38]. The database we constructed contains details on shipment origins and destinations, transport modes, cargo types (e.g., bulk, containerized), cargo volumes, and some shipments that are timestamped. Given the absence of direct observations within the necessary spatiotemporal framework, the model is calibrated using estimates of terminal throughput capacities and railway transport volumes sourced from previous market studies and reports. Calibration is performed by addressing parameter estimation challenges, resulting in a model that aligns well with the established target value ranges. These measures and parameters contribute to enhancing the accuracy of the modeling and enable more effective management of freight transportation, ensuring the required level of service while reducing costs.

3. RESULTS

Table 1 presents the distribution of container shipments from the Port of Aktau into the interior regions of Kazakhstan based on the time of day.

Table 1. Distribution of container shipments (%)

Time Interval (hours)	%
0.00-1.00	0.9
1.00-2.00	0.8
2.00-3.00	0.3
3.00-4.00	1.3
4.00-5.00	1.2
5.00-6.00	3.5
6.00-7.00	5.0
7.00-8.00	4.9
8.00-9.00	6.0
9.00-10.00	6.6
10.00-11.00	6.1
11.00-12.00	8.8
12.00-13.00	7.0
13.00-14.00	7.1
14.00-15.00	6.8
15.00-16.00	7.2
16.00-17.00	6.3
17.00-18.00	6.2
18.00-19.00	3.2
19.00-20.00	2.5
20.00-21.00	3.2
21.00-22.00	0.9
22.00-23.00	1.3
23.00-24.00	1.0

The demand for transportation services within a single day is derived from these empirical distributions, with stochastic demand modeled through Monte Carlo (MC) simulation utilizing repeated random sampling.

In the synchromodal system, where maintaining a high level of service is crucial, the following time constraints are established:

- The maximum dwell time is set at 80 minutes.
- The maximum waiting time is 300 minutes.
- The maximum transportation time is limited to six days.

For model verification and calibration, data from the Port of Aktau were utilized. The parameters for calibration included:

- Handling costs specific to each terminal.
- Costs in TEU-km (Twenty-foot Equivalent Unit-

kilometer) for rail network usage.

- Costs in TEU-km for road transport.
- Freight depreciation costs per type of cargo.

In Table 2, systemic costs are presented for intermodal and synchromodal systems categorized by various types of activities.

Table 2. Transport costs

Cost Categories	Costs (KZT)	
	Intermodal	Synchromodal
Road transport	55,000,000	35,500,000
Rail transport	1,500,000	2,000,000
Waiting at the departure terminal	2,500,000	3,000,000
Dwell time	500,000	1,000,000
Handling	21,000,000	35,500,000
Transfer/transshipment waiting	3,000,000	2,500,000

Analyzing the data presented in Table 2, it can be concluded that the costs for road transport in the synchromodal system (35,500,000 KZT) are significantly lower compared to those in the intermodal system (55,000,000 KZT). This difference is attributed to more efficient route planning and optimized utilization of transport vehicles. Costs for railway transport are higher in the synchromodal system (2,000,000 KZT) compared to the intermodal system (1,500,000 KZT), possibly due to increased use of rail transport in the synchromodal system to reduce overall costs and transport time. Terminal waiting costs are slightly higher in the synchromodal system (3,000,000 KZT) compared to 2,500,000 KZT in the intermodal system, reflecting additional expenses to maintain high service standards. Storage costs are also higher in the synchromodal system (1,000,000 KZT) compared to the intermodal system (500,000 KZT). Processing costs are significantly higher in the synchromodal system (35,500,000 KZT) compared to 21,000,000 KZT in the intermodal system, likely due to higher automation levels and the use of more advanced technologies. Transfer waiting costs are lower in the synchromodal system (2,500,000 KZT) compared to the intermodal system (3,000,000 KZT), indicating more efficient cargo flow management.

Table 3 presents the distances for trucking and railway transportation in the intermodal and synchromodal systems.

Table 3. Transportation by road type

Mode of Transport	Distance (km)	
	Intermodal	Synchromodal
Road	135,000	80,000
Rail	20,000	70,000

Based on the results presented in Table 3, it can be observed that in the synchromodal system, the distance covered by road transport (80,000 km) is significantly less than in the intermodal system (135,000 km). This indicates a more efficient use of rail transport and route optimization to reduce the overall distance. The distance covered by rail transport in the synchromodal system (70,000 km) is greater than in the intermodal system (20,000 km). The increased utilization of rail transport helps to reduce costs associated with road transport and mitigate environmental impact.

Table 4 presents the data on transport time expended in intermodal and synchromodal systems.

Table 4. Transport duration

Cost Categories	Elapsed Time (minutes)	
	Intermodal	Synchromodal
Road transport	100,000	80,000
Rail transport	350,000	400,000
Waiting at the departure terminal	450,000	280,000
Stay	30,000	55,000
Processing	10,000	15,000
Transfer/waiting for transfer	70,000	60,000
Completion of transport	20,000	10,000

Analyzing the time spent on transport operations reveals that in the synchromodal system, the time spent on road transport (80,000 minutes) is lower compared to the intermodal system (100,000 minutes). This reduction is attributed to route optimization and distance reduction. In contrast, the time allocated for rail transport is greater in the synchromodal system, totaling 400,000 minutes, compared to 350,000 minutes in the intermodal system. However, this increase is balanced by a reduction in road transport time. The synchromodal system also exhibits significantly lower waiting times at the departure terminal, with 280,000 minutes compared to 450,000 minutes in the intermodal system. This suggests improved management and coordination of freight flows. While dwell time in the synchromodal system is higher at 55,000 minutes versus 30,000 minutes in the intermodal system (likely due to a commitment to maintaining high service levels), the processing time is slightly elevated as well, with 15,000 minutes in the synchromodal system compared to 10,000 minutes in the intermodal system. Additionally, transfer waiting time is more efficient in the synchromodal system at 60,000 minutes, compared to 70,000 minutes in the intermodal system.

The time for completing the transport operation in the synchromodal system (10,000 minutes) is half that of the intermodal system (20,000 minutes).

Table 5 presents data on the duration of associated operations.

Table 5. Duration of associated operations

Cost Categories	Elapsed Time (minutes)	
	Intermodal	Synchromodal
Road transport	490	420
Rail transport	530	190
Waiting at the departure terminal	50	70
Stay	20	30
Processing	60	50
Transfer/waiting for transfer	60	40

The analysis of the duration of related operations in Table 5 indicates that the time required for rail transport in the synchromodal system is 420 minutes, less than the 490 minutes observed in the intermodal system. This suggests a higher efficiency in rail transportation management. Additionally, waiting time at the terminal in the synchromodal system is significantly reduced to 190 minutes, compared to 530 minutes in the intermodal system, highlighting improved planning and coordination of operations. However, the dwell time in the synchromodal system is longer at 70 minutes, compared to 50 minutes in the intermodal system. Processing time also differs, with the synchromodal system requiring 30 minutes, slightly more than the 20 minutes needed in the intermodal system; this may be due to more complex operational processes.

Furthermore, transfer waiting time is shorter in the synchromodal system at 50 minutes versus 60 minutes in the intermodal system. Finally, the completion time for transport operations is quicker in the synchromodal system at 40 minutes, compared to 60 minutes in the intermodal system, indicating a faster overall operational turnaround. Overall, the analysis of the presented data indicates that the synchromodal transport system offers several advantages compared to the intermodal system. Key benefits include reduced costs for road transport, shorter waiting times at terminals and transfers, and improved coordination and planning of operations. However, the synchromodal system also requires higher investments in rail transport and cargo handling. In general, the synchromodal system enables more efficient management of freight transport, ensuring the necessary level of service and reducing overall costs.

CO_2 emissions from rail transport are calculated based on the nonlinear model outlined in the study by Zhang and Pel [39].

In Table 6, CO_2 emissions for intermodal and synchromodal systems are presented.

Table 6. Carbon dioxide emissions for intermodal and synchromodal systems

Mode of Transport	CO_2 Emissions (kg)	
	Intermodal	Synchromodal
Road	90,000	60,000
Rail	1,000	2,000

For automotive transport in the intermodal system, CO_2 emissions amount to 90,000 kg, significantly higher than in the synchromodal system, where emissions are 60,000 kg. This indicates the advantage of synchromodal systems in reducing emissions from automotive transport.

For railway transport, the intermodal system emits 1,000 kg of CO_2, which is less than the 2,000 kg emitted by the synchromodal system. This difference may be attributed to varying routes or the use of different technologies and types of trains in each system.

Overall, Table 6 demonstrates that the synchromodal system is more effective in reducing CO_2 emissions for automotive transport but less effective for railway transport compared to the intermodal system.

The findings indicate that implementing a real-time synchromodal system can significantly enhance logistics efficiency in Kazakhstan, particularly at the Port of Aktau. The integration of various transport modes allows for flexible route planning and resource allocation, leading to reduced transportation costs and improved service quality. This system also addresses uncertainties in multimodal transport, enhancing resilience against disruptions. Furthermore, the emphasis on environmental sustainability through lower CO_2 emissions aligns with global trends towards greener logistics practices. These implications suggest that policymakers and logistics operators should prioritize the adoption of synchromodal systems to foster economic growth and improve competitiveness in regional and international markets.

While the study provides valuable insights, it has several limitations. First, the analysis relies on modeled data and simulations rather than direct observations, which may not fully capture real-world complexities. Second, the focus on the Port of Aktau and its specific context limits the generalizability of findings to other regions or ports with different infrastructures and economic conditions. Third, the higher costs associated with rail transport and cargo handling in synchromodal systems were not deeply explored in terms of long-term cost-benefit trade-offs. Future research should address these limitations by incorporating empirical data and exploring broader applications in diverse settings.

4. DISCUSSIONS

In this study, intermodal and synchromodal transportation systems used in the Port of Aktau, Kazakhstan, were compared. We analyzed transportation costs, transport times, and CO_2 emissions for both systems. These results can be compared with findings from other researchers to better understand their significance and uniqueness.

Table 7 provides a comparison of our findings with the results of similar studies.

Table 7. Comparison of research results

Publication	Main Findings	Comparison with the Current Study
Kim and Wee [40]	Rail intermodal systems emit less CO_2.	Our study also demonstrates a reduction in CO_2 emissions in synchromodal systems for road transport.
Kim et al. [41]	Transition to intermodal systems reduces CO_2 emissions.	Synchromodal systems show reductions in emissions and costs.
Rudi et al. [42]	Intermodal networks enhance transport operations.	Our findings confirm that synchromodal systems enhance the management and efficiency of freight transport.
Walasek [43]	Railroad intermodal transport is cheaper and more environmentally friendly.	Synchromodal system reduces costs and CO_2 emissions.
Ma et al. [44]	Optimizing intermodal networks reduces CO_2 emissions.	Our study confirms a reduction in emissions due to synchromodal systems.
Kreutzberger et al. [45]	Intermodal systems are more environmentally friendly than road transport.	Synchromodal systems demonstrate lower CO_2 emissions for road transport.
Mes and Iacob [46]	Reduced costs by 10.1% and CO_2 emissions by 14.2%.	Our study shows a reduction in costs by 35.5% and CO_2 emissions by 33.3%.
Zhao et al. [47]	Demand uncertainty increases costs and CO_2 emissions.	Our study emphasizes the importance of managing uncertainty in synchromodal systems.
Park et al. [48]	Trade-offs between costs, time, and CO_2 emissions.	The synchromodal system considers and optimizes costs, time, and emissions.

In summary, Table 7 demonstrates that the results of our study largely correspond to the findings of other researchers, highlighting the efficiency and environmental benefits of synchromodal systems. Synchromodal systems show significant reductions in costs for road transport (by 35.5%) and CO_2 emissions (by 33.3%), as well as a decrease in waiting time at terminals (by 37.7%). This confirms that synchromodal systems can significantly enhance logistical operations, providing more sustainable and economically viable transportation solutions.

The synchromodal system effectively manages disruptions and uncertainties in the transport network by utilizing real-time data integration and adaptive routing. It employs advanced algorithms to analyze current conditions, allowing for dynamic adjustments in transport modes and routes based on factors such as weather, traffic, and vehicle availability. This flexibility enhances resilience by enabling quick responses to unexpected events, minimizing delays, and optimizing resource allocation. Additionally, the system's performance evaluation tools continuously assess the impact of disruptions, facilitating informed decision-making and enhancing overall supply chain reliability. This proactive approach ensures that logistics operations remain efficient even amidst uncertainties.

Implementing synchromodal systems in Kazakhstan's logistics sector faces significant barriers, including the need for substantial infrastructure investments, stakeholder resistance, regulatory challenges, and technology integration. Upgrading existing transport infrastructure to support real-time data exchange and intermodal connectivity is crucial but costly. Stakeholders may resist change due to concerns over costs and operational disruptions. Moreover, the regulatory framework may not adequately support the flexibility required for synchromodal operations, necessitating reforms to streamline processes. To overcome these challenges, Kazakhstan can pursue public-private partnerships to share investment burdens, engage stakeholders through educational programs and pilot projects, and establish a task force to review and amend regulations. Additionally, investing in advanced technologies such as real-time tracking systems and data analytics tools will enhance operational efficiency. These solutions can help create a more efficient logistics environment that leverages synchromodality's potential to improve service quality, reduce costs, and enhance resilience in the face of dynamic market demands. By addressing these barriers proactively, Kazakhstan can position itself as a leader in modern logistics practices.

5. CONCLUSIONS

This study investigates the efficiency of intermodal and synchromodal transportation systems in the Port of Aktau, Kazakhstan. The research aims to identify differences in costs, transportation times, and CO_2 emissions between these two systems, as well as to assess their impact on the economy and the environment.

For our study, key regions of Kazakhstan were selected as primary destinations for domestic container transport, based on historical freight flows, which constitute approximately 90% of the total volume. After conducting the study, it was found that in the synchromodal system, costs for road transportation are 35.5% lower compared to the intermodal system. This is attributed to more efficient route planning and optimized use of transport vehicles. Costs for rail transportation in the synchromodal system are 25% higher than those in the intermodal system. This increase may be attributed to a greater reliance on rail transport, aimed at reducing overall costs and transportation times. Terminal waiting time is significantly lower in the synchromodal system, with a reduction of 37.7% compared to the intermodal system. This improvement suggests enhanced management and coordination of freight flows. Conversely, processing time in the synchromodal system is 33.3% higher than in the intermodal system, likely due to more complex operations and elevated levels of automation. When it comes to CO_2 emissions, road transportation in the intermodal system produces 33.3% more emissions compared to the synchromodal system, underscoring the environmental benefits of synchromodal approaches in reducing road transport emissions. However, CO_2 emissions from rail transportation in the synchromodal system are 50% higher than those in the intermodal system, which may be influenced by different routes or variations in train types and technologies used. Overall, the study has shown that the synchromodal system is more efficient in terms of costs for road transportation, waiting times at terminals, and CO_2 emissions. However, cargo handling and rail transportation constitute significant expenses. In general, the use of the synchromodal system allows for more efficient management of freight transport, thereby reducing overall costs and ensuring the necessary level of service. These findings underscore the potential of synchromodal systems to enhance the efficiency and sustainability of transport operations.

Policymakers and logistics operators in Kazakhstan should focus on several actionable recommendations to enhance the implementation of synchromodal systems. First, they should invest in upgrading infrastructure, particularly intermodal terminals and digital tracking systems, to support seamless transitions between transport modes. Second, fostering public-private partnerships can alleviate financial burdens and encourage innovation in logistics. Third, engaging stakeholders through training and pilot projects will help mitigate resistance to change. Fourth, regulatory reforms are essential to streamline processes and facilitate multimodal operations. Finally, investing in advanced technologies for real-time data management will optimize logistics efficiency and improve service quality.

Future research directions should focus on evaluating the comparative advantages of synchromodal systems over traditional intermodal transport in Kazakhstan, particularly regarding cost-effectiveness and environmental sustainability. Additionally, studies should explore advanced algorithms for real-time decision-making in dynamic logistics environments, incorporating factors like demand variability and infrastructure constraints. Investigating stakeholder engagement strategies to facilitate the adoption of synchromodal practices will also be essential, alongside assessing the integration of green technologies in multimodal transport systems to enhance sustainability. Finally, empirical studies on the performance of synchromodal systems at key transport hubs can provide valuable insights for policy development.

REFERENCES

[1] Xu, X., Wang, H., Deng, P. (2023). Exploring the optimization of synchromodal transportation path under uncertainties. Journal of Marine Science and Engineering, 11(3): 577. https://doi.org/10.3390/jmse11030577

[2] Abdildinova, L., Kassymova, N., Santayeva, K., Abdildanova, A., Kalelova, Z. (2022). Unemployment in the area of construction of the Turkestan-Siberian railroad. Migration Letters, 19(5): 593-601. https://doi.org/10.33182/ml.v19i5.2377

[3] Akhmetzhanov, B.A., Lustov, N.S. (2013). High-speed mainlines and their contribution to regional development. Problems of Economic Transition, 56(3): 44-48. https://doi.org/10.2753/PET1061-1991560305

[4] Ashimova, B., Beisenova, R., Menéndez-Pidal, I., Jumabayev, S., Zhupysheva, A., Tazitdinova, R. (2023). Environmental hazards of the railway infrastructure of Kazakhstan. Sustainability, 15(2): 1321. https://doi.org/10.3390/su15021321

[5] Murzakayeva, M., Musayev, J., Kvashnin, M., Zhunisbekov, S., Zhauyt, A., Azilkiyasheva, M. (2021). Experimental evaluation of railway crew impact on tension rails. International Journal of Mechanical Engineering and Robotics Research, 10(5): 261-269. https://doi.org/10.18178/IJMERR.10.5.261-269

[6] Seilkhanov, A. (2024). Kazakhstan strongly condemns any forms of violence, Kassym-Jomart Tokayev. Kazinform International News Agency. https://qazinform.com/news/tokayev-holds-phone-talk-with-russian-president-putin-41a232.

[7] Bazarbekova, M., Assipova, Z., Molgazhdarov, A., Yessenov, M. (2018). Review of transportation modes in Kazakhstan region, Central Asia. Cogent Engineering, 5(1): 1450799. https://doi.org/10.1080/23311916.2018.1450799

[8] Tilemissova, A., Kozachenko, D., Vernyhora, R., Izteleuova, M., Arpabekov, M. (2023). Competitiveness assessment of the railway network of Kazakhstan in the performance of transit container transportation. Scientific Bulletin of NMU, 4: 130-137. https://doi.org/10.33271/nvngu/2023-4/130

[9] Reddy, T.S., Chand, B.K., Velmurugan, S. (1995). Evaluation and augmentation of road-based urban public transport. International Journal of Transport Management, 19(2): 147-153.

[10] Mi, X.Z., Mei, M.T., Zheng, X.J. (2019). Study on optimal routes of multimodal transport under time window constraints. In 2019 IEEE 23rd International Conference on Computer Supported Cooperative Work in Design (CSCWD), Porto, Portugal, pp. 512-516. https://doi.org/10.1109/CSCWD.2019.8791930

[11] Kaewfak, K., Ammarapala, V., Huynh, V.N. (2021). Multi-objective optimization of freight route choices in multimodal transportation. International Journal of Computational Intelligence Systems, 14(1): 794-807. https://doi.org/10.2991/ijcis.d.210126.001

[12] Kisselyova, O., Abdirassilov, Z., Vakhitova, L., Izbairova, A., Uvaliyeva, A. (2022). Optimization of container traffic distribution on the railway network. E3S Web of Conferences, 363: 01016. https://doi.org/10.1051/e3sconf/202236301016

[13] Zhai, C.X., Meng, C., Sui, H. P., Li, K.X. (2017). The optimization model construction of multimodal transportation route for dangerous goods. In 3rd Annual International Conference on Management, Economics and Social Development (ICMESD 17), Guangdong, China, pp. 302-306. https://doi.org/10.2991/icmesd-17.2017.57

[14] Zhao, Y., Ioannou, P.A., Dessouky, M.M. (2018). Dynamic multimodal freight routing using a co-simulation optimization approach. IEEE Transactions on Intelligent Transportation Systems, 20(7): 2657-2667. https://doi.org/10.1109/TITS.2018.2871946

[15] Li, H.F., Su, L. (2020). Multimodal transport path optimization model and algorithm considering carbon emission multitask. Journal of Supercomputing, 76: 9355-9373. https://doi.org/10.1007/s11227-019-03103-1

[16] Wang, Q.Z., Chen, J.M., Tseng, M.L., Luan, H.M., Ali, M.H. (2020). Modelling green multimodal transport route performance with witness simulation software. Journal of Cleaner Production, 248: 119245. https://doi.org/10.1016/j.jclepro.2019.119245

[17] Mukhametov, A., Yerbulekova, M., Aitkhozhayeva, G., Tuyakova, G., Dautkanova, D. (2022). Effects of ω-3 fatty acids and ratio of ω-3/ω-6 for health promotion and disease prevention. Food Science and Technology (Brazil), 42: e58321. https://doi.org/10.1590/fst.58321

[18] Delbart, T., Molenbruch, Y., Braekers, K., Caris, A. (2021). Uncertainty in intermodal and synchromodal transport: Review and future research directions. Sustainability, 13(7): 3980. https://doi.org/10.3390/su13073980

[19] Lu, Y., Lang, M., Sun, Y., Li, S. (2020). A fuzzy intercontinental road-rail multimodal routing model with time and train capacity uncertainty and fuzzy programming approaches. IEEE Access, 8: 27532-27548. https://doi.org/10.1109/ACCESS.2020.2971027

[20] Sun, Y., Hrušovský, M., Zhang, C., Lang, M. (2018). A time-dependent fuzzy programming approach for the green multimodal routing problem with rail service capacity uncertainty and road traffic congestion. Complexity, 2018: 8645793. https://doi.org/10.1155/2018/8645793

[21] Zhang, X., Jin, F.Y., Yuan, X.M., Zhang, H.Y. (2021). Low-carbon multimodal transportation path optimization under dual uncertainty of demand and time. Sustainability, 13(15): 8180. https://doi.org/10.3390/su13158180

[22] Giusti, R., Manerba, D., Bruno, G., Tadei, R. (2019). Synchromodal logistics: An overview of critical success factors, enabling technologies, and open research issues. Transport Research Part E: Logistics and Transportation Review, 129: 92-110. https://doi.org/10.1016/j.tre.2019.07.009

[23] Šakalys, R., Sivilevičius, H., Miliauskaitė, L., Šakalys, A. (2019). Investigation and evaluation of main indicators impacting synchromodality using ARTIW and AHP methods. Transport, 34(3): 300-311. https://doi.org/10.3846/transport.2019.9718

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

[25] Bal, F., Vieugel, J.M. (2023). Towards climate resilient freight transport in Europe. International Journal of

Transport Development and Integration, 7(2): 147-152. https://doi.org/10.18280/ijtdi.070210

[26] Alazzam, F.A.F., Liubokhynets, L., Kirichenko, O., Struk, N., Bosak, A. (2023). Evaluating the impact of transport and logistics potential on international trade. International Journal of Transport Development and Integration, 7(4): 293-301. https://doi.org/10.18280/ijtdi.070403

[27] van Riessen, B., Negenborn, R.R., Dekker, R. (2015). Synchromodal container transportation: An overview of current topics and research opportunities. In Computational Logistics: 6th International Conference, ICCL 2015, Delft, The Netherlands, pp. 386-397. https://doi.org/10.1007/978-3-319-24264-4_27

[28] Guo, W., Atasoy, B., van Blokland, W.B., Negenborn, R.R. (2020). A dynamic shipment matching problem in hinterland synchromodal transportation. Decision Support Systems, 134: 113289. https://doi.org/10.1016/j.dss.2020.113289

[29] Larsen, R.B., Atasoy, B., Negenborn, R.R. (2021). Model predictive control for simultaneous planning of container and vehicle routes. European Journal of Control, 57: 273-283. https://doi.org/10.1016/j.ejcon.2020.06.003

[30] Zhang, Y., Atasoy, B., Negenborn, R.R. (2022). Preference-based multi-objective optimization for synchromodal transport using adaptive large neighborhood search. Transportation Research Record, 2676(3): 71-87. https://doi.org/10.1177/03611981211049148

[31] Nikolova, M., Kotseva, V., Monov, D., Genov, D., Voikova, P., Ananiev, J., Tanova, R., Kundurdjiev, A., Gancheva, R., Vlahov, Y. (2022). Rhabdomyolysis after the intake of illicit drugs as a cause of acute renal failure. Open Journal of Nephrology, 12: 482-488. https://doi.org/10.4236/ojneph.2022.124047

[32] Batarlienė, N., Šakalys, R. (2021). Mathematical model for cargo allocation problem in synchromodal transportation. Symmetry, 13(4): 540. https://doi.org/10.3390/sym13040540

[33] Guo, W., Atasoy, B., Negenborn, R.R. (2022). Global synchromodal shipment matching problem with dynamic and stochastic travel times: A reinforcement learning approach. Annals of Operations Research. https://doi.org/10.1007/s10479-021-04489-z

[34] van Riessen, B., Mulder, J., Negenborn, R. R., Dekker, R. (2021). Revenue management with two fare classes in synchromodal container transportation. Flexible Services and Manufacturing Journal, 33: 623-662. https://doi.org/10.1007/s10696-020-09394-4

[35] Portaktau.kz. (2024). Official website. https://www.portaktau.kz.

[36] Abdirassilov, Z., Sładkowski, A., Izbairova, A., Sarbaev, S. (2020). Application of artificial neural networks for short-term forecasting of container flows in Kazakhstan. In Modelling of the Interaction of the Different Vehicles and Various Transport Modes. Springer, Cham, pp. 131-158. https://doi.org/10.1007/978-3-030-11512-8_3

[37] Akhmedov, D., Yeryomin, D., Zhaxygulova, D., Kaliyeva, R. (2020). Information support of overland transit freight traffic through the territory of Kazakhstan. Telecommunications and Transport, 14(8): 53-59. https://doi.org/10.36724/2072-8735-2020-14-8-53-59

[38] Akhmetkaliyeva, S., Zhubandyk, A., Musa, K. (2023). Development of container transportation logistics in the Republic of Kazakhstan. Trudy Universiteta, 1(90): 191-195. https://doi.org/10.52209/1609-1825_2023_1_191

[39] Zhang, M., Pel, A.J. (2016). Synchromodal hinterland freight transport: Model study for the port of Rotterdam. Journal of Transport Geography, 52: 1-10. https://doi.org/10.1016/j.jtrangeo.2016.02.007

[40] Kim, N., Wee, B. (2009). Assessment of CO_2 emissions for truck-only and rail-based intermodal freight systems in Europe. Transport Planning and Technology, 32(4): 313-333. https://doi.org/10.1080/03081060903119584

[41] Kim, N.S., Janic, M., Van Wee, B. (2009). Trade-off between carbon dioxide emissions and logistics costs based on multiobjective optimization. Transportation Research Record, 2139(1): 107-116. https://doi.org/10.3141/2139-13

[42] Rudi, A., Fröhling, M., Zimmer, K., Schultmann, F. (2016). Freight transportation planning considering carbon emissions and in-transit holding costs: A capacitated multi-commodity network flow model. European Journal of Transport and Logistics, 5(2): 123-160. https://doi.org/10.1007/s13676-014-0062-4

[43] Walasek, R. (2017). Effectiveness of intermodal transport in Poland–Results of the study. Research in Logistics & Production, 7(2): 159-170. https://doi.org/10.21008/J.2083-4950.2017.7.2.8

[44] Ma, Q.L., Wang, W.Y., Peng, Y., Song, X.Q. (2018). An optimization approach to the intermodal transportation network in fruit cold chain, considering cost, quality degradation and carbon dioxide footprint. Polish Maritime Research, 25(1): 61-69. https://doi.org/10.2478/pomr-2018-0007

[45] Kreutzberger, E., Macharis, C., Woxenius, J. (2006). Intermodal versus unimodal road freight transport: A review of comparisons of the external costs. In Towards Better Performing Transport Networks. Routledge, pp. 17-42. https://doi.org/10.4324/9780203965573-7

[46] Mes, M.R., Iacob, M.E. (2016). Synchromodal transport planning at a logistics service provider. In Logistics and Supply Chain Innovation: Bridging the Gap Between Theory and Practice. Springer, Cham, pp. 23-36. https://doi.org/10.1007/978-3-319-22288-2_2

[47] Zhao, Y., Xue, Q.W., Zhang, X. (2018). Stochastic empty container repositioning problem with CO_2 emission considerations for an intermodal transportation system. Sustainability, 10(11): 4211. https://doi.org/10.3390/SU10114211

[48] Park, D., Kim, N.S., Park, H., Kim, K. (2012). Estimating trade-off among logistics cost, CO_2, and time: A case study of container transportation systems in Korea. International Journal of Urban Sciences, 16(1): 85-98. https://doi.org/10.1080/12265934.2012.668322