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Review on AI-Based Coordinated Traffic Load Scheduling for Rail-Road Freight Corridors

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ABSTRACT
The rapid expansion of freight transportation demand has intensified congestion, operational inefficiencies, and environmental concerns in rail–road freight corridors. Traditional scheduling approaches are largely static and rule-based, making them inadequate for handling dynamic demand fluctuations, infrastructure constraints, and real-time disruptions. This research proposes an AI-based coordinated traffic load scheduling framework for rail–road freight corridors. The study integrates Machine Learning-based demand forecasting, multi-objective optimization techniques, and intelligent decision-support mechanisms to dynamically allocate freight loads across multimodal networks. The proposed model aims to minimize total transportation cost, transit time, and energy consumption while maximizing corridor throughput and system reliability. Real-time data inputs—including traffic conditions, wagon availability, truck fleet status, and terminal congestion—are incorporated to enhance adaptive scheduling capability. The performance of the proposed framework will be evaluated using simulation-based analysis and comparative assessment against conventional scheduling methods. Expected outcomes include improved resource utilization, reduced congestion, lower carbon emissions, and enhanced operational resilience. This research contributes to the advancement of smart and sustainable freight transportation systems by developing a data-driven, adaptive, and scalable AI-enabled scheduling solution for integrated rail–road logistics networks.

Keywords - Artificial Intelligence (AI), Decision Support Systems (DSS), Rail Traffic Flow, Railway Safety, Machine Learning (ML), Predictive Analytics, Predictive Maintenance, Real-Time Traffic Optimization, Traffic Prediction, Risk Management, Autonomous Trains, Smart Rail Networks.

I.INTRODUCTION
The rapid growth of industrialization, e-commerce, and global supply chains has significantly increased freight transportation demand worldwide. In countries like India, large-scale infrastructure initiatives such as the Dedicated Freight Corridor Corporation of India Limited (DFCCIL) are transforming logistics through high-capacity rail corridors. However, despite such developments, efficient coordination between rail and road freight systems remains a major operational challenge.

Rail transport is energy-efficient and suitable for bulk, long-distance freight movement, while road transport offers flexibility and last-mile connectivity. The integration of these two modes—commonly referred to as multimodal or intermodal freight transportation—requires intelligent scheduling mechanisms to optimize traffic load distribution, reduce congestion, and improve delivery performance. Traditional scheduling techniques often rely on static models, historical averages, or rule-based heuristics, which are inadequate for handling dynamic uncertainties such as fluctuating demand, traffic congestion, infrastructure constraints, and real-time disruptions.

Artificial Intelligence (AI) offers transformative potential in this context. AI-based coordinated traffic load scheduling leverages advanced techniques such as Machine Learning (ML), Deep Learning (DL), Reinforcement Learning (RL), and optimization algorithms to dynamically allocate freight loads across rail and road networks. These models can analyze large-scale real-time data—including traffic flow, wagon availability, truck fleet status, weather conditions, and terminal congestion—to generate adaptive and predictive scheduling strategies.

AI-based systems address these challenges by enabling predictive demand forecasting, dynamic route optimization, and coordinated dispatch scheduling. For example, reinforcement learning agents can learn optimal load allocation policies by continuously interacting with simulated or real corridor environments. Similarly, hybrid metaheuristic algorithms can solve multi-objective optimization problems involving cost, time, and environmental impact simultaneously.

From a research perspective, this topic integrates transportation engineering, operations research, intelligent systems, and smart logistics. It aligns with global trends in smart transportation systems and Industry 4.0, where data-driven decision-making enhances operational efficiency and sustainability.

Furthermore, AI-driven coordination supports sustainable freight mobility by reducing empty runs, optimizing train formation planning, and minimizing idle truck waiting time at terminals. This contributes to lower greenhouse gas emissions and supports national and international sustainability goals.

In summary, AI-Based Coordinated Traffic Load Scheduling for Rail–Road Freight Corridors aims to develop an intelligent, adaptive, and multi-objective decision-support framework that enhances freight efficiency, reduces operational costs, and improves system resilience. This research holds significant practical importance for developing countries modernizing their logistics infrastructure, as well as for advanced economies seeking to transition toward smart and sustainable freight transportation systems.

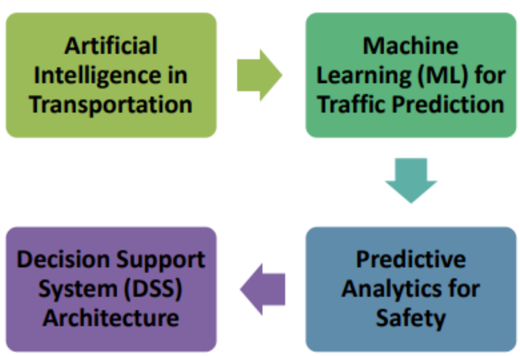

Fig 1: AI and Machine Learning Techniques

II.PROBLEM IDENTIFICATION

The rapid expansion of freight movement along rail–road corridors, particularly in developing economies such as India, has exposed significant inefficiencies in coordinated traffic load scheduling. Although large-scale initiatives like the Dedicated Freight Corridor Corporation of India Limited aim to enhance rail freight capacity, the integration between rail and road systems remains largely fragmented. Existing scheduling practices are predominantly rule-based, static, or dependent on manual decision-making, which are insufficient to handle dynamic freight demand, real-time traffic variability, wagon-truck availability fluctuations, and unexpected disruptions such as infrastructure failures or congestion.

A major problem lies in the absence of an intelligent, real-time coordination mechanism that can optimally distribute freight loads between rail and road modes. This often results in imbalanced load allocation, underutilization of rail capacity, excessive reliance on road transport, increased terminal congestion, prolonged dwell time, higher fuel consumption, and elevated carbon emissions. Additionally, freight terminals face synchronization issues between train arrival schedules and truck dispatch operations, causing delays and operational bottlenecks. The lack of predictive analytics and adaptive optimization tools further restricts the system's ability to respond proactively to demand surges and corridor constraints.

Therefore, the core problem identified in this research is the need for an AI-driven, coordinated traffic load scheduling framework capable of dynamically optimizing multimodal freight allocation under uncertainty, while minimizing cost, delay, congestion, and environmental impact. Addressing this problem is essential for enhancing corridor efficiency, improving resource utilization, and ensuring sustainable freight transportation operations.

III.RESEARCH OBJECTIVES

1. **To develop an AI-based coordinated scheduling framework** for optimal traffic load allocation between rail and road freight corridors.
2. **To design a multi-objective optimization model** that minimizes transportation cost, transit time, and energy consumption while maximizing corridor throughput.
3. **To implement predictive demand forecasting models** using Machine Learning techniques for dynamic freight load estimation.
4. **To enhance real-time decision-making capability** by integrating traffic, terminal, and vehicle availability data into the scheduling system.
5. **To evaluate the performance of the proposed AI model** in terms of efficiency, reliability, congestion reduction, and environmental sustainability compared to traditional scheduling methods.

IV.LITERATURE REVIEW

Shuqi Zhang et al . [1] Given the prevalence of excessive overloading in road freight and its associated environmental impacts, rail has become an increasingly ideal mode of freight transport. The Chinese government implemented the "modal shift from road to railway" policy to redirect bulk cargo transport from roads to railways. This study employs a causal forest approach to evaluate the policy's effects, revealing that it reduced transport costs by 12 %, eased road congestion by 4 %, improved traffic safety by 3 %, and mitigated environmental pollution by 23 %. The policy's effects exhibited regional heterogeneity, particularly on the southeastern side of the Hu Line (China's demographic divide). Furthermore, the present study adopted the partial dependence plots to assess the marginal effects of key drivers. Notably, in regions with a railway mileage of approximately 2320 km, continued expansion of railway infrastructure generates disproportionately high marginal benefits, suggesting an important policy window when rail matters most. The results offer evidence-based guidance and a replicable framework for implementing freight modal shift strategies in developing countries, emphasizing the importance of regionally differentiated policies.

Suraj Kumar et al. [2] Rail freight is vital for economic growth due to its efficiency and environmental benefits, but its lack of fixed schedules due to various delay factors poses challenges for accurate Expected Travel Time (ETT) predictions. This research addresses the need for real-time, accurate and dynamic ETT predictions crucial for maintaining efficient supply chains by developing a novel predictive model that leverages real-time data. The model ensembles Graph Convolutional Network-Long Short-Term Memory (GCN-LSTM) and Kalman Filters (KF) models to capture the complex spatiotemporal interactions and diverse traction behaviours within the freight train railway network. The methodology comprises three phases: modeling, schedule generation, and dynamic updating. In the modeling phase, historical train movement data is used to develop predictive models, with KF handling state-space representation and GCN-LSTM capturing spatial and temporal dependencies. These models are ensembled to enhance prediction accuracy. The schedule generation phase estimates travel times using the ensembled model, the dynamic updating phase refines predictions using real-time data, while congestion is assessed by clustering congested areas with Density-Based Spatial Clustering of Applications with Noise (DBSCAN) and propagating these clusters through KF. The proposed model is compared with different state-of-art predictive models. The methodology's effectiveness was validated using real-world data from Indian Railway freight operations. The proposed model demonstrated superior accuracy, with Mean Absolute Percentage Error of 19.51%, while the moving average-based model which was previously being used by the Indian Railway had an error of 44.34%. This approach, implemented as a decision support system for Indian Railways' daily operations, provides advanced planning solutions to manage the growing complexities of rail freight logistics effectively.

Zdenka Bulková et al. [3] Freight transport is a major contributor to energy consumption and greenhouse gas emissions in the European Union. Despite European Union strategies promoting a modal shift from road to rail, road freight still dominates in Central Europe. This paper addresses the gap in comparative analyses of energy intensity and environmental impact between road and rail freight by proposing a detailed calculation methodology. The approach combines direct measurement of electric locomotive consumption in Austria, Germany, and the Czech Republic with operational data from road freight transport. Specific energy consumption, CO_2 emissions, and transport performance are evaluated and compared using real transport flows in the Czech Republic. The results confirm that shifting 9.75 % of freight from road to rail can reduce energy consumption by 85.3 % and emissions by 75.7 %, equivalent to annual savings of 212 million kWh and 59,000 tonnes of CO_2. Although the case study focuses on the Czech Republic, the proposed methodology is also applicable to other Central European countries with similar transport flows, energy mixes, and infrastructure. The results therefore provide a relevant framework for the broader region, which faces comparable challenges in the decarbonization of freight transport.

Bardo Hörl et al. [4] In most European congested urban areas the rail tracks of the 19th and 20th century serving locations of industry and goods stations were removed, transformed for public passenger transport, closed down or used for other purposes. The main reasons might be the de-industrialisation of the inner cities and the centralisation of the supply-sector (wholesale markets, shopping centres). Simultaneous the urban areas got an excellent road network on the surface and an efficient public transport system in the underground or on dedicated tracks. Nevertheless the amount of goods delivered to urban areas increased due to material prosperity. In this context "METRO.FREIGHT.2020" analysed the possibilities of a reinforced utilisation of railway infrastructure for freight transport on the first and the last miles within the urban regions in Austria as exemplified in case studies for the metropolitan Region of Vienna, the agglomerations of Graz and Linz and for the urbanised Rhine-Valley in Vorarlberg. In this context the focus point of consideration was the interface of transport and urban development, to a lesser extent the theoretical approach behind. As a fundamental milestone a cadastre of existing or recoverable sidings or other rail shipping points has been surveyed. They were evaluated in respect of serviceability concerning tracking freight trains in the rail network and extensibility in the service area which was complemented with propositions for further developing.

Joao Tiago Aparicio et al. [5] What are the latent thematic communities driving transport decarbonisation research across road, rail, maritime, and crossmodal domains? To answer this central question, this work proposes an integrated network model that fuses bibliographic coupling with Sentence-BERT semantic similarities, followed by a statistical analysis using state-of-the-art community detection algorithms. We assess partitions via four complementary metrics, modularity, silhouette, density, and NF1, and compare weighted versus unweighted graphs. Our analysis of mode-specific corpora uncovers distinct clusters: road research splits into urban last-mile automation and rural logistics; rail coalesces around a synchromodal scheduling hub with biofuel and corridor electrification offshoots; maritime divides into green fuels, autonomous safety, and shore-power streams; and crossmodal studies form overlapping triads of electrification, data analytics, and blockchain. Weighted edge integration uniformly enhances thematic clarity without altering algorithm rankings. These findings yield actionable algorithm-selection heuristics and tie each community to specific SDG targets, transforming aspirational goals into a concrete, community-by-community policy roadmap for green logistics.

Mona Ahmadi et al. [6] Rad Passing a Stop Signal (PASS) is a critical safety concern in railway operations, with the potential to cause serious accidents. This study investigates non-human contributing factors to PASS events in Canadian mainline freight operations using machine learning. We analyze incident narratives from the Rail Occurrence Database System (RODS) through text mining and enrich them with geospatial and weather data. We develop a binary classification model using XGBoost and interpret feature importance and interactions with SHAP (SHapley Additive exPlanations). To address class imbalance and improve model performance, we apply a custom sampling method, combined with hyperparameter tuning and data standardization. Key contributors to PASS events include sharp track curvature near signals, downhill grades, low atmospheric pressure, high relative humidity, non-clear weather, and heavy traffic—placing Rocky Mountain subdivisions among the highest-risk areas. The model also reveals that combinations of environmental conditions, such as low temperature, low pressure, and high humidity, increase the likelihood of PASS events by reducing visibility and braking effectiveness. This study offers methodological and empirical contributions by modelling complex operational contexts, incorporating underexplored environmental factors, and producing region-specific insights. The proposed framework informs proactive safety strategies and supports risk analysis in other linear infrastructure systems.

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Trung Anh Nguyen et al. [7] The Lao Cai - Hanoi - Hai Phong - Quang Ninh economic corridor is an important transport axis linking Southwest China with the northern provinces of Vietnam. At the same time, the corridor is a bridge connecting this area to the world. In this paper, the authors uses the traffic simulation tool PTV VISUM to build a traffic network in the corridor area. Use the model to make preliminary assessments of factors affecting the corridor traffic network in different development scenarios, especially directions for developing multi-modal transport combined with inland waterways, railways and roads. The study also evaluated the effectiveness of a number of key projects on the corridor in terms of economics, minimizing traffic congestion, reducing environmental pollution, etc. The paper also gives some recommendations for development this economic corridor.

Gozde Bakioglu et al. [8] Enhancing railway freight logistics efficiency is crucial for strengthening global supply chain performance, yet persistent challenges such as infrastructure limitations, operational inefficiencies, and fragmented intermodal integration hinder optimal performance. Despite its critical role in economic and environmental sustainability, limited research offers comprehensive, universally applicable solutions for addressing these issues. This study bridges this gap by introducing a novel multi-criteria decision-making framework that integrates inter-criteria correlation (CRiteria Importance Through Intercriteria Correlation (CRITIC)) and multi-objective optimization based on ratio analysis (Multi-attribute Multi-Objective Optimization based on Ratio Analysis (MULTIMOORA)) with Q-rung orthopair fuzzy sets (q-ROFSs) to handle complex and conflicting decision-making scenarios. These methods were selected for their complementary strengths. CRITIC effectively quantifies the importance of criteria by considering their interdependencies, MULTIMOORA offers robust multi-objective optimization capabilities, and q-ROFSs manage the inherent uncertainty and ambiguity of real-world logistics problems. Their integration provides a comprehensive framework capable of addressing both the complexity and uncertainty in railway freight logistics decision-making. A two-phase sensitivity analysis validates the framework's reliability and consistency. Results indicate that "infrastructure investment" ranks as the most impactful strategy, followed by "intermodal transportation". These findings offer practical guidance for policymakers and industry leaders, providing actionable solutions to enhance operational performance and sustainability while advancing the theoretical discourse in transportation logistics.

Weipan Zhang et al. [9] Multimodal transport is an effective method to reduce the energy consumption and carbon dioxide (CO_2) emissions in transportation sector. Evaluating the low-carbon performance is a prerequisite for developing multimodal transport. This paper establishes the new cross-efficiency (CE) network data envelopment analysis (DEA) approach, and applies it to evaluate low-carbon efficiency of railway-waterway intermodal transportation (RIT) in China from 2017 to 2022. The proposed approach takes advantage of network DEA and considers the internal structure in the RIT system as well as the interconnections between various transportation modes. This article comprehensively analyzes the evaluation results in terms of the overall situation, geographic distribution characteristics, internal stages and links, external influencing factors, and efficiency prediction, and the results find that: (1) the low-carbon efficiency of China's overall RIT needs further improvement. (2) The geographical distribution shows a trend that the efficiency in the Northern Region is higher than that in the Southern Region. (3) The level of urban industry, external transportation conditions, and foreign trade development will all affect the performance of RIT. Finally, according to the empirical results, management strategies are proposed. The main contributions include: proposing a network-structured CE-DEA method focusing on internal states; The advantages of CE network DEA are utilized to study CO_2 emissions of multimodal transport; The low-carbon efficiency of RIT in China is comprehensively analyzed. This study enriches the research on DEA methods, and the results can provide a basis for decision-making by the government and transport enterprises, help promote the development of low-carbon transport in China, and provide a reference for the optimization of multimodal transport in other countries.

Ximeng Liao et al. [10] Modular vehicles (MVs), equipped with autonomous driving, communication, and platooning capabilities, are emerging as a promising innovation in transportation, offering the potential to enhance operational efficiency, flexibility, and environmental sustainability. However, challenges and barriers to their successful implementation are not yet fully understood, which limits the realization of these benefits. This literature review synthesizes existing research on MVs across various applications, including passenger and freight transport, to provide a systematic evaluation of state-of-art, opportunities and challenges for modular freight transport systems. The review identifies research gaps in five areas, such as their integration with multimodal transportation, and highlights key deployment challenges including regulatory hurdles, human factors, financial constraints, and operational complexities. Our findings emphasize the need for policy development, system design research and further empirical validation to assess the practical feasibility and impacts of MVs in the freight transport sector.

Shaolei Bai et al. [11] Carbon emissions generated by road maintenance are frequently overlooked in life cycle assessment (LCA) studies due to their inherent complexity and uncertainty. This study addresses this gap by systematically reviewing 63 relevant publications and conducting an industry survey of 31 professionals to evaluate methodologies, challenges, and strategies for quantifying and reducing carbon emissions in road maintenance. Three key findings emerge. First, while LCA remains the dominant framework for measuring maintenance-phase emissions, existing methodologies and tools inadequately address the unique complexities of maintenance activities. Second, critical data challenges—including variability in maintenance scheduling, institutional fragmentation leading to inconsistent data practices, and the difficulty of quantifying emissions from traffic congestion during maintenance—hinder accurate carbon accounting. Third, the study identifies actionable reduction strategies supported by practitioners and literature, such as adopting sustainable materials, prioritizing preventive maintenance, coordinating with utility operators to optimize scheduling, and improving pavement rolling resistance to enhance vehicle efficiency. By synthesizing methodological limitations, data barriers, and practical mitigation approaches, this work advances a more robust framework for both quantifying and minimizing the climate impacts of road maintenance. These insights derived hold significant promise for policymakers and practitioners seeking to align infrastructure management with decarbonization goals.

Devrishi Bharadwaj et al. [12] The author proposes the use of customized conveyor belts for handling goods like cement, fertilizers, grains and other packaged commodities. These terminals will allow efficient running of multi-point trains and facilitate train-to-train transfers. At commercially viable places facilities for handling other traffic like containers, perishable products, and automobiles can be integrated. Common facilities will help to decrease the unit costs for the customers and increase the revenue earning potential for the transporter and terminal operator. Value added services like consolidation and breaking up of cargo, packaging, labelling, bar coding, reverse logistics, customs processing etc.; it will enable many customers to dispense with their own supply and forwarding warehouses. Such terminals at Dedicated Freight Corridors in India can capture the emerging fast moving consumer goods and e-commerce traffic. This will simplify supply chains and aid in the reduction of the prices of goods. This is particularly important for India where logistics occupies 13% to 15% of the GDP. Railways having a greater freight market share mean significant environmental benefits. Also the proposed concept will reduce the fleet of trucks and highway congestion. Integrated Freight Terminals (IFT) aided by Automated Freight Management System (AFMS) with automated loading/unloading systems, on-site sorting, storage and transshipment facilities will transform the way commodities are transported by railways. Moreover, faster freight service means faster turnover and return on investment.

Elisabete Arsenio et al. [13] Green and intelligent freight logistics play a crucial role in driving sustainable development and are increasingly recognised as innovations within Logistics 5.0. This research examines the dynamics of knowledge transfer between academia and industry, focusing on intermodal transport and sustainability. By analyzing academic publications from Scopus and patents from PATENTSCOPE (2014–2024), this research employs advanced methodologies, including transformer-based keyword extraction and multilayer network analysis, to investigate indicators of knowledge transfer. Findings reveal distinct phases of technological innovation, including acceleration driven by AI, IoT, and blockchain technologies, followed by stabilization and consolidation in logistical operations. A patent surge after 2018 highlights industry-led advancements, contrasting with academia's focus on theoretical sustainability frameworks. However, cross-layer analyses highlight the declining industry adoption of academic findings, revealing gaps in the effective transfer of knowledge. The integration of mature innovations into logistical practices reflects the emergence of a consolidation phase. The findings underline the criticality of aligning academic discoveries with industrial applications, fostering mutual collaboration to drive the evolution of green logistics. By uncovering the dynamics underpinning sustainable innovation, the research contributes to the discourse on the twin transition towards greener and more intelligent freight logistics, offering pathways to strengthen academia-industry collaborations.

Amin Khajehdezfuly et al. [14] With the advancement of Artificial Intelligence (AI)-based methods and the establishment of diverse databases, significant research has been conducted on the application of AI in railway track monitoring, inspection and maintenance. Although several review studies exist in this field, each has been confined to a limited scope, focusing on specific data types, data collection methods, or AI-based techniques. To date, no comprehensive review has been published that encompasses all data types, data collection methods, and AI-based approaches to assess prior research holistically. This study aims to address this critical gap by covering both passenger and freight railway transport systems. Firstly, the available databases used for AI applications in railway track inspection and maintenance were categorized and reviewed, distinguishing between peer-reviewed and non-peer-reviewed sources. Secondly, this review introduces a novel three-level classification framework,

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based on data acquisition method (including track response methods, on-board data approaches, and remote data methods), target railway track component or feature, and input data type, to systematically organize and analyze 567 studies the field published between 2005 and 2025. The findings reveal that the majority of research in this field (88 %) is concentrated on on-board data methods. Approximately 90 % of these studies focus on railway track components, specifically their identification or damage detection. Among the track components, rails and fastening systems, being both critical and vulnerable, have been the primary focus of most research efforts. Image data emerges as the most prevalent and widely utilized data type in on-board data approaches for all railway track components. An in-depth gap analysis was conducted on the literature to identify the limitations of previous studies and outline a roadmap for future research and open directions from multiple perspectives. A comprehensive review of the literature indicates a pressing need for the development of AI-based methods capable of processing multiple data types simultaneously to identify both internal and external damages across all railway track components. The limited number of studies addressing the integration of multiple data types underscores the significant research opportunities in this area. This review not only synthesizes AI-based methods for railway track monitoring and maintenance but also highlights their role in advancing industrial information integration by enabling scalable and intelligent fusion of multi-source data for real-time decision-making.

Wanjie Hu et al. [15] Fast-growing logistics demand aggravates traffic congestion while posing great pressure on the urban ecology. A prospective solution is to split extensive goods movement from roads to underground, especially the metro systems. This paper proposes a simulation-based approach for supporting the operational decision-making of the metro-based urban underground logistics system (M−ULS). Based on a holistic concept of M−ULS network archetypes, two integration schemes of passengers and freight transport in metro network (i.e., collinear-detached metro and the collinear-trailer metro) are explicated. Next, mechanisms of metro freight service assignment, standardized packing, timetable coordination, and rolling stock circulation are proposed and formulated considering multiple criteria and travel patterns. A data-driven discrete-event simulation model with user interface is developed to acquire the real-time operating states of M−ULS in 36 tested scenarios. Experiments conducted on the Nanjing Metro case show that the proposed method can effectively capture the dynamic performance and bottlenecks of network operations in different operating periods and environments. The two considered system schemes show respective advantages in terms of freight demand backlog, capacity, traffic flow control, and efficiency, both of which have good compatibility with metro passenger services. The value of this paper is to provide a quantifiable design framework and assessment paradigm for M−ULS operations. It also offers new insights for solving "big-city diseases" and the potential innovations of urban underground space and metro systems.

V. CONCLUSION

This review critically examined existing literature on traffic load scheduling, multimodal freight optimization, and AI-driven decision-support systems in rail–road freight corridors. The analysis reveals that traditional freight scheduling models are predominantly based on deterministic optimization, heuristic methods, and static planning frameworks. While these approaches provide foundational insights, they lack adaptability to real-time uncertainties such as fluctuating freight demand, infrastructure constraints, terminal congestion, and network disruptions. Recent advancements in Artificial Intelligence, including Machine Learning, Deep Learning, and Reinforcement Learning, have demonstrated strong potential in improving demand forecasting, route optimization, and dynamic resource allocation. However, most existing studies focus either on rail or road systems independently, with limited research addressing fully coordinated, real-time multimodal scheduling frameworks. Furthermore, integration of multi-objective optimization—balancing cost, time, energy efficiency, and environmental sustainability—remains an open research challenge. In conclusion, the review establishes that AI-based coordinated traffic load scheduling represents a promising and necessary research direction for enhancing operational efficiency, reducing congestion, minimizing environmental impact, and improving system resilience in rail–road freight corridors. Future research should emphasize hybrid AI-optimization frameworks, real-time data integration, digital twin-based simulation environments, and sustainability-oriented performance evaluation metrics to support the development of smart and adaptive freight transportation networks.

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