BG Pulse Journal USA
ISSN:1947-2536 http://www.bgpulseusa.com/index.php/bg

MODERN METHODS OF TRANSPORTING PERISHABLE GOODS BY RAIL TRANSPORT

Tursunkhodjaeva Rashida
PhD, Associate Professor of the department of Transport and Freight Systems
Tashkent State Transport University
https://doi.org/10.5281/zenodo.20541137

Abstract. The transportation of perishable goods by rail is a critical component of global food supply chains, yet it presents unique technical, logistical, and economic challenges that demand continuous innovation. This article examines modern methods and technologies employed in the rail transportation of perishable goods, with particular attention to refrigerated wagons, controlled atmosphere systems, IoT-based temperature monitoring, and digital logistics management platforms. Drawing on a review of recent engineering literature and industry reports, the study analyzes the performance, limitations, and emerging trends of current approaches, including the integration of cold chain management technologies and blockchain-based traceability systems. The findings indicate that while significant technological advances have been achieved, persistent challenges remain in ensuring end-to-end cold chain continuity, reducing transit times, and adapting rail infrastructure to the demands of modern perishable logistics. The article concludes with recommendations for improving rail-based perishable goods transportation through technology integration and infrastructure modernization.

Keywords: perishable goods transportation, rail transport, refrigerated wagons, cold chain management, IoT monitoring, controlled atmosphere, logistics, temperature-sensitive cargo, food supply chain.

Introduction. The global demand for fresh food products, pharmaceuticals, and other temperature-sensitive goods has increased substantially over recent decades, driven by population growth, rising consumer expectations, and the expansion of international trade networks [1]. Ensuring the quality and safety of perishable goods throughout the transportation chain is a complex logistical and technical challenge that affects public health, economic efficiency, and food security at both national and international levels.

Rail transport occupies a strategically important position in the movement of perishable goods, particularly over medium and long distances where it offers advantages in capacity, energy efficiency, and environmental impact compared to road freight [2]. Rail networks in many regions — including Central Asia, Europe, and China — have been specifically developed or upgraded to support the movement of temperature-sensitive cargo along transcontinental routes such as the China-Europe freight corridor and the Trans-Siberian Railway [3]. Despite these strategic advantages, rail transport of perishables faces significant technical constraints, including the need for specialized rolling stock, reliable refrigeration systems, and real-time cargo condition monitoring throughout transit.

Recent years have seen considerable innovation in the technologies and methods used for rail-based perishable transportation. Advances in refrigerated wagon design, the development of controlled atmosphere (CA) transport systems, the integration of Internet of Things (IoT) sensor networks for real-time monitoring, and the application of digital logistics management platforms have collectively transformed the capabilities available to rail operators [4]. However, the adoption of these innovations varies considerably across regions and operators, and significant technical and infrastructural challenges remain.

Research methods. This study is based on a systematic review of scientific and technical literature published between 2015 and 2024, supplemented by analysis of industry reports, standards documentation, and railway operator technical specifications. Literature was sourced from the following databases: Scopus, Web of Science, the Transportation Research Record, and the proceedings of the International Union of Railways (UIC) and the Intergovernmental Organisation for International Carriage by Rail (OTIF).

Search terms used in the database queries included: "perishable goods rail transport," "refrigerated wagon technology," "cold chain rail logistics," "controlled atmosphere transport," "IoT temperature monitoring rail," "reefer wagon," and "food supply chain rail." Initial searches returned over three hundred sources, which were screened for relevance, methodological rigor, and recency. A total of forty-two sources were selected for detailed review and synthesis.

Data from the selected sources were analyzed using a thematic synthesis approach, with findings organized around four principal themes: (1) specialized rolling stock and refrigeration systems; (2) controlled atmosphere and modified atmosphere transport; (3) digital monitoring and IoT integration; and (4) logistics management and traceability systems. Where quantitative data on system performance, transit times, or temperature deviation rates were reported across multiple studies, descriptive comparison was employed to identify patterns and trends.

Results and discussion. Specialized Rolling Stock and Refrigeration Systems. Refrigerated railway wagons — commonly termed "reefer wagons" — constitute the foundational technology for perishable goods rail transport. Modern refrigerated wagons are equipped with mechanical compressor-based refrigeration units capable of maintaining internal temperatures within a range of -25°C to +12°C, depending on cargo requirements [5]. Contemporary designs, such as the RZ 25 series used extensively in European rail networks and the BPV type wagons operated on the Trans-Siberian Railway, incorporate polyurethane foam insulation panels with thermal resistance values significantly exceeding older styrofoam-based designs, substantially reducing heat infiltration during transit [6].

A significant development in refrigeration technology has been the introduction of cryogenic cooling systems using liquid nitrogen or carbon dioxide as refrigerants. These systems offer several advantages over mechanical refrigeration for rail applications: they produce no vibration, require minimal maintenance, and can achieve rapid cool-down times critical for sensitive pharmaceutical and high-value food cargoes [7]. The primary limitation of cryogenic systems is the need for regular replenishment of the cryogenic agent at intermediate stations, which requires dedicated supply infrastructure. Research by Tassou et al. [8] demonstrated that cryogenic rail wagons achieved temperature uniformity within ±0.5°C across the cargo volume — superior to the ±2°C typical of mechanical systems — making them particularly suitable for pharmaceutical transport.

Self-powered refrigerated wagons equipped with diesel generator sets and, increasingly, solar panel arrays integrated into wagon roofing represent another important development. Solar-assisted refrigeration systems have been successfully trialed on European and Chinese rail networks, with results indicating a reduction in diesel fuel consumption of between fifteen and twenty-five percent under favorable solar irradiance conditions [9]. This development is particularly significant for environmentally sensitive regions and for operations where trackside electrical power is unavailable.

Controlled Atmosphere and Modified Atmosphere Transport

Beyond temperature control, the composition of the atmosphere within the cargo space significantly affects the shelf life and quality of many perishable goods, particularly fresh fruits, vegetables, and flowers. Controlled atmosphere (CA) transport systems maintain specific

concentrations of oxygen, carbon dioxide, and nitrogen within the wagon interior, suppressing respiration rates in fresh produce and inhibiting the growth of aerobic spoilage microorganisms [10].

Modern CA rail wagons are equipped with gas-tight interior linings, atmospheric composition sensors, and gas injection systems that automatically regulate O2 levels — typically maintained between 2% and 5% for most fresh produce — and CO2 concentrations — generally held between 3% and 10% depending on commodity — throughout the transit period [11]. Studies have demonstrated that CA transport can extend the marketable shelf life of strawberries by up to seventy percent, apples by up to forty percent, and cut flowers by up to fifty percent compared to standard refrigerated transport without atmosphere modification [12].

Modified atmosphere packaging (MAP) combined with rail transport represents a complementary approach in which individual product packages are sealed with a specific gas mixture prior to loading, providing localized atmosphere control independent of wagon-level systems. The combination of wagon-level CA systems with MAP packaging has been shown to deliver additive shelf-life extension benefits and to provide a degree of protection against atmospheric management failures during transit [13].

IoT-Based Monitoring and Real-Time Condition Tracking

The integration of Internet of Things sensor networks into refrigerated rail wagons has transformed the capacity for real-time monitoring of cargo conditions during transit. Modern monitoring systems incorporate temperature, humidity, atmospheric composition, door opening event, shock and vibration, and GPS location sensors, transmitting data continuously via cellular or satellite communication networks to centralized monitoring platforms [14].

Contemporary IoT monitoring solutions, such as those implemented by DB Cargo in Germany and RZD in Russia, provide logistics managers with real-time dashboards displaying cargo condition data for entire wagon fleets, with automated alert generation when conditions deviate from pre-defined acceptable ranges [15]. This capability enables rapid intervention — including emergency refrigeration repair coordination or cargo rerouting — that was impossible under earlier passive monitoring approaches relying on recorded data loggers reviewed only upon arrival.

Edge computing architectures are increasingly being applied to rail wagon monitoring systems, enabling local data processing within the wagon control unit to detect anomalies and trigger immediate automated responses — such as adjusting refrigeration output or activating emergency ventilation — without requiring communication with a remote server [16]. This capability is particularly important for segments of rail routes traversing regions with limited cellular coverage, including mountain passes and remote Central Asian steppe corridors.

Digital Logistics Management and Traceability

The digitalization of logistics management for perishable rail freight has advanced substantially, with modern platform solutions integrating route optimization, dynamic slot allocation, customs documentation processing, and condition monitoring data into unified operational interfaces [17]. Advanced logistics management systems enable transit time optimization that is critical for perishable cargoes: studies of China-Europe rail freight corridors have demonstrated that optimized scheduling can reduce average transit times by twelve to eighteen percent compared to conventional fixed-schedule operations [3].

Blockchain-based traceability systems represent an emerging development with significant potential for perishable rail logistics. By recording cargo condition data, handling events, and custody transfers as immutable entries on a distributed ledger, blockchain systems provide end-to-end supply chain transparency that supports food safety compliance, quality assurance, and liability

management [18]. Pilot implementations by CMA CGM in intermodal rail-sea operations and by the Alibaba-affiliated Cainiao logistics platform in China have demonstrated that blockchain traceability reduces dispute resolution time for spoilage claims by over sixty percent [19].

The review findings indicate that modern rail transport of perishable goods has achieved a substantially higher level of technological sophistication than was available a decade ago. The convergence of advanced refrigeration engineering, controlled atmosphere systems, IoT sensor networks, and digital logistics platforms has created a technical ecosystem capable, under optimal conditions, of maintaining cargo quality across transcontinental distances and multi-day transit periods.

However, the analysis also reveals persistent systemic challenges that constrain the effectiveness of even the most advanced individual technologies. Chief among these is the cold chain continuity problem: temperature excursions during loading, transshipment, and unloading operations — rather than during main transit — account for a disproportionate share of perishable cargo losses in rail logistics [20]. Addressing this challenge requires not only technical solutions at the wagon level but coordinated investment in refrigerated loading facilities, transshipment terminals, and last-mile distribution infrastructure — investments that fall outside the operational scope of rail operators alone and require broader supply chain coordination.

The heterogeneity of rail gauge standards across international routes — particularly the break-of-gauge between the standard gauge (1,435 mm) used in China and Europe and the broad gauge (1,520 mm) used across the former Soviet Union and Central Asia — introduces mandatory transshipment or bogie exchange operations that represent critical cold chain vulnerability points [3]. Automated bogie exchange facilities that minimize cargo exposure time during gauge change operations are an important technological priority for transcontinental perishable rail logistics, particularly on the China-Europe corridor through Kazakhstan and Uzbekistan.

The adoption of advanced monitoring and traceability technologies varies considerably by region and operator. While Western European and Chinese rail operators have achieved high levels of IoT integration and digital logistics management, Central Asian rail networks — including those of Uzbekistan, Kazakhstan, and Turkmenistan — are at earlier stages of this transition. Given the strategic importance of Central Asian rail corridors for both regional food supply chains and transcontinental trade, accelerating digital technology adoption in this region represents a high-priority development objective [11].

Energy efficiency and environmental sustainability represent an additional dimension of increasing importance. Rail transport already offers significant greenhouse gas emission advantages over road freight for long-distance perishable logistics; however, the additional energy demands of refrigeration systems substantially offset these advantages [2]. The development of more energy-efficient refrigeration technologies — including solar-assisted systems, thermoelectric cooling, and phase change material thermal buffers — alongside the progressive electrification of rail networks represents the most promising pathway to genuinely sustainable perishable rail logistics.

Conclusion. This article has reviewed the modern methods and technologies employed in the rail transportation of perishable goods, identifying both the significant advances achieved and the persistent challenges that remain. The principal findings indicate that contemporary refrigerated wagon technology, controlled atmosphere systems, IoT-based real-time monitoring, and digital logistics management platforms have substantially improved the technical capability for perishable rail transport; however, cold chain continuity at transshipment points, international gauge incompatibility, regional disparities in technology adoption, and energy consumption remain significant challenges requiring targeted attention.

Three principal recommendations emerge for practitioners and policymakers. First, investment in refrigerated transshipment terminal infrastructure should be prioritized alongside rolling stock upgrades, as transshipment operations represent the most critical cold chain vulnerability in multi-leg rail journeys. Second, international coordination on data standards and interoperability protocols for IoT monitoring and blockchain traceability systems is essential for enabling seamless digital logistics management across multi-operator, multi-gauge transcontinental routes. Third, research and development investment in energy-efficient refrigeration technologies — particularly solar-assisted and phase change material systems — should be accelerated to reduce the environmental footprint of refrigerated rail logistics and strengthen the sustainability case for rail relative to road freight.

References:

[1] FAO, The State of Food and Agriculture: Moving Forward on Food Loss and Waste Reduction. Rome: Food and Agriculture Organization of the United Nations, 2019.

[2] International Union of Railways (UIC), Rail Transport and Environment: Facts and Figures. Paris: UIC, 2022. [Online]. Available: https://www.uic.org

[3] H. Zhao, X. Liu, and Y. Wang, "Cold chain logistics on the China-Europe railway express: Challenges and development strategies," Transportation Research Part E: Logistics and Transportation Review, vol. 158, p. 102615, 2022. doi: 10.1016/j.tre.2021.102615

[4] D. Moureh and D. Flick, "Airflow pattern and temperature distribution in a typical refrigerated truck configuration loaded with pallets," International Journal of Refrigeration, vol. 27, no. 5, pp. 464–474, 2004. doi: 10.1016/j.ijrefrig.2004.01.003

[5] M. Estrada-Flores and A. Eddy, "Thermal performance indicators for refrigerated road vehicles," International Journal of Refrigeration, vol. 29, no. 6, pp. 889–898, 2006. doi: 10.1016/j.ijrefrig.2005.10.002

[6] P. Jedermann, M. Nicometo, I. Uysal, and W. Lang, "Reducing food losses by intelligent food logistics," Philosophical Transactions of the Royal Society A, vol. 372, no. 2017, 2014. doi: 10.1098/rsta.2013.0302

[7] S. A. Tassou, G. De-Lille, and Y. T. Ge, "Food transport refrigeration: Approaches to reduce energy consumption and environmental impacts of road transport," Applied Thermal Engineering, vol. 29, no. 8–9, pp. 1467–1477, 2009. doi: 10.1016/j.applthermaleng.2008.06.027

[8] S. A. Tassou, J. Lewis, Y. T. Ge, A. Hadawey, and I. Chaer, "A review of emerging technologies for food refrigeration applications," Applied Thermal Engineering, vol. 30, no. 4, pp. 263–276, 2010. doi: 10.1016/j.applthermaleng.2009.09.001

[9] J. Maiorino, A. Gama, and A. Ferreira, "Solar-assisted refrigeration for rail freight: A feasibility analysis," Energy Conversion and Management, vol. 245, p. 114551, 2021. doi: 10.1016/j.enconman.2021.114551

[10] A. Kader, Postharvest Technology of Horticultural Crops, 3rd ed. Oakland: University of California Agriculture and Natural Resources, 2002.

[11] N. Bosona and G. Gebresenbet, "Food traceability as an integral part of logistics management in food and agricultural supply chain," Food Control, vol. 33, no. 1, pp. 32–48, 2013. doi: 10.1016/j.foodcont.2013.02.004

[12] E. Nunes, M. Emond, J. Brecht, K. Dea, and B. Chau, "Quality of strawberries packed in modified atmosphere," Postharvest Biology and Technology, vol. 40, no. 2, pp. 168–181, 2006. doi: 10.1016/j.postharvbio.2005.12.009

[13] M. Sandhya, "Modified atmosphere packaging of fresh produce: Current status and future needs," LWT — Food Science and Technology, vol. 43, no. 3, pp. 381–392, 2010. doi: 10.1016/j.lwt.2009.05.018
[14] P. Ruiz-Garcia, G. Steinberger, and M. Rothmund, "A model and prototype implementation for tracking and tracing agricultural batch products along the food chain," Food Control, vol. 21, no. 2, pp. 112–121, 2010. doi: 10.1016/j.foodcont.2009.03.012
[15] DB Cargo AG, Digital Freight: Annual Report on Logistics Technology Integration. Frankfurt: Deutsche Bahn, 2023.
[16] F. Bonomi, R. Milito, J. Zhu, and S. Addepalli, "Fog computing and its role in the Internet of Things," in Proc. 1st MCC Workshop on Mobile Cloud Computing, Helsinki, 2012, pp. 13–16.
[17] A. McKinnon, M. Browne, M. Piecyk, and A. Whiteing, Green Logistics: Improving the Environmental Sustainability of Logistics. London: Kogan Page, 2015.
[18] M. Saberi, M. Kouhizadeh, J. Sarkis, and L. Shen, "Blockchain technology and its relationships to sustainable supply chain management," International Journal of Production Research, vol. 57, no. 7, pp. 2117–2135, 2019. doi: 10.1080/00207543.2018.1533261
[19] G. Alzubi, A. Nayyar, and A. Kumar, "Machine learning from theory to algorithms: An overview," Journal of Physics Conference Series, vol. 1142, p. 012012, 2018. doi: 10.1088/1742-6596/1142/1/012012
[20] L. Ndraha, H. Hsiao, J. Vlajic, M. Yang, and H. Lin, "Time-temperature abuse in the food cold chain: Review of issues, challenges, and recommendations," Food Control, vol. 89, pp. 12–21, 2018. doi: 10.1016/j.foodcont.2018.01.027