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Executive Summary

This document presents best practices through specific examples from leading European cities and, based on gaps in the literature, formulates a functional and modern technology concept that facilitates the integration of rail freight with sustainable last-mile solutions such as electric vehicles and cargo bikes, as well as crowdsourced solutions. This includes data gathering and analysis of rail-enabled urban logistics. The document also presents experimental results of data gathered from our industry partners (Czech Post) with the Prague to Pardubice corridor as a case study. The research evaluates the feasibility and performance of a rail-enabled urban logistics system designed to enhance sustainability and economic resilience under emerging carbon pricing regulations, particularly ETS II. The research integrates rail freight as a regional backbone with low-emission last-mile solutions such as electric vans and cargo bikes, supported by urban micro-hubs. Data were gathered from European statistical sources, policy reports, industry benchmarks, and literature-based emission and cost parameters, and analyzed using a simulation-based modeling framework. The analysis compares road-only and rail-integrated configurations under different carbon pricing scenarios, assessing total costs, emissions, and system stability. The experimental results show that rail-integrated modes (rail+bike and rail+van) experience only slight cost increases, showing resilience to carbon pricing. On the contrary, road-only and especially HGV-regional deliveries face a significant cost increase of 11 to 15 percent, with HGV costs exceeding €1125 per month by 2030, based on data from industry partners. These results highlight the vulnerability of fossil-fuel-dependent freight and the attractiveness of rail-based multimodal solutions in balancing cost efficiency with decarbonization goals. Under the baseline condition, where interregional and last-mile van deliveries dominate the system, total emissions remain consistently high, averaging ~2,200 kg CO_2 per month. Interregional HGV operations are the main contributors, accounting for more than 70% of monthly emissions, while last-mile vans contribute an additional 15–18%, highlighting the carbon intensity of the interregional HGV and van-dependent distribution model. Rail and cargo bikes represent only a marginal share of the emissions profile. A 40% modal shift of parcels going directly to the city center from road to rail reduces monthly freight emissions by about 25%, mainly by replacing long-distance truck trips with low-carbon rail transport, while rail-integrated multimodal modes contributed marginally to the emission profile. The rail–bike configuration proves to be the most cost-effective and environmentally resilient under emission trading conditions. Overall, the report offers data-driven guidance for policymakers, logistics providers, and urban planners, emphasizing the strategic importance of multimodal, rail-integrated freight systems for sustainable and resilient urban logistics. The framework supports evidence-based decision-making and contributes to advancing sustainable, multimodal freight networks in European urban regions.

Abbreviations and acronyms

Abbreviation / Acronym	Description
EU	European Union
GHG	Greenhouse Gases
UN	United Nations
ETS	Emission Trading System
HGVs	Heavy Goods Vehicles
CDC	Central Distribution Center
CPM	Cost Per Mode
EEA	European Environment Agency
ITF	International Transport Forum
RQ	Research Question
QGIS	Quantum Geographic Information System
EF	Emission Factors

1 Introduction

The European Union (EU) has set ambitious climate targets as part of its commitment to the Paris Agreement and the European Green Deal. Transport remains a major contributor to greenhouse gas (GHG) emissions, making up about 27% of the EU's total emissions. Unlike sectors such as industry and energy, where emissions have decreased over recent decades, the transportation sector has increased since 1990, posing significant challenges to achieving net-zero emissions by 2050. Intermediate goals, such as a 55% reduction in GHG emissions by 2030 (compared to 1990), are set within the Fit for 55 legislative packages (European Commission, 2025; Plötz, P. et al. 2021).

According to the United Nations' data booklet, the number of people living in urban areas will grow from 3.3 to 6.4 billion by 2050 (UN), leading to increased demand for e-commerce and urban freight services, which is a major hurdle to transportation systems in the most populous European cities, leading to increased traffic, air pollutants, and greenhouse gas emissions. Coupled with the European Green Deal, the EU is completing further climate initiatives, expanding the European Union's (EU) Emissions Trading System (ETS II) to road transportation and buildings (Schlacke, S et al 2022; Maragkogianni, A. et al, 2013). As a result of these regulatory frameworks, freight logistics operators will increasingly be subjected to carbon pricing frameworks. This evolving business carbon regulation and pricing environment makes it urgent to shift from carbon-intensive fossil fuel-based logistics and delivery systems to more resilient, low-emission models. The urban and interregional logistics systems, for the most part, remain unprotected from the future carbon cost shocks because they rely on road transport, thus Heavy Goods Vehicles (HGVs) and light commercial vehicles powered by diesel. Without action, operators will be stuck with shrinking profit margins due to heightened costs, or their services will be priced out for consumers. As a result, there is a need to develop proactive emissions-resilient logistics systems for the business to remain viable. **This discussion leads to the research question (RQ). RQ1: How does a policy-making framework that combines rail transport of shipments with a micro hub at a rail station and direct transshipment by cargo bike delivery, electric van, or pedestrian delivery (crowdshipping) improve carbon emissions, congestion, and efficiency, while acting as a mitigation strategy for emission allowance policy (ETS II)?**

A notable advancement in sustainable city logistics is the incorporation of high-capacity, low-emission rail corridors, along with low or zero-emission vehicles for last-mile delivery. Rome and Antwerp explore scenarios in which metros and trams are modified for freight delivery, integrating other distribution systems, case studies of Rome (Comi, A. & Hriekova, O., 2024; De Langhe, K. et al, 2019). These studies often attempt to balance operational constraints with the anticipated reductions in congestion and emissions. Some of the most advanced work is done using simulation-optimization approaches to study the design and operational viability of the network. Nationally, low-carbon multi-modal networks, including rail, have been modelled using hybrid GIS-based optimization with discrete event simulation by Gallardo et al. (2021). De Langhe et al. (2019) highlight that viability depends on infrastructure, robust operational modeling, and dual-perspective economic analysis (business and social costs/benefits). The need for integrated planning across scheduling, hub placement, and vehicle operations is a recurring theme. Zhao and Li (2025) describe conceptual models for the distribution of "rail + logistics" in rapidly growing Chinese urban areas, highlighting the role of multi-stakeholder collaboration and intelligent distribution platforms. Financial modeling guides investment and policy decisions within the context of sustainable urban logistics. Major modeling approaches that have been addressed in the literature focus on projects that have infrastructure spending, e-fleet deployment, and some other auxiliary facilities as their main economic control centers (De Langhe, K. et al, 2019). These analyses typically consider capital, operations, maintenance, and, in some cases, asset lifespans and residual values. To capture externalities that are not priced in the market, studies integrate shadow prices for carbon, congestion, or noise into their models. García-Ródenas et al. (2025) explicitly include the social costs of carbon and congestion when setting rail access charges, thereby affecting demand and policy outcomes. Literature emphasizes that public policy and finances need to be interconnected to serve social needs and business goals harmoniously in sustainable transport investments. **This discussion leads to the research question (RQ). RQ2: How does the diversion of road freight to rail, complemented by green last-mile logistics, improve logistics operational cost while acting as a mitigation strategy for carbon pricing policy ETS?**

To explore the research questions RQ1 and RQ2, this research examines the EU context logistics sector as a case study using historical data from Czech Post along the Prague-Pardubice corridors. The methodology involves data collection, technology concept formulation, and conducting experiments in Python/MATLAB environments to simulate cost and emissions trajectories under the proposed logistics framework and emission allowance regulatory policy. The research is motivated by the opportunity to leverage existing rail infrastructure as a major asset for decarbonization in regional freight flows. The connection between Prague's main rail terminal through Pardubice and Ostrava (300Km) offers a viable corridor to pilot a rail-enabled urban logistics model that shifts a significant amount of freight away from road transport through combining nighttime rail transshipment with low-carbon last-mile delivery via cargo bikes, electric vehicles, and crowd-shipping, and this model aligns with both climate goals and operational efficiency goals.

This research offers several contributions:

1) A novel technological concept is proposed for integrating interregional night-time rail freight and city logistics to promote seamless cooperation for the distribution of shipments in cities;

2) The proposal of an idea related to the micro-hub location at the railway station in cities that can be beneficial in making delivery operations more manageable and efficient;

3) To illustrate the applicability of the proposed approach, a real-life study application in the context of Pardubice City is demonstrated, which may be considered a practical contribution.

This research presents conclusions drawn from identified gaps in the literature in Section 2, an interactive map of best-practice case studies in Europe in Section 3, technology concept formulation Section 4, gathering and analysis of rail-enabled urban logistics in Section 5, experimental results of simulated data from the case study Section 6, conclusions in Section 7 and next steps and research development Section 8.

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2 Conclusions Drawn from Identified Gaps in the Literature

Rail-enabled urban logistics has garnered considerable attention as a potential solution to address urban congestion and reduce emissions. Several promising solutions have been identified from deliverable 1.1 for the effective implementation of rail transport into a sustainable urban logistics system, such as cargo trams systems, or the use of the metro for the transport of shipments at off peak hours, or the implementation of multimodal centres serving as a trans-shipment point for shipments heading to the city centre to a more environmentally friendly delivery option (e.g. e-cargo bike, electric cars, etc.)

The urban and regional logistics systems, for the most part, remain unprotected from the future carbon cost shocks because they rely on road transport, including Heavy Goods Vehicles (HGVs) and light commercial vehicles powered by diesel. Without action, operators will be stuck with shrinking profit margins due to heightened costs, or their services will be priced out for consumers. As a result, there is a need to develop proactive emissions-resilient functional logistics systems for the business to remain viable. Despite significant policy and research interest, there are currently limited published studies that fully combine rail freight transport with low/zero-emission last-mile delivery and its comprehensive economic evaluation. Although some elements of rail integration and multimodal last-mile logistics have been discussed in prior studies, our contribution lies in the unique and novel combination of backbone rail transport of shipments to an urban micro hub and direct transshipment by cargo bike delivery, electric van, or pedestrian delivery (crowdshipping, etc.) to customers or parcel lockers in the city center. Specifically, prior research has typically investigated either the economic dimension (operational costs, efficiency) or the environmental dimension (emissions reductions, sustainability impacts) in isolation, with a focus on larger cities, where trams and metros are more common and therefore less scalable in mid-sized cities.

The research integrates both into a unified modeling framework, explicitly demonstrating the dual benefits of rail-enabled logistics when carbon pricing is introduced through time-step operational simulation and economic analysis using software applications such as Python, MATLAB, and QGIS, which facilitate seamless integration of regional, intercity rail freight, and green last-mile logistics. A key innovation is the unique shipment configuration, which connects freight movement at the regional levels using a rail network, through a micro hub, then to parcel lockers or recipients using green last-mile logistics such as e-cargo bikes, electric vans, and crowdshipping, providing a solution for mid-size cities. This strengthens the cooperation between regional rail freight and last-mile logistics.

3 Interactive Map of Best Practices Case Studies in Europe

Figure 1 is an interactive map that was developed to visualize and disseminate best practice case studies in sustainable urban freight and multimodal logistics in Europe. The tool functions as a centralized knowledge platform designed to support policymakers, logistics operators, researchers, and urban planners in identifying, comparing, and replicating successful freight solutions. Its primary objective is to enhance accessibility, transparency, and practical application of innovative approaches across different cities and regions. Spatial analysis of the mapped cases shows twenty case study concentrations of rail-enabled freight innovation in Western, Northern, and Central Europe, particularly in Germany, the Benelux region, Scandinavia, and France, with emerging examples in Central and Eastern Europe.

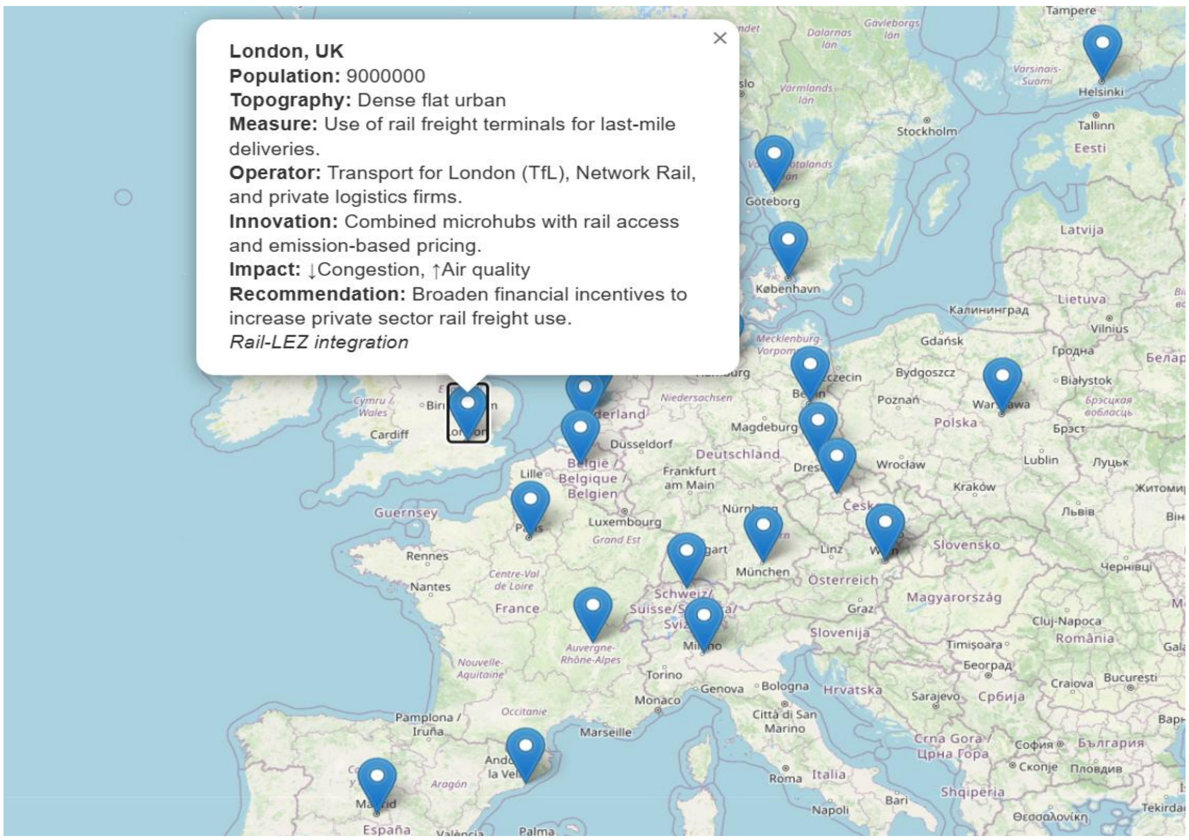

Figure 1. Interactive map of Best Practices case studies in Europe (Source: Author)

Twenty case studies were selected through a structured review of academic literature, policy reports, and stakeholder consultations. Selection criteria included demonstrated environmental impact, operational feasibility, economic viability, scalability, and alignment with European climate and mobility objectives. Each case was standardized into a structured dataset containing geographic location, population, topography, operator, description of the implemented solution, transport modes involved, such as rail, electric vehicles, cargo bikes, quantitative performance indicators, impacts of relevant policy instruments, and recommendations.

The tool was developed using Python-based geospatial libraries combined with OpenStreetMap basemaps. Each location is represented by an interactive marker containing structured information, including city and country, type of rail integration, last-mile delivery mode, key environmental or operational outcomes, and associated policy instruments. Users can explore cases by transport mode, policy framework, or geographic region, facilitating benchmarking and cross-city learning.

The platform highlights emerging trends such as rail integration, low-emission last-mile solutions, and policy-driven modal shifts. By bridging academic research and practical implementation, the interactive map provides a transferable decision-support tool for cities undergoing freight system transitions and supports evidence-based sustainable urban logistics planning. The map is still under development, and additional output will be made available by the end of the project, including updated filters and sliders to improve usability. A sample of rail-enabled logistics case studies with specific examples from three European cities is shown in Table 1.

Table 1: Sample of rail-enabled logistics case studies with specific examples from three European cities

Section	Vienna, Austria	Berlin, Germany	Paris, France
City Name	Vienna	Berlin	Paris
Country	Austria	Germany	France
Population	~1.9 million	~3.7 million	~2.2 million
Topography	Flat with minor hills; located on the Danube River	Flat plain; surrounded by the Berlin-Brandenburg area	Relatively flat; dense urban core with suburban sprawl
Description of Measures	Urban rail freight network integrated with city logistics; dedicated freight terminals.	Urban rail logistics via "BEHALA" for sustainable urban freight distribution.	Urban logistics through the "Chapelle International" rail logistics hub.
Investor/Operator	ÖBB (Austrian Federal Railways), City of Vienna	Berlin Hafen- und Lagerhausgesellschaft mbH (BEHALA), Public-Private Partnerships	Sogaris (logistics company), City of Paris, SNCF Logistics
Innovative Aspects (SMART City Context)	Rail-integrated last-mile delivery reduces road congestion and emissions.	Use of existing rail corridors for sustainable urban freight reduces truck movements.	Multimodal logistics platform enables rail-to-city-center distribution, reducing CO_2 emissions.

Economic Aspects	Significant cost savings from reduced road congestion and fuel costs.	Investment in rail infrastructure supports local businesses and creates sustainable supply chains.	Increased efficiency through rail-centric logistics, reducing last-mile delivery costs.
Geographical Specificity	Inner city and suburban areas integrate with the European freight corridor.	It serves the Berlin metropolitan area and integrates with the European freight network.	It is in northern Paris and serves inner-city and suburban areas.
Primary Impacts of the Measure	Reduced carbon emissions, traffic decongestion, and improved urban air quality.	Reduced heavy vehicle traffic, improved air quality, and increased efficiency in urban goods movement.	Reduced truck traffic, lower greenhouse gas emissions, and enhanced multimodal transport.
Relationship to Other Transport Measures	It integrates with the city tram and metro and aligns with the EU's Green Deal logistics targets.	Connects with Berlin's public transit and road logistics systems for last-mile delivery.	Links with public transit, last-mile electric delivery, and regional freight corridors.
Experience and Recommendations from Cities	The successful use of rail for urban freight highlights the need for ongoing public investment and regulatory support.	Demonstrates how existing rail infrastructure can be repurposed for sustainable urban logistics.	Supports the need for dedicated urban rail hubs and comprehensive city planning.
The Situation in the Czech Republic	Similar models can be adopted in Pardubice by integrating rail terminals with urban logistics.	Lessons can inform Czech cities on using existing rail infrastructure for sustainable logistics.	The Paris model offers a blueprint for establishing dedicated urban logistics hubs in the Czech Republic.
Examples of Good Practice	Vienna's Urban Rail Freight and Cargo Tram System.	Berlin's "BEHALA" urban rail logistics for sustainable goods movement.	Chapelle International multimodal logistics hub and rail freight corridor.

References	European Commission reports (2022), ÖBB publications.	BEHALA case studies, German Federal Ministry for Digital and Transport reports.	Sogaris and SNCF reports (2023), European Urban Freight Case Studies (2022).

4 Technology Concept Formulation

4.1 Basic Elements of the Innovative Technological Concept for the Case Study

The research's core technology concept is a unique combination of rail-transport shipments, an urban microhub at a railway station, and direct transshipment via cargo bike, electric van, or pedestrian delivery (crowdshipping). This technology model promotes cooperation between green last-mile logistics and rail freight, enhancing cross-modal logistics as shown in Figure 2.

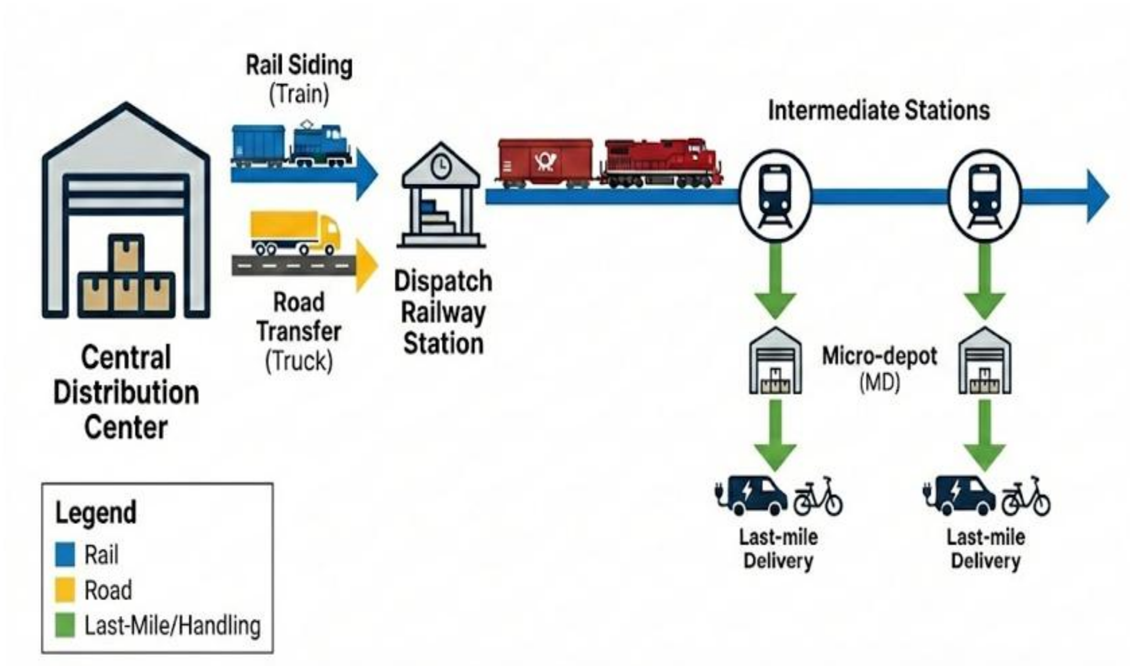

Figure 2. Technology Concept of the Shipment Distribution Problem (Source: Author)

This concept was developed in close consultation with industry partners, including CD Cargo and Czech Post, with a focus on Subsystem E-commerce. The technology concept uses a railway wagon as a loading unit, with either leased or shared capacity for parcels from different logistics operators, such as Czech Post, DHL, and PPL. Parcels are packed into movable postal cages with labels as shown in Figure 3, which are then transported from central distribution centers by operators such as Czech Post, DHL, and others, to a dispatch station equipped with handling ramps. Handling unit refers to transporting parcels in boxes, postal cages, or on pallets, so the entire wagon is not loaded directly with parcels. Logistics operators then receive and sort shipments at the unloading area (microhub) for the specific destinations. Next, the operator arranges the transshipment process based on the station's capabilities, which may include edges, ramps, platforms, or elevators. Green last-mile solutions, such as cargo bikes, electric vans, or pedestrian (crowdshipping) delivery, ultimately deliver shipments to parcel lockers. Providing sustainable and multimodal freight solutions for both larger and mid-sized cities, serving as a strategy to mitigate emission allowances (ETS II).

Figure 3. Postal cage for the storage of parcels (source: author).

4.2 Model of Total (Transportation) Costs – CTotal (EUR)

The total transportation cost of the proposed rail-enabled urban logistics system is represented by the Total Cost Model (CTotal), which captures all operational cost components involved in moving parcels from the central distribution center to final urban customers. The model reflects the multimodal nature of the logistics chain, integrating rail transport as the regional backbone with road-based transfers, hub operations, and last-mile delivery services. Specifically, the total cost comprises expenses for loading and handling at the central distribution center, transfer operations to the dispatch railway station, rail freight transport along the corridor, and unloading at intermediate or destination stations. Additional cost components include transfers to urban micro-depots, consolidation and sorting activities at these hubs, and last-mile delivery to end customers via sustainable urban delivery modes. The model also incorporates any additional operational costs arising from integrating rail into the logistics system, such as supplementary vehicle deployment or increased transfer requirements. By aggregating these components, the model provides a comprehensive framework for evaluating the economic performance of rail-enabled urban logistics systems and comparing them with conventional road-based distribution models.

CTotal = CLH + CTS+CHDS+ CRC + CUH + CTMD + CCC + CLM + CADD (1)

Where:

CLH - loading/handling costs at the Central distribution centre (CDC)

CTS- transfer costs from CDC to the dispatch railway station

a. Rail siding

b. Road

CHDS- handling/transhipment costs at the dispatch station

CRC – rail transportation costs from the dispatch station through intermediate stations to the destination

CUH- unloading/handling costs at intermediate/destination station

CTMD- transfer costs from station to micro-depot (micro hub)

CCC- consolidation, sorting costs at the micro-depot (hub)

CLM- Last-mile delivery costs from micro-depot (hub to end customers (urban delivery)

CADD- additional cost induced by rail integration (outside rail, but caused by the chosen rail-enabled solution), e.g. supplementary vehicle deployment or extra depot transfer

5 Analysis of Collected Data from Case Study

5.1 Methodology

This section presents how the data were gathered and the methodology used to analyze them. The research proposes a technology concept, a hybrid simulation and economic evaluation framework in Python environments to analyze the effectiveness of a rail-enabled urban freight system that incorporates electric vehicles and cargo bikes, as well as crowd-sourced low-emission last-mile delivery options (See Appendix 1 for code). The approach consists of four interconnected elements: operational simulation, emissions modeling, economic analysis, and policy sensitivity analysis. The simulation model functions in discrete time steps, estimating freight movement from rail terminals to urban micro hubs and onwards to end recipients, and detailed simulation code can be found in Appendix 1 of this report. Key variables include freight demand by distance and mode, microhub throughput capacity, last-mile vehicle trip rates, and rail diversion rates, which are influenced by policy measures and infrastructure capacity. These inputs are sourced from Eurostat data, scientific literature, and policy reports to ensure empirical relevance. To ensure the reliability of the results, we worked in cooperation with our industry partners, Czech Post and CD Cargo, who provided real-world data used in the simulations. Monthly transport costs were estimated per wagon based on the volume of parcel data received from industry partners. Model parameters and assumptions are provided in Table 2 below. The reference value of rail cost per ton/km was validated from the website of Costmine (2024, March 26) https://www.costmine.com/2024/03/26/rail-transport-costs-how-much-have-they-increased/ and supported by comparative freight cost analyses from the International Transport Forum (ITF, 2021). The cost of cargo bike operations was estimated based on urban micro-distribution studies, assuming minimal fuel costs and primarily labour-driven expenses (Markham, D. 2024).

For the breakeven analysis, the model below was used to simulate average cost per parcel, with the analysis focusing primarily on the rail and road components.

The average transport cost of a parcel per mode CPM is expressed as:

$$CPM = AWp \times D_i \times A_i \qquad (2)$$

Where:

AWp = Average weight per parcel in tons,

D_i = Distance travelled by mode $i \in$ {road, rail, bike} /km,

A_i = Average cost per mode $i \in$ {road, rail, bike}, per ton/km,

To assess environmental performance, emissions from each freight mode are calculated based on activity levels and energy intensity. The total emissions E_t at time step t are expressed as:

$$E_t = \sum_i V_{i,t} \cdot e_i \qquad (3)$$

Where:

- $V_{i,t}$ is the volume of freight transported by mode i at time t,
- e_i is the emission factor (kg CO_2/km) for the mode i, $i \in$ {road, rail, bike},

- Modal emission factors reflect diesel for road freight, electric/hybrid systems for rail, and zero/low-emission technologies for last-mile vehicles.

Derivation of Freight Transport Emission Factors

The emission factors in the simulation were derived by converting standard European freight transport emission intensities from grams of CO_2 per tonne-kilometre (gCO_2/ton-km) into tonnes of CO_2 per tonne-kilometre (tCO_2/ton-km), which is the unit required for carbon pricing and logistics cost calculations.

Primary sources used include the European Environment Agency (EMEP/EEA Guidebook, 2023) and International Transport Forum (2021) freight transport studies.

Representative European freight transport intensities adopted in the model were: Rail freight = 20 gCO_2/ton-km, Heavy goods vehicles (HGVs) = 120 gCO_2/ton-km, and Light commercial vehicles (LCVs) = 180 gCO_2/ton-km.

The conversion formula applied was: $EF = gCO_2 / 1{,}000{,}000$, where EF is the emission factor expressed in tonnes of CO_2 per tonne-km.

Rail freight emission factor derivation: 20 / 1,000,000 = 0.00002 tCO_2/ton-km.

Heavy goods vehicle emission factor derivation: 120 / 1,000,000 = 0.00012 tCO_2/ton-km.

Light commercial vehicle emission factor derivation: 180 / 1,000,000 = 0.00018 tCO_2/ton-km.

Cargo bikes were assumed to have zero direct operational emissions in the simulation framework.

The general emissions equation used in the model is: $E = W \times D \times EF$, where E is emissions, W is parcel weight (tons), D is transport distance (km), and EF is the emission factor.

Example rail freight calculation: $E = 0.002 \times 120 \times 0.00002 = 0.0000048$ tCO_2, equivalent to 4.8 gCO_2 per parcel. These emission factors enable consistent comparison between transport modes and support evaluation of EU ETS II carbon pricing impacts, transport decarbonization, and sustainable urban logistics policies.

To validate estimated emissions for both road and rail transport, the EcoTransIT World simulator (EcoTransIT World Initiative, n.d.) was used, as shown in Figs. 7 and 8. Emissions are monetized using a shadow price of carbon, allowing externalities to be evaluated in economic terms. The economic analysis model computes indicators such as break-even analysis to evaluate economic viability. **Two scenarios were considered for the study: the base case and the post-carbon-pricing case, using price levels of 2027 (65€/tCO_2) and 2030 (140€/tCO_2)**. Finally, a policy sensitivity analysis explores how carbon pricing influences system outcomes. This integrated methodology supports a nuanced understanding of the interactions between logistics infrastructure, policy design, and sustainability objectives in urban freight systems.

Table 2. Parameters and assumptions used in the simulation

Parameter	Value	Unit	Assumption / Meaning
Average parcel weight	0.002	tons	Each parcel weighs 2 kg
Regional HGV distance	150	km	Long-haul regional freight movement
Local road delivery distance	30	km	Direct urban van distribution
Rail transport distance	120	km	Intercity rail freight corridor
Last-mile distance	5	km	Final delivery distance from hub
Revenue per parcel	1.5	€	Revenue earned per delivered parcel
Rail cost factor	0.12	€/ton-km	Rail operational cost
Van cost factor	0.25	€/ton-km	Urban delivery van cost
Cargo bike cost factor	0.30	€/ton-km	Cargo bike operational cost
HGV cost factor	0.15	€/ton-km	Heavy goods vehicle transport cost
Hub transshipment cost	0.05	€/ton	Handling cost at rail micro-hub
Rail emissions factor	0.00002	tCO_2/ton-km	Electrified rail assumption
Van emissions factor	0.00018	tCO_2/ton-km	Diesel/electric mixed urban fleet
Cargo bike emissions factor	0.0	tCO_2/ton-km	Zero tailpipe emissions
HGV emissions factor	0.00012	tCO_2/ton-km	Conventional freight truck
ETS carbon price (2027)	65	€/tCO_2	EU ETS II projected carbon cost
ETS carbon price (2030)	140	€/tCO_2	Higher future carbon pricing scenario

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6 Experimental Results of Simulated Data from the Case Study

The simulation and economic evaluation from a case study based on data from industry partners (Czech post) provides compelling evidence of the economic and environmental feasibility of rail-enabled urban logistics systems when combined with low-emission last-mile delivery modes.

6.1 Case Illustration

Figure 4 illustrates the spatial context and infrastructure elements considered for the Pardubice case study developed with QGIS, which serves as a pilot location for evaluating the proposed rail-enabled urban logistics system. Pardubice is strategically located within the Czech Republic's national rail network and along a major rail corridor connecting Prague, Pardubice, and Ostrava, making it an appropriate test environment for integrating rail freight with sustainable urban last-mile distribution. The figure presents three key spatial components of the case study.

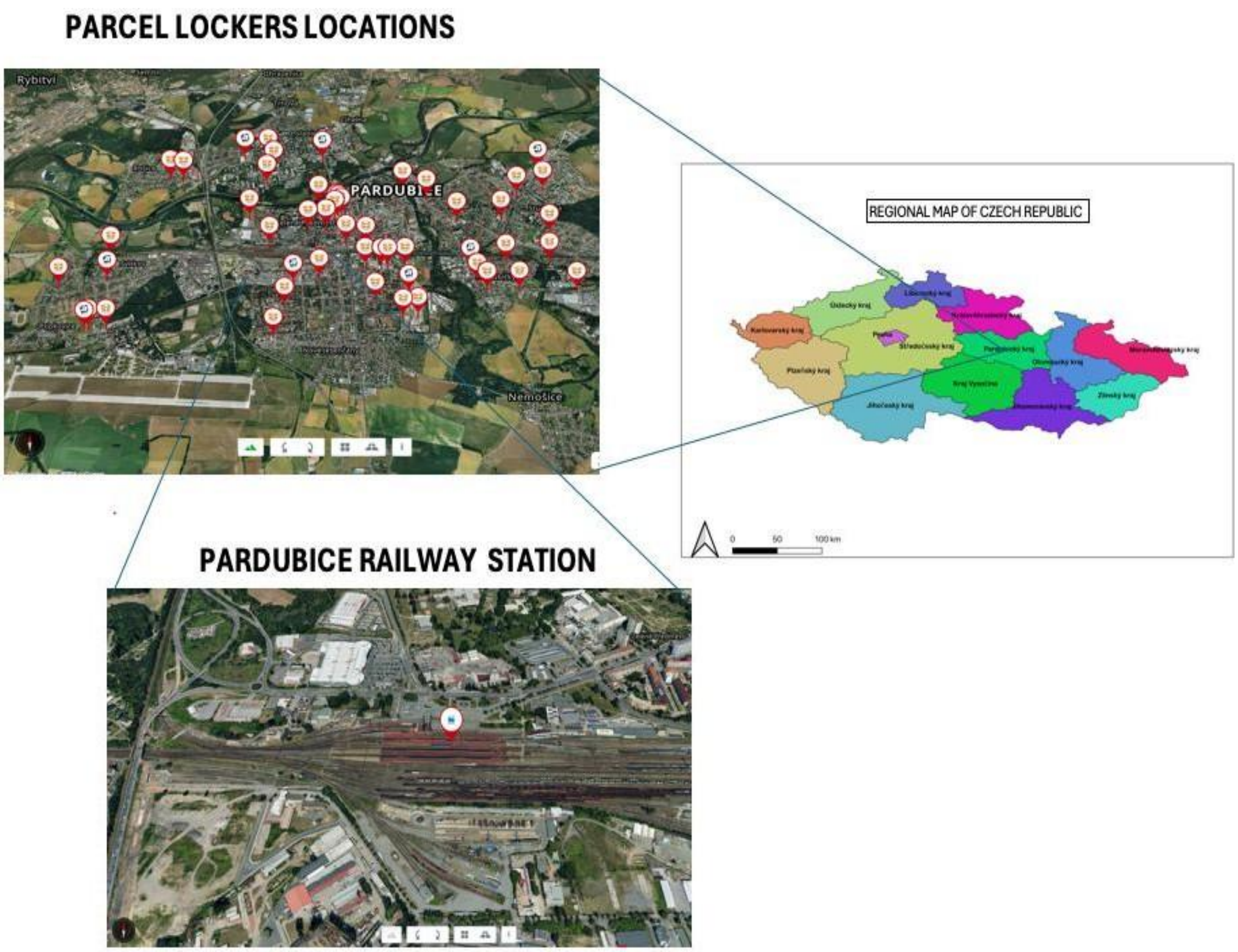

Figure 4. The locations of parcel lockers and railway station are shown on the regional map of the Czech Republic (Source: Author)

First, the regional map of the Czech Republic situates Pardubice within the broader national logistics and transportation network. This geographic location underscores the city's role as an intermediate rail node that supports interregional freight redistribution. Moreover, the Pardubice railway station is shown as the central logistics gateway for the proposed system. The station functions as the primary rail transshipment point (Microhub), where parcels transported via rail from upstream distribution centres are unloaded and transferred to urban distribution systems. Its existing rail infrastructure and connectivity make it suitable for handling interregional freight flows while minimizing reliance on long-distance road transport.

Finally, the map of parcel locker locations within the city of Pardubice illustrates the spatial distribution of urban delivery points. These locker locations represent potential demand nodes for parcel deliveries and serve as an important element of the last-mile logistics network. Their distribution across residential and commercial areas demonstrates the potential coverage of urban delivery services supported by micro-hubs or consolidation points. Together, these elements illustrate how the proposed logistics concept operates within the local urban and regional context. Rail freight transports parcels to the Pardubice station, after which shipments are transferred to micro-depots or distribution hubs and delivered to customers through sustainable last-mile solutions such as electric vans, cargo bikes, or parcel locker networks. This case study, therefore, provides a practical spatial framework for evaluating the operational feasibility, environmental benefits, and cost implications of implementing a rail-enabled urban logistics system in a medium-sized European city.

6.2 Operational Simulation and Scenario-testing ETS impacts on cost structures

Figures below illustrate the cost of parcel delivery per unit in four operational modes under two scenarios: the base case (excluding carbon pricing) and the carbon pricing scenario. The results demonstrate significant cost differences between rail-integrated solutions and road-only systems, with clear implications for the long-term sustainability of urban freight.

Comparative Cost Performance

Figure 5&6 present parcel delivery costs across modes under baseline calculated using equation 2, 2027 (65€/tCO_2), and 2030 (140€/tCO_2) ETS II scenarios. Rail-integrated modes (rail+bike and rail+van) experience only slight cost increases, showing resilience to carbon pricing. On the contrary, road-only and especially HGV interregional deliveries face a significant cost increase of 11 to 15 percent, with HGV costs exceeding €1125 monthly by 2030. These results highlight the vulnerability of fossil-fuel-dependent freight and the attractiveness of rail-based multimodal solutions for balancing cost efficiency with decarbonization goals.

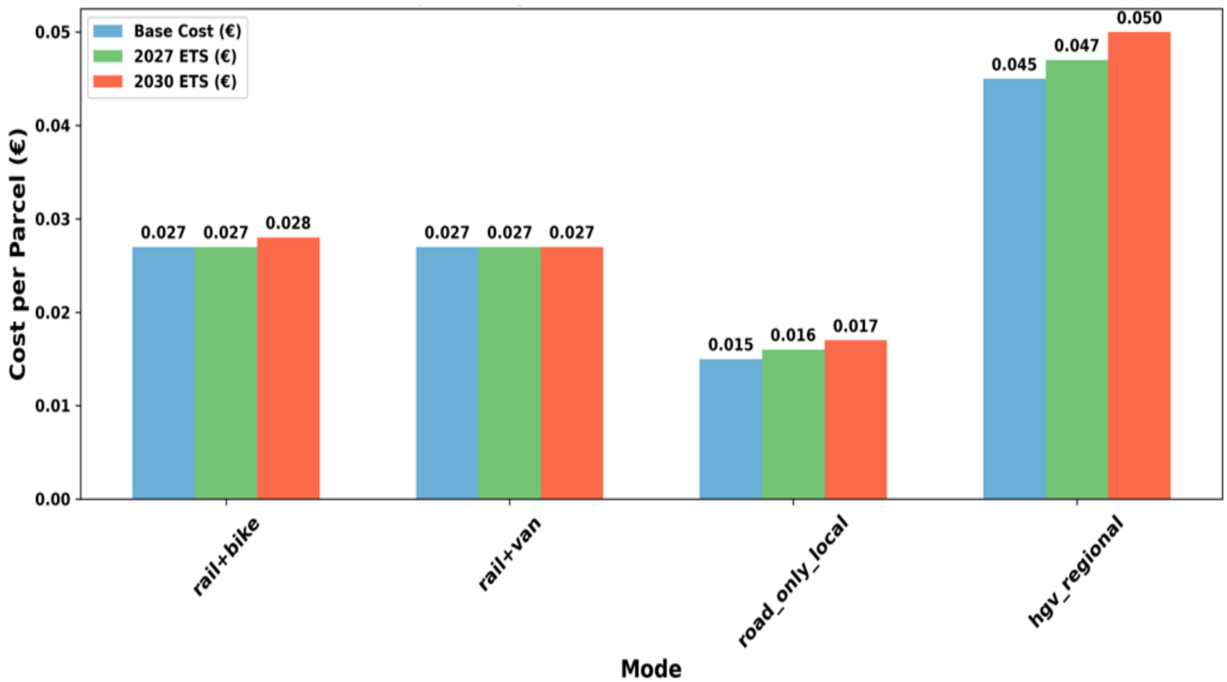

Figure 5. Parcel delivery cost per unit across four operational modes under two scenarios: the base case (excluding carbon pricing) and the carbon-pricing scenario for long-haulage (Source: Author)

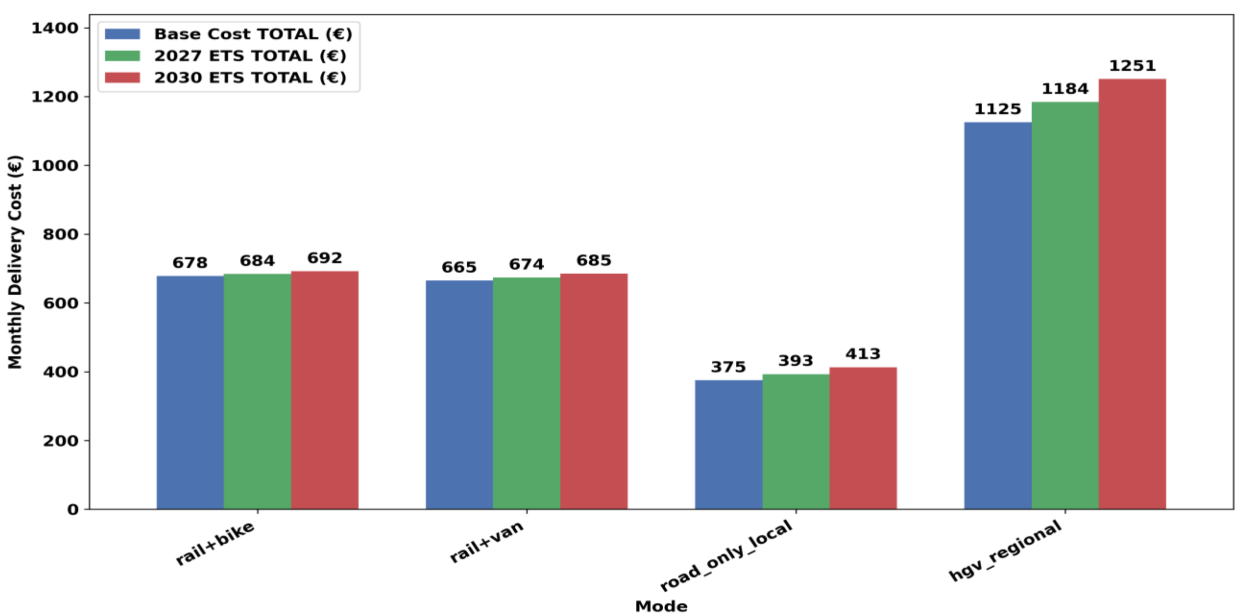

Figure 6. Monthly parcel delivery cost per unit across four operational modes under two scenarios: the base case (excluding carbon pricing) and the carbon-pricing scenario for long-haulage (Source: Author)

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6.3 Emissions Reductions

The comparative assessment of monthly emissions before and after the introduction of the European Union Emissions Trading System (ETS) provides clear evidence of the structural impact of rail diversion on freight decarbonization.

Baseline (Before ETS)

Under the baseline condition, where interregional and last-mile van deliveries dominate the system, total emissions remain consistently high, averaging ~2,200 kg CO_2 per month using equation 3, as shown in Figure 7. Interregional HGV operations are the main contributors, accounting for more than 70% of monthly emissions, while last-mile vans contribute an additional 15–18%. Rail and cargo bikes represent only a marginal share of the emissions profile, highlighting the carbon intensity of the van-dependent distribution model.

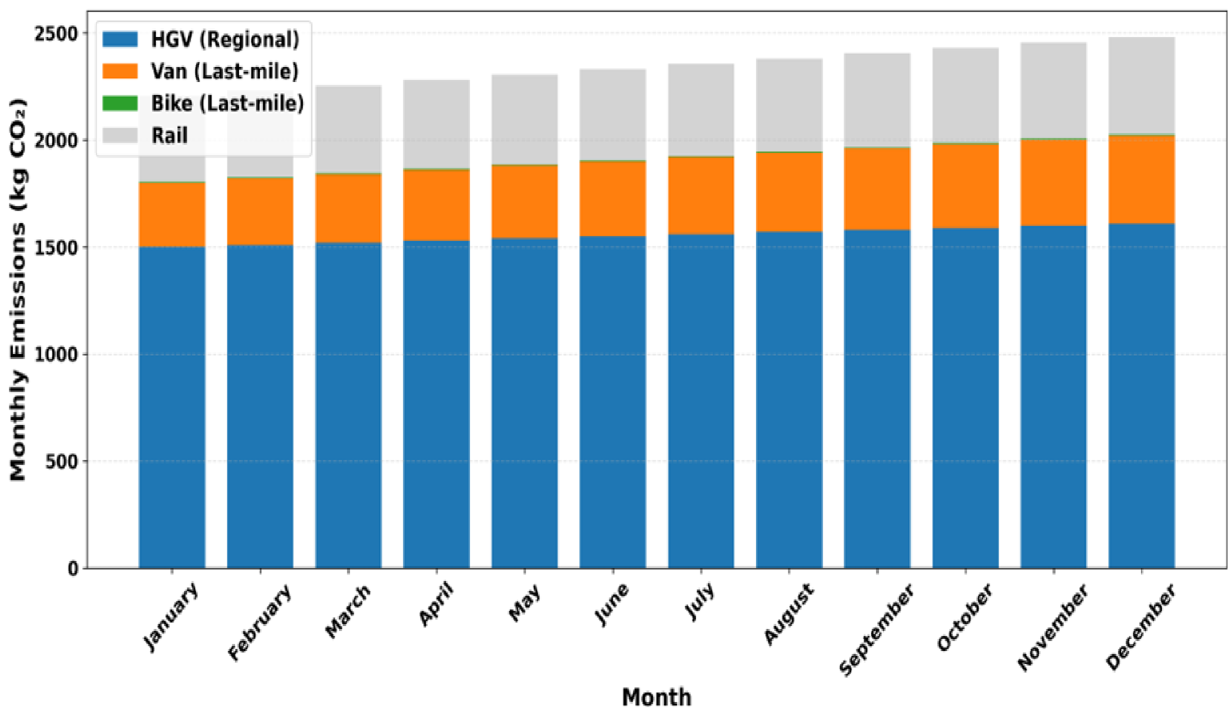

Figure 7. Monthly emissions by transport modes before the carbon pricing policy (ETS II) (Source: Author)

Post-ETS with Rail Diversion

As a result of the introduction of ETS and the diversion of 40% of parcel flows to rail, monthly emissions decrease significantly, averaging ~1,650 kg CO_2 calculated using equation 3 as shown in Figure 8. This represents an approximate 25% reduction in overall system emissions, indicating a promising future for the implementation of rail and multimodal transport systems. The emissions profile shifts notably:

- Interregional HGV dependency declines, with their share reduced to ~25% of total emissions.
- Rail emerges as a central mode, absorbing a substantial portion of demand while maintaining a comparatively low-carbon footprint.

- Cargo bikes and electric van fleets become more relevant, contributing minimally to total emissions but playing a crucial role in sustainable last-mile delivery.

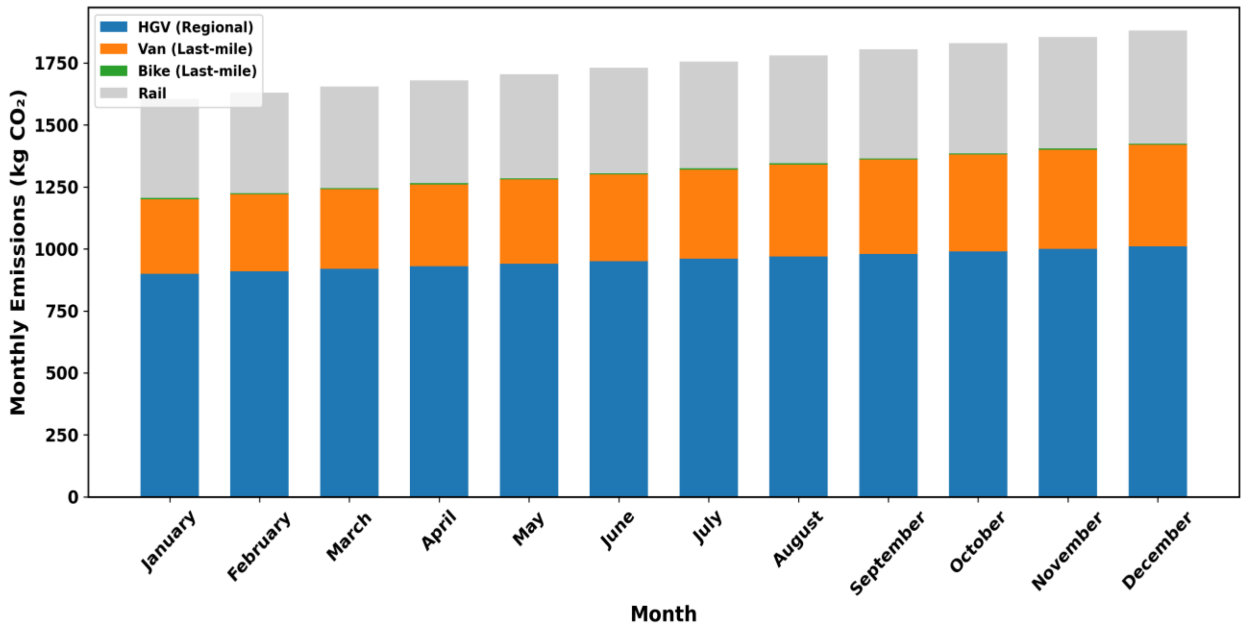

Figure 8. Monthly emissions by transport modes after the carbon pricing policy (ETS II) (Source: Author)

Comparative Insights

The results clearly demonstrate that the ETS may act as a regulatory catalyst, altering the competitiveness of transport modes. In the baseline, the dominance of road freight is linked to short-term cost advantages but carries a disproportionate climate burden. Once carbon costs are internalized, the system realigns towards rail-integrated multimodality, which not only reduces emissions but also ensures long-term operational resilience.

6.4 Discussion and Conclusions of Experimental Results

This research provides timely insight into the economic and operational viability of rail-enabled urban logistics networks, complemented by sustainable last-mile delivery systems such as electric vans and cargo bikes. The integrated modelling approach demonstrates how such multimodal logistics configurations can contribute to broader sustainability goals, particularly within the climate-neutral mobility strategies of the European Union (European Commission, 2021). The Fit-for-55 package of the European Union and the progressive expansion of the EU Emission Trading System (EU ETS) to include road transport are set to transform the cost structures of last-mile and interregional delivery services.

The comparison of parcel delivery costs under baseline and carbon pricing scenarios demonstrates how regulatory instruments reshape modal competitiveness. In the baseline, road-only local deliveries and rail-integrated solutions (rail+van, rail+bike) show relatively similar cost levels, while interregional HGV-only operations recorded the highest monthly transport cost (≈ €1125). Once carbon pricing is applied, this cost discrepancy increases substantially; the cost of interregional HGV-only operations increases by 11 to 15 percent per parcel, while rail-integrated modes remain cost-stable, with minimal increases. Under

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decarbonization policies, these findings underscore the economic vulnerability of fossil fuel-dependent modes and highlight rail as a more resilient option.

Emissions analysis provides complementary evidence of the ETS impact. In the baseline scenario (before ETS), the total monthly emissions average ~2,200 kg CO_2, with interregional HGVs accounting for more than 70% of the carbon footprint. Following the diversion of 40% of flows to rail under ETS, monthly emissions fall to approximately 1,650 kg CO_2, representing a 25% reduction. The emissions liability shifts away from HGV, while rail and sustainable last-mile modes (cargo bikes, e-vans) gain significance. The integration of rail not only delivers absolute emissions reductions but also creates a more balanced and resilient modal structure. The findings have important implications for both policymakers and logistics operators. For regulators, the research demonstrates that carbon pricing is an effective tool for internalizing environmental costs and promoting a shift toward more sustainable transport modes. For operators, early adoption of rail-integrated supply chains reduces long-term exposure to carbon costs and strengthens competitiveness in a decarbonizing market. Complementing rail freight with cargo bikes and electric vans for last-mile delivery enhances operational flexibility, supports intermodal solutions, and aligns with urban sustainability objectives.

The research contributes to Sustainable Development Goals 11 (Sustainable Cities and Communities), 9 (Industry, Innovation, and Infrastructure), and 13 (Climate Action). By integrating environmental, economic, and operational dimensions, the research bridges academic modeling with policy development and investment planning, offering a framework applicable to European cities transitioning toward more sustainable freight systems. Carbon pricing coverage is expanding, now applying to about a quarter of global emissions, but price levels and policy stringency remain insufficient for deep decarbonization (Matsuki, T. et al. 2020; Agnolucci, P. et al. 2024). Achieving climate targets will require higher carbon prices, broader coverage, and integration with other policy instruments. Political-economic constraints and the need for international coordination remain significant hurdles (Ceccato, R. and Gastaldi, M., 2023). In summary, carbon pricing is effective for incremental emissions reductions and as part of a comprehensive climate policy package, but alone is unlikely to deliver the deep decarbonization required to meet global climate goals. Addressing equity, political feasibility, and complementary measures are essential for scaling up its impact.

This research demonstrates that integrating rail into urban and interregional parcel distribution enhances both economic resilience and environmental performance under emerging carbon regulations. Cost analysis shows that road-only operations using Heavy Goods Vehicles face significant cost increases under carbon pricing, whereas rail-based multimodal systems remain comparatively stable, shielding operators from regulatory shocks. Emissions results indicate that shifting 40% of interregional freight to rail reduces monthly CO_2 emissions by about 25%, with further benefits achieved through sustainable last-mile solutions such as cargo bikes and electric vans. While road transport is typically more flexible and suitable for short-distance or time-sensitive shipments, rail becomes more cost-efficient for high-volume, long-distance movements despite its higher fixed infrastructure and handling costs. The most economical choice depends on shipment size, distance, and urgency.

Overall, rail plays a dual role: mitigating compliance costs under carbon pricing and supporting decarbonization goals. Beyond cost and emissions, the findings suggest a structural rebalancing of freight transport, with rail as the backbone and low-emission last-mile modes maintaining urban service quality. The research shows that carbon pricing can drive market transformation toward low-carbon logistics. However, implementation challenges include infrastructure investment, capacity limits, data sensitivity, and zoning constraints. Future research should address dynamic demand, life-cycle impacts, and scalability to strengthen resilient and equitable rail-enabled freight systems.

7 Conclusions

The data gathering and analytical assessment of rail-enabled urban logistics systems demonstrate the strategic potential of integrating rail freight into regional and urban distribution networks under emerging carbon pricing regimes. By combining empirical data from European statistical sources, industry benchmarks, and policy frameworks with simulation-based modeling, the research provides a structured evaluation of both economic and environmental performance across different modal configurations.

The findings confirm that road-dependent freight systems are increasingly vulnerable to carbon pricing mechanisms such as ETS II, leading to rising operational costs and reduced cost stability. In contrast, rail-integrated multimodal systems exhibit greater resilience to fluctuations in carbon costs while delivering measurable reductions in CO_2 emissions. The cooperation with sustainable last-mile solutions, such as electric vans and cargo bikes, further enhances environmental performance and operational flexibility in urban areas. The analysis also highlights the importance of accurate demand estimation, realistic emission factors, and transparent cost assumptions in ensuring model reliability. Sensitivity testing underscores that modal shift levels, carbon price trajectories, and hub handling efficiency significantly influence system outcomes. These results reinforce the need for coordinated policy support, infrastructure readiness, and industry collaboration to scale rail-enabled logistics solutions effectively.

Beyond these findings, the research makes several important contributions. First, it provides a data-driven modeling framework that integrates operational cost analysis, emissions modeling, and policy sensitivity analysis to evaluate rail-enabled urban logistics systems. Second, the research contributes to the strategic understanding of how rail freight can function as a backbone for sustainable urban logistics, particularly when integrated with low-emission last-mile solutions. Third, the work offers evidence-based insights for policymakers and industry stakeholders, highlighting the role of modal shift strategies and multimodal logistics systems in addressing both climate targets and operational efficiency. However, implementation challenges include infrastructure investment, capacity limits, data sensitivity, and zoning constraints. In addition, expanding the technology concept to multiple European urban regions and logistics corridors would help evaluate the transferability and scalability of rail-enabled logistics systems.

Overall, the research concludes that rail-enabled urban logistics represents a viable and forward-looking framework for supporting decarbonized, economically stable, and policy-aligned freight systems in European cities. The research contributes a data-driven foundation for strategic planning and future implementation of multimodal freight networks.

8 Next Steps and Research Development

Further research involves delving into the specifics of the technology concept and providing recommendations for the involved stakeholders. Machine learning techniques may be used for parcel demand forecasting and to simulate freight flows under carbon and capacity constraints. The objective is to improve predictive accuracy and system adaptability by modeling dynamic demand patterns and operational uncertainties. However, a key challenge lies in limited access to high-quality, large-scale operational datasets required for robust machine learning and deep learning applications. Data fragmentation across countries and operators further complicates cross-border model calibration and transferability.

To address these challenges, we are actively seeking international research and industry collaboration with rail freight operators and urban logistics stakeholders. Potential partners include Austrian rail carrier Rail Cargo Austria AG (RCA), ÖBB + City Logistics (Austria), Mercitalia (Italy), BVG and the Senate of Berlin (Germany), DSB Logistics (Denmark), ADIF and RENFE Mercancías (Spain), among others. Such collaboration would enable access to empirical freight data, validation of simulation results, and comparative cross-country analysis, thereby strengthening the scientific rigor and practical relevance of the research. The interactive map is still under development, and additional output will be made available by the end of the project, including updated filters and sliders to improve usability.

Through these next steps, the PhD aims to deliver a validated, data-driven, and policy-responsive rail-enabled urban logistics framework capable of supporting the railway sector’s strategic transition under emerging carbon regulation regimes.

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Appendix 1: Simulation code with detailed parameters

```
# Parameters
avg_parcel_weight = 2 / 1000  # tons
parcel_distance_regional = 150  # km (HGV)
parcel_distance_road = 30 # km (local van)
parcel_distance_rail = 120 # km (rail intercity)
last_mile_distance = 5 # km
revenue_per_parcel = 1.5 # €
# Base unit costs (€/ton-km or €/ton)
base_costs = {'rail': 0.12, 'van': 0.25, 'bike': 0.30, 'hgv': 0.15, 'hub': 0.05}
# Emissions factors (tCO₂ per ton-km)
emissions_factors = {'rail': 0.00002, 'van': 0.00018, 'bike': 0.0, 'hgv': 0.00012}
# Carbon price scenarios (€/tCO₂)
ets_prices = {'2027': 65, '2030': 140}
# Cost calculation
def calc_cost(mode):
  if mode == "rail+bike":
    return (avg_parcel_weight * parcel_distance_rail * base_costs['rail'] +
        avg_parcel_weight * base_costs['hub'] +
        avg_parcel_weight * last_mile_distance * base_costs['bike'])
  elif mode == "rail+van":
    return (avg_parcel_weight * parcel_distance_rail * base_costs['rail'] +
        avg_parcel_weight * base_costs['hub'] +
        avg_parcel_weight * last_mile_distance * base_costs['van'])
  elif mode == "road_only_local":
    return avg_parcel_weight * parcel_distance_road * base_costs['van']
  elif mode == "hgv_regional":
    return avg_parcel_weight * parcel_distance_regional * base_costs['hgv']
  return 0
# Emissions calculation (tCO₂ per parcel)
def calc_emissions(mode):
  if mode == rail+bike
    return (avg_parcel_weight * parcel_distance_rail * emissions_factors['rail'] +
        avg_parcel_weight * last_mile_distance * emissions_factors['bike'])
```


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```
    elif mode == "rail+van":
        return (avg_parcel_weight * parcel_distance_rail * emissions_factors['rail'] +
                avg_parcel_weight * last_mile_distance * emissions_factors['van'])
    elif mode == "road_only_local":
        return avg_parcel_weight * parcel_distance_road * emissions_factors['van']
    elif mode == "hgv_regional"
        return avg_parcel_weight * parcel_distance_regional * emissions_factors['hgv']
    return 0
# Modes
modes = ["rail+bike", "rail+van", "road_only_local", "hgv_regional"]
# Compute results
results = []
for mode in modes:
    base_cost = calc_cost(mode)
    emissions = calc_emissions(mode)
    costs = {"base": base_cost}
    for year, price in ets_prices.items():
        costs[year] = base_cost + emissions * price
    results.append((mode, costs, emissions))
# Prepare DataFrame
df = pd.DataFrame({
    "Mode": [r[0] for r in results],
    "Base Cost (€)": [r[1]["base"] for r in results],
    "2027 ETS (€)": [r[1]["2027"] for r in results],
    "2030 ETS (€)": [r [1]["2030"] for r in results],
    "Emissions (tCO₂)": [r[2] for r in results]
})
# Plot with labels on bars
ax = df.set_index("Mode")[["Base Cost (€)", "2027 ETS (€)", "2030 ETS (€)"]]. plot(
    kind="bar", figsize=(10,6), color=["skyblue","lightgreen","salmon"] )
plt.ylabel("Cost per Parcel (€)")
plt.title("Parcel Delivery Cost per Mode (Base vs. ETS II 2027 & 2030)")
plt.grid(axis="y", linestyle="--", alpha=0.6)
# Add value labels on bars
for container in ax.containers:
```


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```
    ax.bar_label(container, fmt="%.3f", fontsize=9, label_type="edge", padding=2)
plt.tight_layout()
plt.show()
```