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Doctoral Dissertation
Doctoral Program in Energetics (37^{th}cycle)

Synergies between Bimodal Freight Electric Multiple Units Trains and Advanced ICE Technologies for Sustainable Intermodal Transport

By

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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2025

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Ai miei genitori, le mie solide fondamenta,
che con amore instancabile hanno costruito i ponti
su cui ho mosso i primi passi della mia strada.

A chi con un sorriso ha rischiarato ogni curva,
rendendo più dolci le salite e più lievi le discese.

Ai percorsi intrecciati con tanti compagni di viaggio,
che mi hanno sostenuta e guidata come fossero
un motore potente che mi spinge su dei binari d'acciaio
che corrono verso i miei sogni.

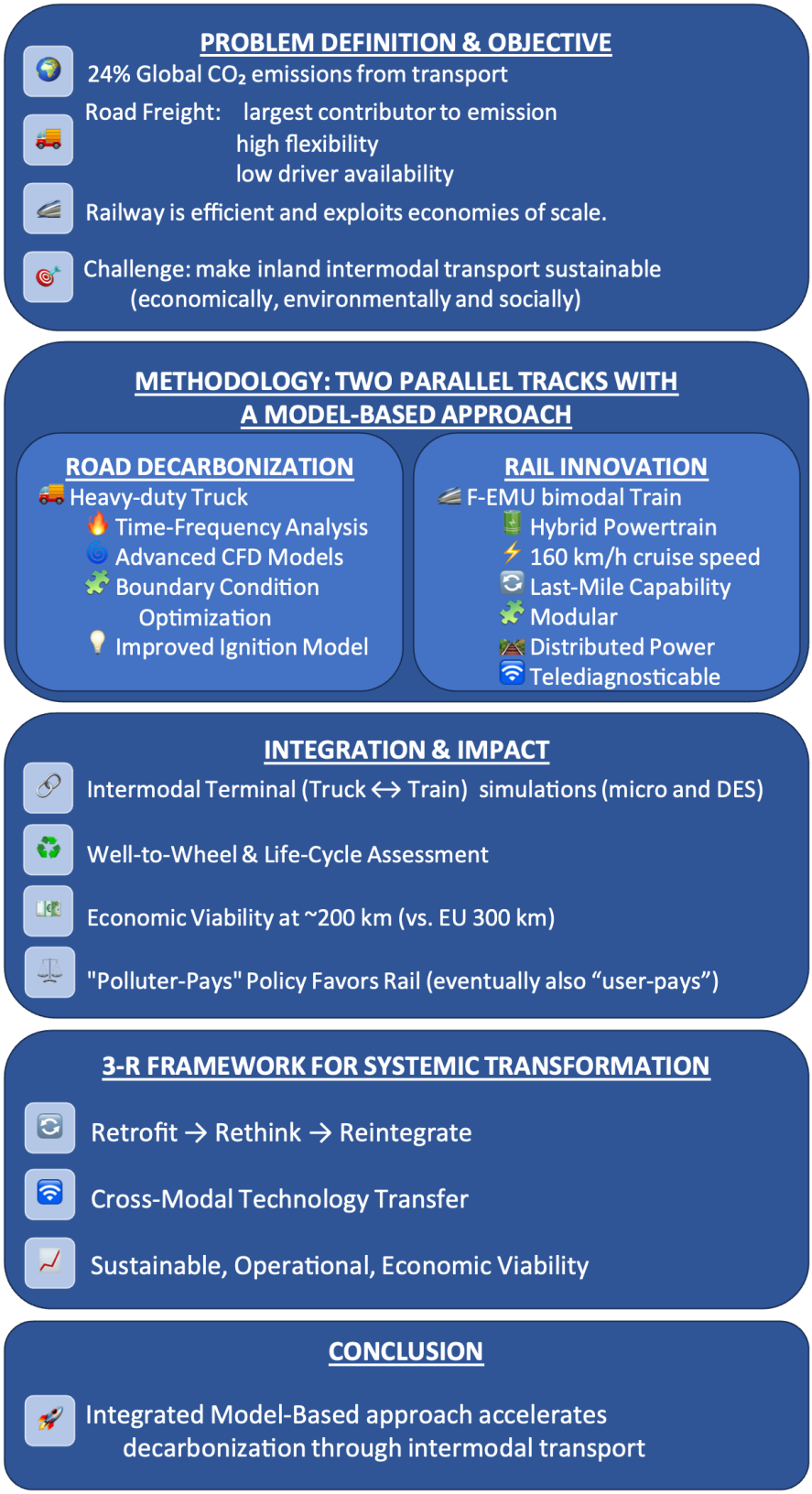
Abstract

This doctoral thesis addresses the challenge of decarbonizing intermodal transport chains through an integrated model-based approach that leverages synergies between road and rail technologies. The transportation sector accounts for approximately 24-26% of global CO_2 emissions and 28-31% of global energy consumption, with the majority of its energy demand met by fossil fuels. The percentage gap between energy use and CO_2 emissions is primarily due to two factors: the contribution of guided transport systems (approximately 80% of European railway networks is already electrified and one-third of traction energy is currently derived from renewable sources, with rail standing as the only transport mode realistically capable of operating entirely without fossil fuels or batteries in the near term) and the adoption of advanced road propulsion technologies with higher efficiency. This work leverages both these factors to address environmental imperatives and comply with evolving regulatory frameworks, while maintaining operational and economic viability.

The thesis employs a progressive widening of scope with a bottom-up approach, starting from component-level analysis and expanding to encompass vehicles and entire inland transport chains. In Part 1 the foundations for the investigation are laid with basic definitions and objectives. In Part 2, the focus is on road transport decarbonization, particularly heavy-duty applications where electrification faces major limitations. The first step in doing so is having high reliability of the computational models needed when transitioning to alternative fuels. This research focuses exactly on this using time-frequency analysis TFA and creating interplay between 1D-3D computational fluid dynamics. A new spark energy deposition model improves ignition accuracy by capturing physical kernel temperatures, while a new boundary condition optimization methodology achieves <1% error in pressure prediction at spark timing and <5% error in intake mass. TFA allows detecting

combustion events and anomalies, key factor for smooth defossilization. In a broader sense, at a vehicle level, a well-to-wheel approach should be used for assessing the potential of a specific powertrain solution. Part 3 presents an innovative concept for railway freight: the Bimodal Freight Electric Multiple Unit (F-EMU). Using Model-Based Systems Engineering, its functional architecture, requirements, and subsystems are developed. The F-EMU's distributed power architecture enables operation at 160 km/h on high-speed infrastructure while its hybrid powertrain facilitates last-mile operations and power boosting. Microsimulation and discrete event simulations (DES) demonstrate its operational improvements. The F-EMU's modular architecture enables adaptation to demand fluctuations, while the integrated monitoring systems allow for high operational reliability. Finally, Part 4 examines intermodal integration. A multi-criteria analysis reveals that combined road-rail operations could become economically viable at distances of <200 km, below the EU's current 300 km threshold for modal shift targets. Policies emphasizing sustainability through "polluter-pays" approaches would further shift modal choice. Synergistic opportunities between road and rail powertrain technologies are highlighted, including the adaptation of heavy-duty ICE technology with alternative fuels for railways, for which a life-cycle assessment shows better sustainability scores than fuel-cell solutions.

This research contributes to transportation sciences by presenting an integrated technological approach spanning vehicle powertrains, system architectures, and operational strategies across transport modes. Rather than pursuing siloed solutions, the thesis demonstrates that cross-modal technology transfer accelerates innovation while optimizing resource allocation. The proposed Retrofit-Rethink-Reintegrate framework provides a phased roadmap for systemic transformation, to achieve sustainability targets without compromising economic and operational performance of modern logistics. The methodologies developed and the brand-new F-EMU architecture, provide tools for future research and policies in sustainable transportation technologies.


PROBLEM DEFINITION & OBJECTIVE
24% Global CO_2 emissions from transport
Road Freight: largest contributor to emission
high flexibility
low driver availability
Railway is efficient and exploits economies of scale.
Challenge: make inland intermodal transport sustainable
(economically, environmentally and socially)
METHODOLOGY: TWO PARALLEL TRACKS WITH A MODEL-BASED APPROACH
ROAD DECARBONIZATION
Heavy-duty Truck
Time-Frequency Analysis
Advanced CFD Models
Boundary Condition Optimization
Improved Ignition Model
RAIL INNOVATION
F-EMU bimodal Train
Hybrid Powertrain
160 km/h cruise speed
Last-Mile Capability
Modular
Distributed Power
Telediagnosticable
INTEGRATION & IMPACT
Intermodal Terminal (Truck ↔ Train) simulations (micro and DES)
Well-to-Wheel & Life-Cycle Assessment
Economic Viability at ~200 km (vs. EU 300 km)
"Polluter-Pays" Policy Favors Rail (eventually also “user-pays”)
3-R FRAMEWORK FOR SYSTEMIC TRANSFORMATION
Retrofit → Rethink → Reintegrate
Cross-Modal Technology Transfer
Sustainable, Operational, Economic Viability
CONCLUSION
Integrated Model-Based approach accelerates decarbonization through intermodal transport

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Simona