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Typology of Five Generations of Heavy Trucks

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Abstract

This paper presents a detailed typology of heavy-duty truck development, systematically analyzing the sector's evolution from the early Pioneer Workhorse to the emerging Interconnected Autonomous Innovator. Going beyond a simple, technology-focused narrative, the study applies the Multi-Level Perspective (MLP) from Socio-Technical Transitions (STT) theory to reveal a complex, multi-path transition characterized by the coexistence and competition of different socio-technical regimes. The analysis identifies five categories in the typology: The Mechanical Workhorse, The Diesel Dominator, The Electric Steward, The Green Transformer, and The Interconnected Autonomous Innovator, each distinguished by unique combinations of technology, energy sources, software integration, organizational complexity, and key players. A major finding is the shift in innovation leadership from Western brands to China, beginning with The Mechanical Workhorse, culminating in The Diesel Dominator, and gaining momentum with The Electric Steward. However, due to rapid technological innovation in the green sector and a focus on renewable energy, Chinese heavy truck manufacturers strongly positioned themselves with The Green Transformer and became leaders with The Interconnected Autonomous Innovator. This change and re-positioning were radical and driven not by component-level superiority but by a strategic, collective, and co-created model of systemic integration of new technologies. Chinese actors, especially through battery swapping, have pioneered a new approach that emphasizes operational uptime, total cost of ownership, and servitization over incremental hardware improvements. The paper demonstrates that China's ability to coordinate an ecosystem—aligning industrial policy, energy infrastructure, and corporate innovation—has enabled a form of technological leapfrogging, thereby bypassing the fragmented, market-driven approach of the West in the face of technological disruptions. The future of freight is envisioned as a resilient, interconnected system in which electrification, automation, a multitude of energy storage solutions, and digitalization come together to form a seamless integrated logistics network. In this future, trucks are not just isolated vehicles but nodes within a larger energy and data ecosystem, with the lines between trucks, batteries, and charging stations merging into a unified, service-oriented mobility model. Achieving this vision will require full integration of advanced technologies, including AI-driven autonomy, 6G-enabled real-time connectivity, and universal standards for wireless charging and modular energy systems. The success of this vision depends on unprecedented collaboration among stakeholders to mobilize the entire industry—from solar technology and semiconductor manufacturing to cloud computing and smart city infrastructure. As China has shown, integrating these technologies within a collaborative, co-created framework positions the next dominant regime not just on technological breakthroughs but also on the ability to coordinate complex networks and systems of technology, policy, and infrastructure into a comprehensive, adaptable, and sustainable system. This study concludes that future industry leadership will rely on systemic resilience and integration, providing a vital framework for navigating the transformative future of global mobility.

Keywords

Heavy Trucks, Typology, Socio-Technical Transitions, Multi-Level Perspective, Battery Swapping, Electrification, Autonomous Vehicles, Technological Innovation, China, Sustainable Logistics, System Integration, Freight Transport

1. A Historical Development of the Heavy Trucks

1.1. Introduction

The development of heavy trucks over the past century has been a vital part of global industrialization, shaping logistics networks, trade routes, and economic systems of modern society. From the early mechanical haulers of the late 19th century to the modern, intelligent, electrified platforms of the 21st century, the industry has undergone multiple waves of technological advancements. Conventional stories often describe this evolution as a straight line—from steam to internal combustion, from manual to automated systems, from fossil-based to clean and renewable energy—viewing each new generation of vehicles as a direct successor to the previous one. While such simple histories provide useful context, they overlook a more complex reality: today's heavy-duty vehicle landscape is marked not by a single, straight path but by the coexistence of multiple, competing technological regimes. While new technologies are gaining ground and becoming dominant in the West and China, the old, fossil-based, diesel-heavy trucks coexist. This paper argues that a more detailed analytical framework is necessary—one that moves beyond basic chronological narratives to a typological classification based on socio-technical transitions theory.

The historical development of heavy trucks can be divided into distinct phases. From the 1890s to the 1920s, the first era was characterized by *The Mechanical Workhorse*, a basic vehicle designed for durability and high load capacity. This was followed by the rise of *the Diesel Dominator*, which emerged in the mid-20th century and was characterized by the widespread use of diesel engines, turbocharging, intensive long hours of operations, and increasingly advanced hybrid systems combining mechanical and electric technologies. Companies such as Daimler, Volvo, and Scania gained recognition for their engineering excellence, making incremental improvements within a framework heavily reliant on fossil fuels and a globally connected supply chain [1] [2]. In contrast, China's entry into the industry started in the 1950s, and initially relied on technology transfer from the Soviet Union, Japan, and the West.

However, from the 2000s onward, government-led industrial policies and large-scale infrastructure investments spurred rapid modernization. Chinese manufacturers transitioned from imitators to innovators. In 2023, China accounted for over 70% of global electric truck sales, with over 130,000 electric heavy-duty trucks on the road—far exceeding the combined total of all other regions [3].

This transformation is exemplified by *The Green Transitionist*, a category defined by full electrification and innovative infrastructure solutions, such as battery swapping and hydrogen energy, reflecting a systemic, ecosystem-based approach to a fully integrated infrastructure for charging, energy supply, and vehicle systems based on system innovation [4] [5].

To understand these diverging paths of traditional fossil and diesel-based heavy trucks and the fully integrated renewable energy-based fully-electric, this paper employs the Multi-Level Perspective (MLP) on socio-technical transitions, a robust framework that views technological change as a nonlinear, contested process resulting from the interaction of landscape pressures, stabilized regimes, and new niches [6]. This approach enables a critical analysis of how and why different technological routes develop, emerge, vanish, persist, or compete, particularly within the growing divide between Western and Chinese technology development models.

1.2. Problematization

Despite the abundance of historical and technical literature on heavy truck development, prevailing narratives still follow a linear, evolutionary model that assumes a one-way progression toward increased efficiency, sustainability, or automation. This perspective, grounded in technological determinism, risks reinforcing a dominant view of innovation that favors Western technological leadership while ignoring alternative pathways that could be just as, or even more, effective in specific contexts [7]. It also fails to recognize the continued existence of multiple technological regimes, such as in today's situation: diesel-powered trucks still dominate long-haul freight across North America, Europe, and the Global South, while battery-electric models are gaining popularity in urban delivery in China; hydrogen prototypes are being tested in Europe, and modular battery-swapping systems are rapidly expanding in industrial zones in China. In 2024, China accounted for over 90% of global sales of electric heavy-duty trucks (Class 8 equivalents) [8]. Of the approximately 65,000 electric heavy trucks sold in China in 2024, about 25,000 - 28,000 (or roughly 40% - 43%) were battery-swapping models [9]. This shows significant growth, up from around 25% in 2023. The rest were mainly plug-in models, especially for short-haul and municipal use [9]. China New Energy Commercial Vehicle Annual Report 2025 states: "*Battery-swapping models accounted for* 42% *of new energy heavy-duty truck sales in* 2024, *up from* 27% *in* 2023."

This coexistence of different technologies shows that performance metrics alone do not determine technological adoption; rather, they are deeply embedded in socio-technical systems, including charging and refueling infrastructure, policy incentives, operational economics, and institutional support. Our observation is that "*the future of trucking will not be won by the most advanced engine or the most elegant algorithm, but by the most integrated and resilient system*." This insight questions the sufficiency of longitudinal analyses and emphasizes the need for a typological approach—one that classifies trucks not by their position in a timeline but by their underlying socio-technical and commercial configurations.

A key challenge is avoiding technological reductionism—viewing trucks solely as engineering achievements. Instead, this study emphasizes the co-evolution of technology and society, recognizing that vehicles are part of broader systems of production, regulation, and use. Another challenge is that these typologies are dynamic: they are not fixed categories but evolving regimes, susceptible to disruption, hybridization, and geopolitical conflicts. For example, the success of The Green Transformer in China is not just due to technological advantage but also because of a coordinated industrial strategy that aligns manufacturers, battery producers, and energy providers under government guidance [10].

In contrast, Western innovation, often driven by market competition and private R&D, has led to slower, more fragmented adoption of sustainable solutions. This divergence raises critical questions about the future of global technology development, the adoption of standards, the role of government in technological progress, and the ethical implications of these shifts for sustainability and equity.

1.3. Purpose

The primary purpose of this paper is to develop and apply a framework for analyzing the diversity and evolution of the global heavy truck industry and to develop a typology to understand this development.

This paper argues that understanding this transformation requires not a timeline, but a typology—one that reflects the variety of futures already developing on the world's roads.

This study goes beyond just providing a chronological account to classify heavy trucks into five distinct types: 1) *The Mechanical Workhorse*, 2) *The Diesel Dominator*, 3) *The Electric Steward*, 4) *The Green Transformer*, and 5) *The Interconnected Autonomous Innovator*. Each type is defined by a unique mix of technological, organizational, and institutional factors, reflecting not only engineering choices but also entire socio-technical systems.

This typology serves as an analytical and predictive tool, enabling a more detailed comparison of how different technological pathways respond to specific operational needs and systemic limitations. It shifts the focus from *which* and *when* technologies emerge to *how* they are integrated into functional systems and *why* certain configurations become dominant in particular regions and contexts. In doing so, the paper examines China's role in global innovation, highlighting a unique trajectory that emphasizes systemic integration, rapid deployment, and institutional coordination over incremental improvements. As the industry advances toward electrification, autonomy, and full integration into intelligent logistics networks, the concept of a "truck" is being rethought.

1.4. Main Research Questions

The following central research questions guide this study:

1) How can a typological framework, based on Socio-Technical Transitions (STT) theory, offer a more complete understanding of the structural diversity and coexistence of technological regimes in the heavy truck industry?

2) What are the key socio-technical configurations—covering technology, energy sourcing, software integration, infrastructure, and system integrators—that differentiate the five identified truck types?

3) How do the different innovation models in Western and Chinese contexts reflect varying political economies, institutional logics, and approaches to systemic integration, and what are the implications of these differences for global technological leadership?

4) What are the mechanisms of transition, hybridization, and competition among these typologies, and how do landscape pressures (e.g., climate policy, digitalization) interact with entrenched regimes and emerging niches to influence the future of freight transport?

5) What are the normative implications of these technological shifts for sustainability, equity, and a just transition, especially regarding the environmental costs of battery manufacturing, the decarbonization of energy grids, and the potential displacement of professional drivers?

By addressing these questions, this paper aims to provide a robust typology, context-aware framework for researchers, policymakers, and industry stakeholders navigating the complex, rapidly evolving landscape of heavy truck development.

2. Methodology

This study uses a qualitative, interpretive research method to organize and analyze secondary data and to create a typology of heavy truck development. In our research, we synthesize and critically reevaluate existing knowledge through the framework of Socio-Technical Transitions (STT) theory, with special focus on the Multi-Level Perspective (MLP). This approach allows for a systemic understanding of how technological, organizational, and institutional structures co-evolve across different generational archetypes, moving beyond simple progress narratives toward a detailed mapping of overlapping socio-technical regimes.

Data collection focused on peer-reviewed scholarly articles, industry reports, policy documents, technical specifications, and the authors' prior longitudinal research [5] [11] [12].

The literature search was conducted systematically across major academic databases, including Google Scholar, Web of Science, and Scopus for high-impact journals in innovation studies and sustainability transitions; ScienceDirect (Elsevier) for energy and transportation policy; IEEE Xplore for technical papers on electrification, battery systems, and autonomy; SpringerLink for works on industrial systems and economic geography; and CNKI (China National Knowledge Infrastructure) to include Chinese-language scholarly and policy sources crucial for understanding China's context. Government and intergovernmental reports—from the European Commission, the International Energy Agency (IEA), China's Ministry of Industry and Information Technology (MIIT), and the Swedish Transport Administration (Trafikverket, TRV)—were also reviewed to contextualize regulatory and strategic drivers.

The search strategy combined controlled vocabulary with iterative keyword strings (e.g., "heavy-duty truck," "battery swapping," "socio-technical transition," "Multi-Level Perspective," "servitization," "system integration") and was refined through pilot searches and citation tracking.

Data analysis used an inductive, thematic coding process aligned with principles of qualitative synthesis. Initial open coding identified recurring patterns across technological design, energy infrastructure, software integration, business models, and actor networks. These patterns were then organized into analytical categories that matched MLP constructs: landscape pressures (e.g., climate policy, digitalization), regime characteristics (e.g., diesel infrastructure, OEM networks), and niche innovations (e.g., battery-swapping ecosystems, autonomous pilots). The emerging typology—comprising The Mechanical Workhorse, The Diesel Dominator, The Electric Steward, The Green Transformer, and The Interconnected Autonomous Innovator—was continuously questioned and developed through empirical sources and refined through constant comparison and reflection. This process was further supported by the authors' prior work, enabling a deeper contextual pre-understanding of systemic shifts in innovation leadership and institutional coordination, as well as of the development context in China and the West.

Our analysis provides a nonlinear, politically and ethically aware view on the different development pathways of the Western and Chinese models. Ultimately, this approach shows that isolated technological breakthroughs do not determine the future of freight; rather, it is the ability to coordinate complex socio-technical systems—an ability increasingly centralized within China's government-led, co-created innovation ecosystem.

3. Theoretical Framework

To understand the development of heavy-duty trucks, it is important to go beyond simple stories of technological advances and adopt a more detailed, systemic approach that reflects the complexity, debate, and coexistence of multiple technological pathways. This paper uses the theoretical framework of Socio-Technical Transitions (STT), particularly the Multi-Level Perspective (MLP), which provides a powerful analytical tool for examining the various structures and innovation paths within the global freight industry [6] [13]. The MLP views technological change not as a predictable process driven by individual breakthroughs but as a non-linear, contested evolution that results from interactions among three levels: landscape, regime, and niche. This approach is particularly useful for analyzing the heavy truck sector, where the persistence of established systems, the rise of radical innovations, and the influence of deep social, political, and economic forces shape how and how fast change happens.

At the landscape level, broad external pressures set the stage for change. Heavy-duty transportation includes the worsening climate crisis, the need for energy security, the digitalization of economies, and shifting geopolitical dynamics. These pressures do not directly cause change but instead act as background forces that destabilize current regimes and create opportunities for alternative technologies. For example, stricter emissions standards, such as the European Union's Euro VII regulations [14], demonstrate how landscape pressures translate into regulations that challenge the dominance of internal combustion engines. Likewise, national strategies for energy independence and industrial leadership—especially in China—serve as strong landscape-level drivers shaping technological development.

The regime level comprises the stable, dominant socio-technical system that resists change through co-evolution and mutual reinforcement. In the heavy truck industry, the Diesel Dominator regime includes a tightly linked network of technologies (diesel engines, fuel injection systems, mechanical gearboxes, transmissions, and power trains), infrastructure (a global network of diesel refueling stations), institutions (regulatory standards, driver licensing), and actor networks (OEMs like Daimler and Volvo, component suppliers like Bosch, and fossil fuel companies) [1]. This regime shows significant inertia, often called "carbon lock-in," where the interdependence of its components creates strong resistance to radical innovations [15]. The value of the Diesel Dominator lies in its maturity, reliability, and worldwide reach, but its future is increasingly threatened by the same landscape pressures it was meant to address. Its persistence is not due to technological superiority but to the strength of its systemic embedment, which makes incremental improvements more attractive to many Western players than disruptive change.

In contrast, radical innovations develop at the niche level, protected from full market competition and regime rivalry. Niche innovations are often less efficient or more expensive at first, but they can introduce a fundamentally different approach. The Electric Steward, The Green Transformer, and The Interconnected Autonomous Innovator exemplify such niches in this analysis. These new vehicles and socio-technical setups challenge the core logic of the current regime. For instance, the development of battery swapping in China is more than just a new charging method; it is a systemic innovation that redefines how the vehicle, energy supply, and logistics operations interact [5]. These niches are supported through strategic niche management, a process that involves deliberate experimentation, learning, and scaling, often aided by government intervention, targeted funding, and the creation of protected markets [16].

The core of the MLP is the dynamic interaction among these three levels. A transition happens when a niche innovation, through learning and development processes, aligns with shifting landscape pressures and outcompetes or reconfigures the existing regime. This can follow different paths, including technological substitution, reconfiguration, or de-alignment followed by re-alignment [13]. Analysis of the five truck typologies shows that the current transition is not just a simple shift from diesel to electric powertrains, but a process of system reconfiguration. The Green Transformer isn't just an electric version of the Diesel Dominator; it is a new system based on different principles of integration, flexibility, and servitization. Its success depends on aligning multiple functions within an innovation system, such as entrepreneurial activities, knowledge development, market formation, resource mobilization, and legitimation [17].

This framework also supports the analysis of path dependence and increasing returns, concepts that explain why certain technological trajectories become dominant [18]. The dominance of the Diesel Dominator in the West resulted from early investments in diesel technology, fuel infrastructure, and engineering expertise, creating a self-reinforcing cycle of development and adoption. Conversely, China's strategy aims to break this dependence and establish a new one focused on electrification and systemic integration. This is not a matter of technological convergence but of diverging innovation paths shaped by different institutional logics and policy environments [19]. The Chinese government acts not only as a regulator but also as a key system integrator, coordinating industrial policy, energy strategy, and urban planning to promote a new technological regime [10].

Additionally, the MLP is enhanced by concepts from actor-network theory [20], which emphasizes the role of various actors—both human and non-human—in shaping technological development. The Interconnected Autonomous Innovator, for example, is created by engineers and results from a network that includes AI algorithms, 6G networks, cloud platforms, and cybersecurity protocols. The framework also integrates framing and overflowing [21], acknowledging that different actors assign unique meanings to the same technology. For Western OEMs, autonomy might be viewed as a safety feature, while for Chinese tech firms, it is seen as a data-driven logistics platform.

This debate over meaning is central to the politics of technological change. By adopting this multi-faceted theoretical framework, this paper moves beyond simple description to provide an analytical tool for understanding the systemic nature of technological change in the heavy truck industry. It demonstrates that the rise and persistence of each typology are not due to isolated technological advantages but stem from the complex interaction of landscape pressures, regime inertia, niche innovation, and deliberate governance. This framework clearly explains how and why different technological pathways emerge, persist, and compete, especially amid the increasing divergence between Western and Chinese development models.

4. Results—Towards a Typology of Technological and Systemic Transformation

4.1. Introduction

The evolution of heavy-duty trucks is not a straightforward progression of engineering milestones, but a complex, multi-layered process of socio-technical change shaped by the interaction of technological innovation, institutional structures, economic needs, and geopolitical struggles. While the industry is often told through a chronological lens—highlighting the shift from steam to diesel, and from manual to automated systems—such narratives risk oversimplifying a reality marked by the coexistence, competition, and blending of multiple technological regimes. This chapter proposes a typological framework that captures this complexity by identifying five distinct generational archetypes: *The Mechanical Workhorse*, *The Diesel Dominator*, *The Electric Steward*, *The Green Transformer*, and *The Interconnected Autonomous Innovator*. These are not just phases in a historical timeline, but analytically strong socio-technical regimes, each characterized by a consistent set of technologies, infrastructure, organizational structures, and system integration. Based on the Multi-Level Perspective (MLP) of socio-technical transitions [6], this typology critically explains how different pathways form, stabilize, and compete across various institutional and geographical settings.

The first generation, from the late 19th to the early 20th century, is characterized by The Mechanical Workhorse. These early vehicles were simple mechanical carriers, directly based on horse-drawn carriages, powered by internal combustion engines. Their design prioritized durability and load capacity over efficiency, comfort, or safety, reflecting the early stage of automotive engineering and the immediate logistical needs of industrialization and military mobilization [22]. Development was driven by individual inventors, craftsmen, and small manufacturers, with limited standardization and no formal regulatory framework. Despite their technological simplicity, these vehicles laid the groundwork for all future heavy-duty vehicles and paved the way for innovation. The appearance of Karl

Benz's DRP 37,435 patents in 1886 was a significant milestone during this phase, establishing the foundation for motorized freight. However, these early systems were isolated artifacts, lacking the systemic integration that would characterize later eras.

The second phase was characterized by growth and standardization from the 1930s to the 1950s. During this period, the West's trucking industry saw significant consolidation, especially as the post-World War II economic boom created unprecedented demand for efficient logistics. The diesel engine emerged as the primary power source, offering better fuel economy and more torque for heavy freight tasks [23]. Companies like Daimler, Volvo, and Scania advanced their manufacturing, resulting in more reliable vehicles and the expansion of global supply chains. This period laid the institutional and technological foundation for what would become The Diesel Dominator—a system marked by hybrid mechanical-electrical systems, centralized manufacturing, and ongoing innovation driven by competition and regulation (Daimler Truck AG, 2023). The development of automated transmissions, such as Volvo's I-Shift, showcased this era's focus on improving driver comfort and operational efficiency [22]. This system was not solely about technology but also involved a socio-technical network connected with fuel stations, service centers, and regulations that reinforced its dominance.

The third phase, from the 1960s to the 1990s, marked an era of modernization and specialization. Trucks became more advanced, with innovations in aerodynamics, braking systems, and driver safety that enhanced both performance and reliability. During this period, the market fragmented, leading to the emergence of The Electric Steward—vehicles designed for specific, high-demand applications such as mining, construction, and refrigerated transport. These trucks featured custom chassis, reinforced suspensions, and application-specific software, optimized for extreme durability and operational efficiency. Development was driven by OEMs working closely with end-users, supported by a network of component suppliers and engineering firms. This phase demonstrated how a dominant technological regime could diversify into sub-regimes, each tailored to a particular function, yet still dependent on the broader diesel-based infrastructure. The continued presence of The Diesel Dominator during this time reflects the concept of "carbon lock-in" [15], where entrenched systems resist radical change due to the co-evolution and mutual reinforcement of their technological, economic, and institutional components.

The fourth phase, spanning from the 2000s to the 2010s, was marked by globalization and efforts to promote sustainability. As environmental concerns grew, regulatory agencies in Europe and North America enforced stricter emissions standards, leading to the creation of Euro norms. These standards prompted manufacturers to innovate in engine design and after-treatment technologies [14]. This period also saw China's rise in the global truck industry. Initially relying on technology transfer and joint ventures, Chinese companies such as Sinotruk, Foton, and Dongfeng quickly modernized, leveraging government support and large domestic markets to achieve economies of scale. While Western innovation mainly focused on advancing the internal combustion engine, the foundation for a new approach was being laid. The Chinese government began to see itself as a regulator and system integrator, combining industrial policy, energy strategy, and urban planning to develop a new technological pathway toward clean and fossil-free energy. The search for a new technological direction—a new paradigm—was also initiated to create opportunities for developing independent domestic technologies and trucks.

The period from 2020 to the present marks the Green & Autonomous Revolution. This era is defined by a major challenge to the diesel-powered system, driven by the urgent need to decarbonize transportation. Two new types have emerged. The first is The Green Transformer, a model that has gained significant traction in China. Characterized by full electrification and innovative energy solutions like battery swapping, this type represents a systemic, ecosystem-based approach to innovation. Unlike the gradual electrification seen in the West, the Chinese model emphasizes rapid deployment, scalability, and institutional coordination, with the government serving as a key system integrator [4] [10]. Battery-swapping networks, developed in partnership with Chinese energy companies such as State Power Investment Corporation (SPIC), enable continuous operation in high-utilization corridors, bypassing the limitations of ultra-fast charging infrastructure. This model challenges the idea that technological superiority equates to novelty, emphasizing the importance of systemic integration and contextual relevance.

The second emerging typology is the Interconnected Autonomous Innovator, a vehicle that is not just a mode of transportation but a software-defined, AI-controlled platform connected to surrounding systems. Still in the pilot phase, this typology relies on a complex stack of sensors, radar and lidar, cameras, machine learning algorithms, and cloud control systems, promising a future of self-driving freight [24]. Its development is led by tech-focused companies such as Tesla, DeepWay, and WindRose, often working with logistics firms. Unlike earlier typologies, the value of the Interconnected Autonomous Innovator extends beyond physical transportation to data, connectivity, and predictive analytics. Its success depends on technological maturity, regulatory approval, and public trust. This typology shows the shift from hardware-focused to software-driven innovation, where the truck becomes part of a digital, autonomous-operated logistics system.

This typology of generational evolution shows that the history of heavy trucks is not just a simple story of progress but a dynamic interaction between technological lock-in and radical innovation [15]. The continued presence of *The Diesel Dominator* alongside the rise of *The Green Transformer* and *The Interconnected Autonomous Innovator* illustrates a multi-path transition process. Each typology represents a coherent socio-technical regime, shaped by a unique combination of technology, infrastructure, organizational structure, and institutional support embedded in a political, institutional, regulatory, and commercial context.

The framework also highlights a major geopolitical divide: while Western innovation is often driven by market competition and private R&D, leading to fragmented and slower deployment, China's coordinated and collaborative approach enables large-scale, systemic change [19]. This sets the stage for the comparative analysis in Chapter 3, which examines each typology in detail and directly results in the creation of Table 1.

Table 1. Categorizes five types of heavy trucks and identifies each type using distinguishing features.

Discriminating Aspects	Type 1: The Mechanical Workhorse	Type 2: The Diesel Dominator	Type 3: The Electric Steward	Type 4: The Green Transformer	Type 5: The Interconnected Autonomous Innovator
Key Technology	Mechanical powertrain based on internal combustion engines (ICE).	Hybrid mechanical-electric powertrain with integrated batteries and mechanical gearbox and powerr train.	Fully electric powertrain with software-driven vehicles, optimized for new vehicle platforms.	Advanced electric powertrain with multi-energy sourcing (battery swapping, hydrogen, cable charging), modular and flexible design.	Software-defined vehicles with autonomous driving, AI integration, cloud computing, interconnected, and extended system solutions for logistics.
Dominant Technology	Diesel trucks based on ICE platform.	Electric trucks built on existing ICE platforms with hybrid powertrains.	Electric trucks designed from scratch for optimal performance, efficiency, and software integration.	Electric trucks with integrated energy systems, flexible battery designs, and advanced autonomy features.	Intelligent trucks with full autonomy, real-time data exchange, and seamless integration into logistics ecosystems.
Energy Sourcing and Management	ICE, diesel fuel.	Integrated batteries with limited range; reliance on hybrid systems.	Integrated batteries with improved range and efficiency; fully electric operation.	Integrated vehicle system solutions combining battery swapping, hydrogen refueling, and cable charging.	Integrated vehicle-environment system solutions with extended logistics supplier-customer integration and energy optimization.
Technological and Organizational Complexity	Low.	Low to Medium.	Medium.	High.	Very High.
Role of Software and Intelligence	Extra features (e.g., diagnostics, basic electronics).	Adds functions such as battery management and energy optimization.	Key technology integration; software controls core vehicle functions.	Software-integrated vehicle with advanced energy management and connectivity.	Software-defined vehicle with AI, cloud computing, and autonomous decision-making capabilities.

Continued

Battery Swapping	No.	Yes, introduced as a new technology route.	Yes, determined during the design phase for flexibility.	Yes, flexible battery design with options for swapping, hydrogen refueling, and cable charging.	Yes, flexible battery design with options for swapping, hydrogen refueling, and cable charging.
Battery Swapping Initiative	Not relevant.	Energy company SPIC initiates early adoption of battery swapping.	Battery producer CATL leads development of standardized swapping solutions.	OEMs like DeepWay and WindRose develop system-level solutions for battery swapping and energy sourcing.	OEMs like DeepWay and WindRose integrate battery swapping into intelligent logistics systems.
Interconnectivity	No.	Limited; supports basic charging infrastructure.	Limited; supports advanced charging infrastructure and fleet management.	Integrated with roads, cities, and business functions for seamless logistics operations.	Software-driven extended system integration, connecting vehicles, operators, customers, roads, and cities in real-time.
Charging Solutions	No.	External suppliers provide basic charging infrastructure.	OEM-developed solutions tailored for specific use cases.	OEM-developed solutions integrating multiple energy sources (battery swapping, hydrogen, cable charging).	OEM-developed solutions leveraging AI, big data, and 6G for intelligent energy management and logistics optimization.
Commercially Available	Now, with declining sales of pure diesel solutions due to stricter emissions regulations.	Now, shifting to hybrid solutions as a transitional technology.	2023-2024; expected to dominate medium- and long-haul freight.	2025; expected to become mainstream for multi-energy sourcing and flexible logistics.	2023-2024; early adoption in autonomous urban logistics and geofenced areas.
Key Development Actors	OEMs (e.g., Volvo, Scania, Dongfeng).	OEMs, energy companies, and battery suppliers (e.g., Volvo, Scvania, Daimler).	OEMs, energy suppliers, and charging solution providers (e.g., Tesla Semi, Volta, CATL).	Software providers, energy companies, and OEMs (e.g., DeepWay, WindRose, SPIC, CATL, hydrogen suppliers).	Internet and AI technology suppliers (e.g., Baidu, Tencent, Google, Apple) collaborating with OEMs and logistics providers.

Continued

Key Suppliers and System Integration	Petrol companies (BP, Shell), injection system manufacturers (Bosch).	Battery suppliers (CATL), hybrid system providers, and charging infrastructure developers.	Battery suppliers (CATL), charging infrastructure developers, and software integrators.	Battery suppliers (CATL), hydrogen & fuel cell suppliers, energy providers, and 6G network operators.	Big data, cloud system providers, AI-supported solutions, and 6G network operators (e.g., Baidu, Tencent, CATL).
Dominant Brands	Volvo, Scania, Dongfeng, MAN, Mercedes-Benz.	Volvo, Scania, Einride, Foton, Sany.	Tesla Semi, Volta, BYD Q3, XPENG Motors.	WindRose, JAC, Geely Farizon, DeepWay.	DeepWay, Farizon, Nuro, PlusAI.
Business Model of Dominant Brands	Selling points: horsepower and freight weight; focus on hardware sales.	Selling points: electric and hybrid solutions; shifting focus to greenification and sustainability.	Selling points: system integration of vehicles and charging solutions; servitization of green services.	Selling points: services, functionality, flexibility, and adaptability; extended servitization of green services.	Selling points: unmanned truck business models, total system solutions, and extended servitization of green services.

Source: Authors.

4.2. A Systemic Application of Socio-Technical Transitions Theory—Creating the Typology of Heavy Trucks

The evolution of heavy-duty trucks showcases a dynamic interaction between technological progress, socio-economic shifts, and environmental objectives. Each type illustrates different phases of human creativity, industrial growth, and societal change, from the basic Mechanical Workhorse to the sophisticated Interconnected Autonomous Innovator. This analysis explores the main features of these types, emphasizing their technical bases, energy sources, organizational complexity, software systems, refueling and charging methods, and main development contributors. By understanding these elements, the paper moves beyond a simple timeline to offer a systemic classification framework that highlights structural diversity and the coexistence of various technological regimes within the global freight industry.

The idea that a single technological solution can meet the diverse operational, environmental, and economic needs of global freight transport is becoming less realistic. The development of heavy trucks varies depending on specific logistical needs, regulatory environments, infrastructure, and market conditions. In long-haul transport across North America, the main focus remains on fuel efficiency and driver comfort, supporting the continued use of diesel systems. Conversely, urban delivery in large cities like Shenzhen or Shanghai emphasizes zero-emission operations, high utilization, and minimal downtime, creating opportunities for battery-electric and battery-swapping options. Similarly, the needs of mining or construction industries require vehicles built for extreme durability and custom configurations, while the growth of smart logistics corridors in Europe and the U.S. encourages experimentation with autonomous platooning.

This variability emphasizes the limitations of a "one-size-fits-all" approach to truck development. The future of freight isn't a single destination but a landscape of coexistence and competition among various technological paradigms. The proposed typology is therefore intended to reflect this diversity. It is based on the socio-technical transitions (STT) framework, especially the Multi-Level Perspective (MLP), which considers technological change as the interaction among landscape pressures, stable regimes, and emerging niches [6] [25]. This framework helps pinpoint key features that define each typology, moving beyond isolated technical details to include the broader systemic contexts in which trucks operate. These features include the dominant technology, energy sourcing, and charging infrastructure; the role of software intelligence; organizational complexity; and the key actors and system integrators involved in development. The resulting classification doesn't represent a series of generations but a map of coexisting regimes, each providing a coherent response to specific contextual challenges.

The five typologies of heavy-duty trucks—The Mechanical Workhorse, The Diesel Dominator, The Electric Steward, The Green Transformer, and The Interconnected Autonomous Innovator—are more than just categories of technological generations. They represent distinct socio-technical regimes, each characterized by a unique combination of technological, organizational, and institutional factors. This chapter offers a comprehensive, theory-based analysis of these typologies by systematically applying the Socio-Technical Transitions (STT) framework introduced in Chapter 5. The Multi-Level Perspective (MLP) serves as the primary analytical tool, providing a deeper understanding of how each typology developed, stabilized, and interacted with the broader landscape of pressures and opportunities. The analysis proceeds chronologically from Type 1 to Type 5, demonstrating that the core concepts of the theoretical framework—landscape pressures, regime inertia, niche innovation, strategic niche management, and system integration—are not only present but also actively influence the industry's observed evolution.

Type 1: The Mechanical Workhorse—The Foundational Regime

The Mechanical Workhorse is the basic model of the modern heavy-duty truck, appearing in the late 19th and early 20th centuries. This model features a mechanical drivetrain powered by an internal combustion engine (ICE), relying solely on fossil fuels and lacking electronic control systems. Its technology and organization were simple, reflecting an era of isolated inventions by individuals like Karl Benz and Gottlieb Daimler [1] [26]. Software and smart systems were not involved; interconnectivity was absent, and charging stations were not yet relevant. Major brands, including Volvo, Scania, MAN, and Mercedes-Benz, primarily competed based on hardware specifications such as horsepower, load capacity, and durability. The business model focused solely on transaction sales of a physical product. From the perspective of the perspective, this regime directly responded to the demands of industrialization and military mobilization, which required replacing animal-powered transport. It established key design principles for heavy trucks—chassis design, axle setup, and cargo systems—that became the "DNA" of all subsequent developments [2]. However, its separation from larger systems and lack of integration made it vulnerable to more advanced regimes. Its persistence was not because it was better, but because no better options existed, making it a classic example of an initially stabilized regime within a growing socio-technical system. This phase can also be viewed through the concept of "technological momentum" [27], where early choices set a path that future innovations follow, embedding a specific technological logic within the industry.

The Mechanical Workhorse forms the core socio-technical system of the heavy-duty truck industry, emerging in the late 19th and early 20th centuries. This type features a purely mechanical drivetrain powered by the internal combustion engine (ICE), relying solely on fossil fuels with no electronic control systems. The technological and organizational complexity was minimal, reflecting an era of isolated technological artifacts created by individual inventors and early automakers such as Karl Benz and Gottlieb Daimler [1] [26]. Software and intelligence played no role, interconnectivity was nonexistent, and charging infrastructure was irrelevant. The leading brands—Volvo, Scania, MAN, and Mercedes-Benz—competed on hardware features such as horsepower, load capacity, and durability. The business model was strictly transactional, focused on selling a physical product. From the MLP's perspective, this system was a direct response to the pressures of industrialization and military mobilization, which required replacing animal-powered transport. It established the fundamental principles of heavy truck design—chassis, axle configuration, and cargo integration—that became the "DNA" of all subsequent developments [2]. This system exemplifies an initially stabilized structure, in which technological choices were made amid low complexity and high uncertainty. Its durability was not due to inherent superiority but to the lack of viable alternatives, making it a typical example of an initial system stabilizing in response to its environment. The lack of integration with broader systems foreshadowed its eventual vulnerability to more advanced regimes capable of delivering greater efficiency and reliability.

Type 2: The Diesel Dominator—The Era of Incremental Refinement

The rise of the Diesel Dominator marked a major evolution of the existing regime, driven by landscape pressures from post-World War II technological development, economic growth, and the demand for more efficient, reliable, and scalable freight transportation. This typology, dominant from the 1930s to the 1990s, was characterized by the widespread adoption of diesel engines, turbocharging, and hydraulic braking systems, resulting in a mechanical-electric hybrid system. The regime was stabilized and reinforced by a centralized network of Western OEMs such as Daimler, Volvo, and Scania, supported by complex global supply chains and an extensive network of diesel refueling stations [28]. Organizational complexity increased to a medium level, reflecting the scale and sophistication of technologies of heavy trucks, manufacturing, suppliers, and logistics systems. Software began playing a supporting role with the introduction of engine management units and basic telematics, but it remained a tool for optimizing mechanical systems rather than a core component. The primary development actors were these established OEMs, which worked closely with regulatory agencies that drove incremental innovation through increasingly strict emissions standards, such as the Euro norms [14]. This regime exemplifies the concept of "carbon lock-in" [15], in which the interdependence of technology, infrastructure, and institutions creates strong inertia against radical change.

The persistence of the Diesel Dominator highlights the strength and resilience of regime-level stabilization and its resistance to change toward electrification, with small improvements favored over disruptive innovation. This period also illustrates the concept of "regime branching," where a stable system evolves by creating specialized variants to meet different market needs [25]. The regime's resilience stems from its "functional differentiation," in which various actors—OEMs, suppliers, regulators, and fuel companies—play distinct yet complementary roles, forming a strong, self-reinforcing system.

The continued dominance of The Diesel Dominator is a testament to the strength of regime-level stabilization, where small improvements are favored over disruptive innovation. This period also illustrates the concept of "regime branching," in which a stable system evolves by creating specialized variants to meet diverse market needs [25]. The regime's resilience stems from its "functional differentiation," in which different actors—OEMs, suppliers, regulators, and fuel companies—play distinct yet complementary roles, thereby creating a strong, self-reinforcing system. The dominance of this regime in the West reflects an innovation model based on engineering excellence and incremental refinement, which has proven highly effective within the current system's limits but less so in addressing systemic challenges, such as decarbonization.

Type 3: The Electric Steward—Strategic Diversification within the Regime

The Electric Steward signifies a strategic diversification within the dominant system, rather than a direct challenge to it. Emerging from the 1960s to the 1990s, this category responded to industry pressure for increased operational efficiency in high-demand, niche markets such as mining, construction, and refrigerated transport. These trucks featured custom chassis, reinforced suspensions, and application-specific engineering, often with hybrid powertrains and early digital monitoring systems. The organizational complexity was high, requiring close cooperation among OEMs, engineering firms, and end-users. Software played a larger role, with application-specific programs enabling monitoring and performance optimization. While still relying on the broader diesel infrastructure, this category demonstrated the system's ability to differentiate and adapt internally. It operated as a protected sub-niche within the larger system, where innovation could occur without threatening the core system. The development of The Specialized Performer illustrates the concept of "regime branching," where a stable system evolves by creating specialized variants to meet diverse market needs [25]. Notably, Chinese manufacturers such as Sinotruk, Foton, and Dongfeng began establishing their presence, leveraging government support and large domestic demand to develop vehicles tailored to China's extensive infrastructure projects. Their entry into this sub-region marked a shift from followers to proactive participants, laying the groundwork for future leadership.

This phase demonstrated a pragmatic approach to innovation, where new technologies were adopted not for their novelty or value creation, but for their ability to address specific operational challenges, such as noise reduction in urban construction or zero-emission operations in underground mines. This exemplifies "user-led innovation" [29], in which the needs of end users in demanding environments drive the development of new technological configurations.

The Electric Steward represents a strategic diversification within the dominant system rather than a direct challenge to it. Emerging from the 1960s to the 1990s, this category responded to market pressure to enhance operational efficiency in high-demand niche applications such as mining, construction, and refrigerated transport. These trucks featured custom chassis, reinforced suspensions, and application-specific engineering, often including hybrid powertrains and early digital monitoring systems. The organizational complexity was high, requiring close cooperation among OEMs, engineering firms, and end-users. Software played a key role, with application-specific programs enabling monitoring and performance optimization. Although still relying on the broader diesel infrastructure, this typology demonstrated the regime's ability to internally differentiate and adapt. It served as a protected sub-niche within the dominant system, allowing innovation without threatening the core. The development of The Specialized Performer illustrates the concept of "regime branching," where a stable system evolves by creating specialized variants to meet diverse market needs [25]. Significantly, this is when Chinese manufacturers such as Sinotruk, Foton, and Dongfeng began asserting their presence, leveraging state support and large domestic demand to develop vehicles suited for China's extensive infrastructure projects. Their entry into this sub-regime marked the shift from followers to active participants, laying the groundwork for future leadership.

This phase reflected a practical approach to innovation—adopting new technologies not just for novelty but to solve specific operational challenges, such as reducing noise in urban construction or achieving zero-emission operation in underground mines. This exemplifies "user-led innovation" (von Hippel, 1986), where end-user needs in demanding environments drive the development of new technological solutions. The Chinese approach to this typology was notable in its scale and alignment with national development goals, foreshadowing the systemic model that would dominate in later generations.

Type 4: The Green Transformer—A Radical Niche and Systemic Leap

The Green Transformer marks a significant shift from the current system, emerging as a true niche innovation in the 2020s in direct response to increasing concerns about climate change and energy security. This type, mainly developed in China, features a fully electric drivetrain and a systemic, ecosystem-oriented approach to innovation. Its key characteristic is the integration of battery swapping, a technology developed and utilized almost exclusively by Chinese companies.

Unlike the Western focus on incremental electrification with ultra-fast charging, the Chinese model emphasizes operational uptime and scalability, with battery swapping networks built in partnership with state-owned energy companies such as the State Power Investment Corporation (SPIC) [5]. This initiative is not just a minor technology but a core element of a new socio-technical regime. It involves high organizational complexity, bringing together a coordinated ecosystem of automakers, battery manufacturers like CATL, energy providers, and grid operators. Software integration supports fleet management and energy optimization. This type exemplifies "strategic niche management" [16], where a new innovation is nurtured and protected through deliberate policy actions, infrastructure investments, and market development.

The Chinese government acts not just as a passive regulator but as a collective coordinator and system integrator, coordinating industrial policy, energy strategy, and urban planning to foster a self-reinforcing ecosystem for electric freight [10]. This exemplifies a form of "collective-led co-created innovation" [19], where the government actively supports technological development to achieve strategic national goals. The success of The Green Transformer challenges the idea that innovation is confined to the West, highlighting a parallel, potentially more scalable way to improve environmental outcomes and decarbonization. This approach is a form of technological leapfrogging, enabling China to bypass the technological and infrastructural dead ends of the West and move directly toward a more integrated and resilient system.

The Green Transformer marks a significant shift from current systems, emerging as a specialized innovation in the 2020s to tackle increasing concerns about climate change and energy security. Mainly developed in China, this model features a fully electric drivetrain and an ecosystem-based approach to innovation. Its most notable feature is the integration of battery swapping, a technology developed and used nearly exclusively by Chinese companies. Unlike the incremental electrification seen in the West, which emphasizes ultra-fast charging, the Chinese model focuses on operational uptime and scalability, with battery-swapping networks built through partnerships with state-owned energy firms such as the State Power Investment Corporation (SPIC) [5]. This is not just a minor technology but a central element of a new socio-technical regime. It involves high organizational complexity, uniting a collective-coordinated ecosystem of automakers, battery producers such as CATL, and energy providers. Software plays a vital role, supporting fleet management and energy optimization. This initiative exemplifies "strategic niche management" [16], where a new innovation is nurtured and protected through targeted policy efforts, infrastructure investments, and market development. In China, the government acts not just as a regulator but as a key system integrator, aligning industrial policies, energy strategies, and urban planning to foster a self-sustaining ecosystem for electric freight [10]. This illustrates a form of "collective-led and coordinated innovation" [19], where the government actively guides technological development to meet national strategic goals. The success of The Green Transformer challenges the idea that innovation mainly originates in the Global North, highlighting an alternative, potentially more scalable approach to decarbonization. This approach exemplifies technological leapfrogging, enabling China to bypass technological and infrastructural dead ends faced by the West and move directly toward a more integrated and resilient system. Leading companies like DeepWay and WindRose have shifted their business models from hardware sales to servitization, offering comprehensive system solutions and performance-based service contracts deeply rooted in their clients' operational realities.

Type 5: The Interconnected Autonomous Innovator—The Converging Niche of the Future

The Interconnected Autonomous Innovator is the most advanced niche, currently in its early growth stage but potentially ready to become the next dominant regime. This typology envisions trucks as software-defined, AI-guided platforms capable of self-driving, predictive maintenance, and real-time route optimization, connected with the environment, other vehicles, and roads. Its development is led by tech-forward companies such as Tesla in the West, and DeepWay, WindRose, and Baidu's Apollo in China. The organizational complexity is very high, involving a decentralized network of data platforms, AI developers, and cybersecurity providers. Unlike previous typologies, the value of the Interconnected Autonomous Innovator extends beyond physical transportation to goods, data, connectivity, and predictive analytics. Its success depends on technological maturity, regulatory approval, public trust, and access to clean energy and electricity. From an STT perspective, this typology is currently in the "niche development" phase, undergoing experimentation and learning. Its future will depend on its ability to adapt to changing landscape pressures and to outcompete or reconfigure the existing regime. A key observation is the convergence of this niche with The Green Transformer in China, where autonomous electric trucks are being tested on routes with battery-swapping stations. This integration of electrification and autonomy within a unified, collectively coordinated framework gives Chinese developers a strategic advantage as they build an ecosystem in which these technologies reinforce each other. In contrast, Western developers often treat them as separate challenges, leading to fragmented solutions with longer development and scaling times and extended manufacturing lead times. This convergence shows how a new regime can emerge not just through disruptive technology but also through the reconfiguration of multiple niches into a coherent, superior system [13]. This process is best understood as a "systemic innovation," where value is created by integrating various components into a new, higher-level system.

The Interconnected Autonomous Innovator represents the most advanced niche, still in the pilot phase but with the potential to become the next dominant regime. This typology envisions trucks as software-defined, AI-controlled platforms capable of self-driving, predictive maintenance, and real-time route optimization. The organizational complexity is very high, involving a decentralized network of data platforms, AI developers, and cybersecurity companies. Unlike previous typologies, the value of The Interconnected Autonomous Innovator lies not only in physical transportation but also in data, connectivity, and predictive analytics. Its success depends on technological maturity, regulatory approval, and public trust. From an STT perspective, this typology is currently in the "niche development" phase, undergoing experimentation and learning. Its future path will depend on its ability to adapt to changing landscape pressures and to out-compete or reconfigure the incumbent regime. A key observation is the convergence of this niche with The Green Transformer in China, where autonomous electric trucks are tested on routes with battery-swapping stations. The integration of electrification and autonomy within a unified, collective, coordinated framework gives Chinese developers a strategic advantage, as they build an ecosystem where these technologies reinforce each other, whereas Western developers often treat them as separate challenges. This convergence illustrates how a new regime can emerge not through a single disruptive technology but through the reconfiguration of multiple niches into a coherent, superior system [13]. This process can be viewed as a "systemic innovation," where value is created by integrating various components into a new, higher-order system. The dominance of Chinese firms in this converging niche stems from their ability to coordinate complex networks of technology, policy, and infrastructure—an increasingly vital skill for leadership in the 21st century.

In conclusion, this paper has developed a strong, context-aware typology to understand the structural diversity and systemic evolution of the global heavy truck industry. It has been shown that technological change is not a deterministic process but rather a contested, socially influenced phenomenon. The five typologies are not fixed endpoints but dynamic regimes in flux, shaped by the interaction of technological innovation, institutional structures, and geopolitical dynamics. This framework provides a valuable tool for researchers, policymakers, and industry stakeholders, offering a crucial perspective for navigating the complexities of industrial transformation. As the industry reaches a critical turning point, the ability to coordinate complex networks of technology, policy, and infrastructure will be vital for leadership in the 21st century. The decisions made today will greatly influence global freight for decades, and this typology lays the groundwork for understanding and guiding that transformation toward an efficient, sustainable, equitable, and resilient future.

4.3. Analysis of the Typology

The analysis of these typologies reveals a significant shift in how competition functions in the heavy-duty truck industry. It's no longer just about individual technologies or hardware specs, but about complete system solutions and companies' ability to connect them into coherent systems and operate in an interconnected way. With its fragmented, market-driven R&D, the Western approach struggles to bring together key players—OEMs, energy companies, telecom providers, and software developers—to form a cohesive ecosystem. In contrast, the Chinese model, with the government acting as a central coordinator, can align these players under a common strategy. This skill to integrate systems is quickly becoming the main factor determining industry leadership. The dominance of Chinese brands in emerging markets is driven not just by lower prices but also by their ability to offer a comprehensive, ready-to-use package, including vehicles, energy infrastructure, batteries, manufacturing and assembly lines, and service contracts. This all-in-one solution appeals much more to logistics companies seeking to reduce risk and maintain smooth operations than a high-performance but isolated electric truck with uncertain charging options. This shift is also evident in the evolution of business models. Moving from selling horsepower to offering mobility services marks a major change in what customers value. The servitization model, where value depends on total ownership costs, uptime, and performance-based agreements, is driven by customer testing and adaptation.

Chinese companies aren't developing technology in isolation; they are addressing real-world customer issues through rapid prototyping and deployment along high-utilization routes. Their focus on operational continuity rather than incremental technological improvements has been more effective in bringing products to market and fostering adoption. The ability to combine technologies into comprehensive system solutions—guided by customer needs and supported by government coordination—forms the core of China's strong position and explains why it can leap ahead technologically. As the industry moves toward fully integrated intelligent logistics networks, managing complex systems will play a key role in shaping the future of global freight.

The analysis of the five heavy truck typologies—The Mechanical Workhorse, The Diesel Dominator, The Electric Steward, The Green Transformer, and The Interconnected Autonomous Innovator—reveals a complex and dynamic industry undergoing a significant structural shift. This comparative analysis, based on the theoretical framework of Socio-Technical Transitions (STT) as outlined in Chapter 5 and applied in Chapter 6, shows that the development of heavy-duty trucks is not a straightforward path of technological progress but a multi-directional, contested process characterized by the coexistence, competition, and hybridization of different socio-technical regimes. Each typology represents a cohesive system of interconnected elements, including leading technologies, energy sources, software integration, organizational structures, and key industry players. By examining these typologies through the Multi-Level Perspective (MLP), this chapter provides a strong theoretical explanation of how landscape pressures, regime resistance, and niche innovations interact to shape the distinct trajectories of Western and Chinese innovation models.

The comparative analysis of the five heavy-duty truck types uncovers a significant and swift shift in the global freight industry, extending beyond simple technological updates to include a fundamental overhaul of innovation strategies, business models, and international leadership. By examining how key factors—such as primary technology, advanced technology, energy sources, software applications, battery swapping, connectivity, and business models—interact and how leading brands evolve, it becomes evident that a major shift in competitive dynamics is underway. This shift is characterized by the decline of Western dominance in incremental hardware improvements and the rise of Chinese leadership in system integration, servitization, and ecosystem-based innovation, with battery swapping becoming a critical technological and strategic differentiator.

At a basic level, the Mechanical Workhorse signifies a period of technological isolation and dominance of mechanical technology. Leading brands, including Volvo, Scania, MAN, and Dongfeng, competed based on physical features such as engine power, load capacity, and durability. The technology and organizational complexity were straightforward, with no role for software or connectivity, and energy was derived solely from diesel fuel. The business model was purely transactional, focusing on hardware sales. Although this type still exists in older fleets, its market importance is decreasing due to emissions regulations [14], and it mainly serves as a historical reference for how the sector has evolved.

The Diesel Dominator represented the peak of Western technological progress, with brands like Daimler, Volvo, and Scania establishing a system of high-precision engineering. This era introduced hybrid mechanical-electrical powertrains, including automated transmissions such as Volvo's I-Shift and Bosch's Common Rail injection system, which improved fuel efficiency and driver comfort [22], [30]. Organizational complexity rose to low or medium levels, supported by centralized manufacturing and global supply chains. Software played a secondary role, enabling basic telematics and engine management. However, the core value proposition remained hardware-focused, with brands competing on reliability, fuel economy, and driver comfort. The business model continued to emphasize hardware sales, although a new focus on sustainability emerged as emissions standards became stricter [28]. While Chinese brands like Foton and Dongfeng participated in this regime, they mainly did so through technology transfer and joint ventures, positioning themselves as cost-competitive alternatives rather than technological leaders.

The emergence of The Electric Steward marked the first major turning point, where innovation shifted from hardware to system integration. This type features fully electric powertrains built from the ground up, with software becoming essential for managing core vehicle functions. Brands like Tesla Semi and BYD Q3 exemplify this shift. Tesla, a Western company, introduced a software-driven approach to trucking, combining advanced battery technology with a vertically integrated charging network. However, its strategy continued to emphasize proprietary infrastructure and premium markets. Meanwhile, Chinese brands such as BYD, Sanny, Foton, and XCMG adopted a more systematic approach, integrating battery swapping into the vehicle architecture from the start. This was not just about charging but a strategic decision to prioritize operational uptime over charging speed, which is critical for high-utilization logistics. The push for standardization was led by battery giant CATL, which developed the EVOGO swapping platform to enable interoperability among different OEMs [5]. This collaboration between OEMs like Sanny, Foton, and XCMG and suppliers such as battery manufacturer CATL signals a shift toward open ecosystems—a model largely absent among Western competitors. The business model also evolved from hardware sales to the servitization of green services, in which value is created by integrating the vehicle and its charging solution.

The Green Transformer indicates a clear shift, with Chinese brands having caught up and now leading the market. This model features an advanced electric powertrain with multi-energy sources—battery swapping, hydrogen refueling, and cable charging—in a modular and adaptable design. Notably, battery swapping is a technology developed and implemented almost exclusively by Chinese brands and their ecosystem partners. Western manufacturers, including Daimler, Volvo, and Traton, have largely overlooked battery swapping in favor of ultra-fast charging, a strategy that reflects their engineering traditions but does not address the downtime challenges faced by heavy logistics operations. Conversely, Chinese OEMs like DeepWay and WindRose have made battery swapping a core feature, developing system-level solutions that integrate swapping stations with logistics planning and energy management. For instance, DeepWay's "Starship" model is designed for a 5-minute swap, enabling continuous operation on fixed routes. This is supported by a nationwide network of swapping stations, many of which were built in collaboration with state-owned energy companies, such as the State Power Investment Corporation (SPIC), which pioneered the early adoption of this technology [10].

The organizational complexity of The Green Transformer is high, involving a network of software providers, energy companies, and 6G network operators. The role of software is no longer secondary but essential, enabling advanced energy management and connectivity with urban infrastructure. Interconnectivity is integrated with roads, cities, and business functions, allowing seamless logistics operations. The main development players are no longer just OEMs but system integrators like DeepWay and WindRose, who coordinate the entire ecosystem. The leading brands—Geely Farizon, JAC, and Foton—are competing not on horsepower or range, but on services, functionality, flexibility, and adaptability. Their business model is one of extended servitization, offering total cost of ownership guarantees, battery leasing, and performance-based service contracts. This model is inherently scalable and is being exported to emerging markets in Southeast Asia, Africa, and Latin America, where Chinese brands are gaining significant market share due to their affordability and operational efficiency [31].

The most advanced typology, the Interconnected Autonomous Innovator, represents the pinnacle of this trend. Here, the truck is a software-defined, AI-controlled platform with full autonomy, enabling real-time data exchange and seamless integration into logistics ecosystems. While Western companies lead in autonomous technology, their efforts are often isolated, focusing on platooning or geofenced applications that rely on traditional charging methods. In contrast, Chinese developers are combining autonomy with the Green Transformer ecosystem. Companies like Baidu's Apollo and Pony.ai are testing autonomous electric trucks on dedicated highways alongside battery-swapping stations. This integration of electrification, autonomy, and swapping creates a uniquely strong and efficient system. The organizational complexity is quite high, involving internet and AI giants such as Baidu and Tencent, which provide cloud computing, big data analytics, and 6G connectivity necessary for real-time decision-making [24]. The key suppliers are no longer traditional automotive parts manufacturers but providers of digital infrastructure. The business model is shifting toward unmanned truck operations and comprehensive system solutions, where value is gained from data-driven logistics optimization, rather than just freight transport. Brands like DeepWay and WindRose are leading the way, demonstrating that freight's future is electric or autonomous and an integrated, intelligent network.

The competitive analysis between Western and Chinese brands shows a clear difference in strategic focus. Western manufacturers, such as Volvo and Daimler, continue to focus on incremental improvements to existing platforms, targeting the premium market with high-margin, reliable vehicles [32]. Their approach to electrification is cautious, emphasizing ultra-fast charging and hydrogen technologies that align with their engineering strengths but require significant, broad infrastructure investments. They have mostly ignored battery swapping, a decision that could prove strategically costly as operational uptime becomes increasingly important in logistics.

Chinese brands, in contrast, have adopted a disruptive, ecosystem-based approach. By embracing battery swapping, they have addressed the critical charging downtime bottleneck, enabling continuous operation. This represents a minor improvement and a systemic overhaul of the logistics value chain. Collaboration among OEMs (DeepWay, WindRose), battery producers (CATL), energy companies (SPIC), and tech firms (Baidu, Tencent) creates a self-reinforcing ecosystem that is difficult for Western competitors to imitate. This model is supported by strong national support, which shapes industrial policies, infrastructure investments, and regulatory frameworks [19]. Consequently, Chinese brands are not just competing on cost; they are shaping the next wave of freight transport through systemic integration and servitization.

In conclusion, the empirical evidence indicates that the future of the heavy-duty truck market will be shaped more by systemic resilience and integration than by isolated technological dominance. The shift from the Diesel Dominator to the Green Transformer and the Interconnected Autonomous Innovator is not just a change in powertrain, but a reimagining of the truck as part of a digital and energy network. Through their strategic focus on battery swapping and ecosystem-based innovation, Chinese brands are gaining ground and actively shaping the industry's future. The dominance of Western brands in hardware refinement is being replaced by a new model where the ability to coordinate complex systems of technology, policy, and infrastructure offers a competitive advantage. This transition signals a significant geopolitical shift, with China emerging as a leader in the next phase of sustainable and intelligent freight.

4.4. Concluding Remarks

The analysis in Chapters 2 and 3 reveals a major shift in heavy-duty truck development, moving from a simple, technology-focused story to a complex, socio-technical framework characterized by five distinct types. These types—The Mechanical Workhorse, The Diesel Dominator, The Electric Steward, The Green Transformer, and The Interconnected Autonomous Innovator—are not just sequential stages but represent complementary, coherent socio-technical regimes, each shaped by specific combinations of technology, infrastructure, organizational complexity, and institutional support. The factors listed in **Table 1** provide a strong analytical tool for comparing these regimes, demonstrating that the evolution of freight transport is increasingly driven not by isolated technological breakthroughs but by the systemic integration of vehicle, energy, software, and logistics ecosystems.

A key finding of this analysis is the major shift in innovation leadership from the Global North to China, starting with The Electric Steward and growing through The Green Transformer and The Interconnected Autonomous Innovator. While Western manufacturers have traditionally led with incremental engineering improvements and high-precision component development, exemplified by the Diesel Dominator regime led by firms like Daimler, Volvo, and Scania, their methods have been less effective in tackling systemic challenges such as decarbonization and operational scalability [22] [28]. Conversely, Chinese companies have used state-led industrial policies to build a model of systemic innovation, in which the government serves as a key system integrator, aligning industrial strategies, energy infrastructure, and urban planning to rapidly deploy new technologies [5] [19]. This approach is particularly clear in the development of battery swapping, which has moved from a marginal technology to a core part of The Green Transformer. Unlike the fragmented, market-driven charging networks in the West, China's coordinated rollout of swapping stations by leading electric power firms such as State Power Investment Corporation (SPIC) and battery leader CATL has created a scalable, high-volume model well-suited for dense urban logistics and long-haul routes [10].

The significance of software and intelligence further emphasizes this difference. In The Electric Steward, software begins to play a central role in vehicle control and energy management. However, software becomes the defining feature in The

Green Transformer and The Interconnected Autonomous Innovator. In these cases, vehicles are no longer standalone machines but nodes within a larger digital ecosystem, where AI, cloud computing, and real-time data sharing enable predictive maintenance, dynamic route optimization, and seamless integration with logistics platforms. The organizational complexity of these systems increases significantly, involving not only traditional OEMs but also internet and AI companies like Baidu and Tencent, energy providers, 6G network operators, and logistics providers [24]. This blending of sectors reflects a broader trend toward the servitization of mobility, in which value is generated from hardware sales, integrated services, adaptability, and operational uptime. The business models of leading brands such as DeepWay and WindRose, which focus on complete system solutions and extended servitization, demonstrate this shift (Yang *et al.*, 2023). Evidence from the commercial availability and deployment of these typologies suggests that systemic integration is becoming the main driver of competitive advantage.

Dominator remains common in Western markets; its future is limited by carbon lock-in and the high costs of retrofitting old systems to become sustainable [15]. In contrast, China's strategic investment in purpose-built electric platforms and multi-modal energy sourcing—combining battery swapping, hydrogen refueling, and cable charging—has positioned The Green Transformer as a flexible, scalable solution for mass adoption by 2025. Similarly, the early deployment of The Interconnected Autonomous Innovator in geofenced urban logistics demonstrates that integrating autonomy with electrification within a coordinated ecosystem is feasible—a goal that remains difficult in more fragmented Western markets.

Another key observation is the changing role of the main development actors. In earlier classifications, innovation was led by OEMs and component suppliers working within a mechanical engineering framework. As the sector has evolved, the focus of innovation has shifted toward system integrators—initially energy companies like SPIC during the Diesel Dominator phase, then battery producers such as CATL in The Electric Steward, and ultimately OEMs and tech firms in The Green Transformer and The Interconnected Autonomous Innovator. This shift marks a move from component-level innovation to platform-level coordination, where managing complex networks of technology, data, and infrastructure is essential for success. The dominance of Chinese brands in recent typologies is not due to the superiority of individual parts but to their skill in uniting different players into a cohesive, government-supported ecosystem.

In conclusion, the empirical findings across these chapters show that the future of heavy-duty trucking will depend not only on technological advances but also on systemic resilience, integration, and adaptability to different contexts. The presence of multiple typologies highlights a global industry in transition, with regions and markets following distinct paths shaped by their institutional frameworks, policies, and infrastructure priorities. China's rise as a leader in the latest truck technologies underscores a geopolitical shift in technological leadership, rooted in a government-coordinated innovation model that enables rapid scaling and systemic change. As the industry advances toward full electrification, autonomy, and digital connectivity, the main challenge will be ensuring this shift is not only technologically effective but also socially fair, incorporating just transition frameworks that address impacts on jobs, resource use, and energy justice [33].

The typology framework developed here offers a predictive and explanatory tool for understanding these developments, laying a foundation for future research into governance, ethics, and international standards for next-generation freight systems.

5. Discussion: Resilient, Interconnected Systems, Challenges and Future Directions

The Future of Freight: A Typology-Driven Perspective

The previous analysis, based on the theoretical framework of Socio-Technical Transitions (STT) and the Multi-Level Perspective (MLP), has established a clear typology for understanding the complex development of the heavy-duty truck industry. By dividing the sector into five distinct socio-technical regimes—The Mechanical Workhorse, The Diesel Dominator, The Specialized Performer, The Green Transitionist, and The Autonomous Innovator—this study has moved beyond a simple, technology-focused story to reveal a dynamic landscape of systems that coexist, compete, and hybridize. This final chapter builds on this typological analysis to offer a future outlook for freight. It argues that the industry's direction will not be driven solely by the progress of any single technology but by the systemic integration, resilience, and adaptability of the emerging socio-technical regimes. The future of freight is being reshaped not just by hardware but by coordinating technology, policy, and infrastructure into comprehensive, customer-focused solutions.

Type 1: The Mechanical Workhorse—A Legacy System in Decline

The Mechanical Workhorse, characterized by its mechanical drivetrain and complete dependence on fossil fuels, serves as the industry's foundational system. While its core architectural principles remain embedded in subsequent developments, the typology itself is a legacy system in irreversible decline. Its low technological and organizational complexity, lack of software integration, and absence of charging infrastructure make it fundamentally incompatible with the growing pressures of climate change, digitalization, and sustainability. As emissions regulations tighten worldwide, exemplified by the European Union's Euro VII standards and similar policies in North America and China, the commercial viability of pure diesel solutions is decreasing [14]. This typology persists only in niche applications or in regions with underdeveloped infrastructure, serving as a historical reference rather than a viable future path. Its trajectory is one of managed phase-out, driven by regime de-alignment as the socio-political and environmental costs of operating it become unsustainable. The MLP framework shows that such legacy regimes don't disappear overnight; instead, their influence diminishes as landscape pressures grow and niche innovations strengthen, ultimately leading to a transition.

Type 2: The Diesel Dominator—Incremental Refinement and Eventual Obsolescence

The Diesel Dominator, with its hybrid mechanical-electrical powertrain and centralized manufacturing approach, represents the pinnacle of Western engineering achievement. However, its future is likely to be marked by gradual improvements followed by decline. This system, supported by a global network of OEMs, suppliers, and refueling infrastructure, shows significant inertia—a phenomenon known as "carbon lock-in" [15]. This lock-in has enabled decades of incremental advances in engine efficiency and emissions control. Yet, this very strength is becoming its biggest weakness.

The system's heavy dependence on fossil fuels makes it increasingly vulnerable to shifts in climate policy and energy security issues. While hybrid solutions and transitional technologies, like integrated batteries, provide only short-term relief, they fall short of the deep decarbonization needed. Although extensive, this system's organizational complexity is mainly focused on hardware and component integration rather than on systemic solutions such as energy management and digital connectivity. Therefore, the Diesel Dominator will likely serve as a transitional phase—a bridge from the past to the future—and cater to specific niche markets that are difficult to electrify. Its legacy will be one of reliability and efficiency, but its long-term survival depends on its ability to evolve into a new configuration—a change the current Western innovation model has struggled to achieve.

Type 3: The Electric Steward—A Bridge to the Future

The Electric Steward plays a unique role as a link between the current system and emerging markets. Characterized by custom engineering and application-specific software, it was designed to increase operational efficiency in demanding environments like mining and construction. Its high organizational complexity, involving close cooperation among OEMs, engineering firms, and end-users, hints at future collaborative models. Notably, this marks the point when Chinese manufacturers began establishing a presence, supported by government efforts to develop vehicles for large-scale domestic infrastructure projects. This typology illustrates "regime branching," in which a stable system diversifies to meet new market demands [25]. Moving forward, the Electric Steward will not simply be replaced but will evolve. Mechanical and diesel parts will be phased out and replaced with fully electric drivetrains, advanced autonomous features, and integrated energy systems. The knowledge and collaborative practices developed within this subregime will be vital for successfully deploying The Green Transformer and The Interconnected Autonomous Innovator in complex, high-stakes environments. The evolution of this typology demonstrates the concept of "reconfiguration," where elements of an old regime are adapted and integrated into a new one, enabling a smoother transition [13].

Type 4: The Green Transformer—The Emerging Dominant Regime

The Green Transformer is not just a potential future; it is the emerging dominant system, especially within China's collective-led innovation model. Characterized by its fully electric drivetrain, multi-energy sources (including battery swapping, hydrogen, and cable charging), and high organizational complexity, this system represents a comprehensive, ecosystem-based approach to innovation. Its success results not from a single technological breakthrough but from the alignment of industrial policy, energy strategy, and urban planning, with the state serving as a key system integrator [10]. The integration of battery swapping, a technology almost exclusively developed and deployed by Chinese companies, is a strategic move that emphasizes operational uptime and scalability over charging speed, solving a vital bottleneck for high-utilization logistics [5].

This system exemplifies "strategic niche management," where a new innovation is nurtured and protected through deliberate policy measures and infrastructure investments [16]. The business model of leading brands like DeepWay and WindRose has shifted from hardware sales to servitization, offering comprehensive system solutions and performance-based service contracts. This model, which highlights the total cost of ownership and operational continuity, is increasingly appealing to fleet operators compared to the hardware-focused models common in the West. The commercial availability of this system, starting in 2025, indicates its transition from a niche to a mainstream market, particularly in Asia, Africa, and Latin America, where Chinese brands are gaining a sizable market share due to their affordability and operational efficiency [31].

Type 5: The Interconnected Autonomous Innovator

The Interconnected Autonomous Innovator represents the most advanced and transformative vision for the future of freight. This type envisions trucks not as isolated vehicles but as software-defined, AI-controlled platforms fully integrated into digital logistics ecosystems. Its development remains in the pilot stage, but its potential is enormous. The organizational complexity is very high, involving a decentralized network of data platforms, AI developers, and cybersecurity firms. The value derives not only from physical transportation but also from data, connectivity, and predictive analytics. From an STT perspective, this type is currently in a phase of "niche development," undergoing rapid experimentation and learning. Its future trajectory will depend on its ability to adapt to changing landscape pressures and to outcompete or reconfigure the existing regime. A key observation is the convergence of this niche with The Green Transformer in China, where autonomous electric trucks are being tested on routes with battery-swapping stations. This integration of electrification, autonomy, and swapping within a unified, collectively coordinated framework gives Chinese developers a decisive strategic advantage [24] (SAE International, 2023). This convergence exemplifies how a new regime can emerge not solely through a single disruptive technology but through the reconfiguration of multiple niches into a coherent, superior system

[13]. The future Autonomous Innovator will likely build on the energy and data infrastructure developed for The Green Transitionist, pointing toward a convergence into a single, software-defined platform. This dynamic interaction between types underscores that the future of freight is not a single endpoint but a complex, evolving system.

In conclusion, this paper has developed a robust, context-aware typology to understand the structural diversity and systemic changes in the global heavy truck industry. It demonstrates that technological change is not a predetermined process but a debated and socially influenced phenomenon. The five typologies are not fixed points on a timeline but active regimes in flux, shaped by the interplay of technological innovation, institutional frameworks, and geopolitical factors. This framework provides a valuable tool for researchers, policymakers, and industry stakeholders, enabling more detailed analysis of technological competition and informing scenario planning for sustainable logistics. The analysis indicates that the future of freight transport will depend not on a single most advanced technology but on integrated, resilient, and adaptable systems. As the industry faces a pivotal moment, the ability to coordinate complex networks of technology, policy, and infrastructure becomes increasingly crucial for leadership in the 21st century. The choices made today will shape global mobility for years to come, and this typology offers an essential perspective for understanding and directing that change toward an efficient, sustainable, equitable, and resilient future.

6. Conclusions

6.1. Systemic Integration over Component Superiority: How China's Ecosystem Approach Is Redefining Global Trucking Leadership

The traditional view of technological leadership in the automotive industry has long centered on excellence in components or sub-systems—such as engine efficiency, transmission design, fuel economy, or aerodynamics. However, this paper argues that this approach is increasingly outdated amid systemic challenges such as decarbonization, digitalization, and supply chain resilience. Future leadership will depend less on the quality of individual parts and more on integrating diverse technologies into a cohesive, functional ecosystem.

China's rise to dominance in the heavy truck sector isn't due to better individual parts, but to its unmatched ability to integrate systems. This is especially clear in the Green Transformer and Interconnected Autonomous Innovator models, where vehicles are more than just standalone machines—they're active parts of a larger network involving energy, data, and logistics. The Chinese government, acting as a main system integrator, coordinates industrial policy, energy infrastructure, and urban planning to create a self-sustaining innovation ecosystem (Wang and Liu, 2020; Zhang, Gallagher, and Karplus, 2014). This top-down, mission-driven approach allows for quick deployment of integrated solutions that would be impossible in the fragmented, market-driven environments typical of the West.

For example, integrating battery swapping—developed by CATL—with OEM logistics planning, such as DeepWay's, and energy supply from state-owned enterprises like SPIC creates a seamless operational environment for high-utilization fleets. This ecosystem approach ensures that technological development is not isolated but aligned with the practical needs of fleet operators, such as minimizing downtime and lowering the total cost of ownership. The Multi-Level Perspective (MLP) framework shows that such integration is a vital part of a successful transition, in which niche innovations (e.g., battery swapping) align with landscape pressures (e.g., climate policy) to challenge and transform the current regime [6]. China's model, therefore, represents a significant shift from component-based to system-based innovation, redefining what it means to have a competitive advantage in the global trucking industry.

6.2. From Hardware to Holistic Service: The Rise of Servitization in Chinese Heavy Trucking and Its Disruptive Impact on Western Business Models

The business model in the heavy-duty truck industry is experiencing a major shift, moving from a focus on selling products and hardware to a service-based approach that provides complete mobility solutions. This change, called servitization, is more than just adjusting prices; it involves a complete redefinition of the value offered. During the Diesel Dominator era, value was based on the truck's physical features—its horsepower, fuel efficiency, and durability. The sale was final: the customer purchased the truck, and the OEM's role largely ended there. However, the new Green Transformer and Interconnected Autonomous Innovator models focus on ongoing service relationships, where the OEM retains ownership of key components and provides a full range of vehicle, energy, and data services.

Chinese brands are leading in servitization driven by digitalization and connectivity. Companies like DeepWay and WindRose don't just sell trucks; they provide mobility-as-a-service. Their business models include battery leasing, performance-based service agreements, and guarantees on vehicle availability and uptime. This is enabled by integrating technologies such as battery swapping, which allows OEMs to maintain control over the battery's lifecycle. This helps them optimize charging, manage second-life applications, and ensure predictable service costs. Today, the value isn't in the vehicle itself but in the operational continuity and cost certainty it offers to the customer.

This model presents a direct and disruptive challenge to Western business models, which mainly focus on hardware sales. While Western OEMs are beginning to explore subscription services and digital features, these often remain optional rather than central to their offerings. In contrast, the Chinese approach is fundamentally different: the vehicle functions as a platform for delivering a service, with technology designed to support this model from the start. This shift highlights that new socio-technical regimes are technologically distinct and organizationally and economically separate. The MLP framework demonstrates that successful transitions include technological change and changes across the entire regime, including business models and institutional structures [13]. Therefore, China's adoption of servitization is not just a minor trend but a major factor in boosting its competitive advantage.

6.3. Battery Swapping as a Strategic Linchpin: How China's Infrastructure-Led Innovation Is Enabling Unmatched Operational Uptime and Market Scalability

Battery swapping is often dismissed in Western analyses as a niche or transitional technology, overshadowed by the pursuit of ultra-fast charging and longer-range batteries. However, this paper argues that battery swapping is not just a marginal feature but the strategic core of China's entire electric freight strategy. It is a deliberate, infrastructure-led innovation designed to address the most critical bottleneck in electric logistics: operational downtime. While a diesel truck can refuel in minutes, even the fastest chargers require a significant amount of time, making them impractical for high-utilization fleets that operate around the clock. Additionally, the mega chargers pose special challenges for the entire electric distribution system, given their local, high-power-capacity usage, which requires large-scale batteries or other electricity-balancing capacity—something that comes automatically with a battery-swapping system that offers cable charging, swapping, energy balancing, and energy storage.

China's approach to battery swapping is well-organized and coordinated. Unlike the market-driven, fragmented charging networks in the West, China's swapping infrastructure is built through a government-supported partnership involving OEMs, battery manufacturers, and energy companies. This encourages quick standardization, economies of scale, and nationwide deployment. For example, the EVOGO platform by CATL is designed to work with different vehicle brands, creating shared infrastructure that lowers costs and boosts convenience for fleet operators [5]. This level of coordination results from the government's role as a system integrator, aligning the interests of multiple stakeholders toward a common goal.

The strategic value of battery swapping lies in its ability to support a new business model focused on maximizing operational uptime. By reducing swap time to under five minutes, Chinese operators can achieve nearly continuous operation and three-shift operations, making electric trucks environmentally friendly and economically viable. This operational advantage enhances China's capacity to expand into emerging markets, where logistics efficiency is essential. From a theoretical perspective, battery swapping exemplifies "strategic niche management" [16], in which a new innovation is nurtured and protected through targeted policy measures and infrastructure investments. It does not compete on the same terms as the existing system; instead, it creates a new playing field where the rules of competition are based on integration and service, rather than just hardware.

6.4. Technological Leapfrogging in Action: China's Convergence of Electrification, Autonomy, and Digital Infrastructure as the Blueprint for the Future of Freight

The idea of technological leapfrogging—where a latecomer skips intermediate stages of development to adopt advanced technologies directly—is often discussed in the context of mobile phones in developing countries. This paper demonstrates that China is undergoing a similar leapfrog in the heavy-duty truck industry. Instead of following the Western approach of gradual electrification followed by autonomy, China is developing a convergent model in which electrification, autonomy, and digital connectivity are integrated from the outset. This integration is intentional, not accidental. Autonomous electric trucks from companies like Baidu's Apollo and Pony.ai are being tested on specialized highways near battery-swapping stations. This setup allows the vehicle's energy supply and operational autonomy to be managed as a unified system. Data from the autonomous driving system can help optimize battery use and plan swaps, while a dependable energy supply ensures autonomous vehicles' safe and consistent operation. This level of integration provides an advantage over Western developers, who often must treat electrification and autonomy as separate challenges due to a lack of unified infrastructure.

This convergent model envisions the future of freight as a fully integrated, intelligent logistics network, where vehicles serve not only as transportation tools but also as data-generating, decision-making platforms. The MLP framework demonstrates that transitions often occur through "reconfiguration," in which different niches come together to create a new dominant regime [13]. China's strategy is to ensure that the niches of electrification and autonomy are not isolated but are actively combined into a single, more efficient system. This is not just a technological milestone but a strategic move that positions China as a leader in shaping the next dominant regime in global freight.

6.5. Orchestrating the Future: How Collective-Led and Co-Created System Integration in China Is Establishing the Global Benchmark for Sustainable and Intelligent Logistics

This paper's key insight is that future technological leadership depends not only on innovation but also on the ability to coordinate the development of complex systems. In the West, innovation is often seen as a spontaneous result of market competition and private R&D. In China, it is a planned and coordinated effort led by the government. The Chinese collective approach manages and actively shapes technological progress by aligning industrial, energy, and urban policies with its strategic goals.

This collective leadership, co-creation, and coordination are key factors in China's success. They enable fast infrastructure growth, technology standardization, and alignment among various players—OEMs, suppliers, energy companies, and tech firms—around a shared goal. This is quite different from the West, where innovation often remains scattered, fragmented, and slow due to the lack of a central coordinating body. The result is a system that is more integrated, resilient, and scalable.

This model is setting a new global standard for what defines a "sustainable and intelligent" logistics system. Having a low-emission vehicle alone isn't enough; the entire system must be designed for sustainability and intelligence. China's approach shows that this requires a level of coordination and long-term planning that is hard to achieve in purely market-driven economies. As the world faces urgent challenges like climate change and supply chain disruptions, the Chinese model of collective-led system integration offers a compelling, though debated, blueprint for the future. It challenges the idea that technological progress is best left to the market and suggests that collective-led systemic solutions might be the most effective path forward in an era of systemic challenges.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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