



**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



# **Navigating Technology Adoption in Industries Undergoing Twin Transition**

A Case Study on Electrification and Automation in Road Haulage

Master's thesis in Management and Economics of Innovation

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## Abstract

The global push for sustainability combined with technological advancements in digitization like AI and automation, often referred to as twin transition, represents a significant overhaul of long-established industry practices. This thesis explores the twin transition of the road haulage industry, which faces intense pressure to decarbonize and improve operational efficiency through automation. A critical bottleneck in this transition is the charging infrastructure, where current cable charging requires manual interaction, posing a barrier to fully autonomous vehicles. The aim of this thesis is to examine the determinants of technology adoption and diffusion during the early stages of the twin transition. By integrating concepts of twin transition and technological transitions with traditional diffusion literature, this study provides nuanced insights into the complexities of early-stage industry transformation. Using a case study approach with an industry-wide perspective, this thesis examines the widely-used cable charging and six emerging alternatives: robotic arms, battery swapping, conductive charging, inductive charging, electric roads, and pantograph systems.

Findings reveal that the road haulage industry's twin transition is sequential, prioritizing electrification over automation, with the subsequent autonomous transition evolving from and being constrained by the established electrified system. Furthermore, the findings underscore the reduced lock-in effects from the dominant cable charging due to the formation of technology clusters and stakeholder's strategic flexibility. The clusters highlight the role of technology spillover and learning effects, which allow for collaborative development and testing of new solutions, whereas the flexibility means that industry actors experience less switching costs.

**Keywords:** Automation, Charging Infrastructure, Decarbonization, Dominant Design, Electrification, Road Haulage, Socio-Technical System, Technology Adoption, Technological Transitions, Twin Transition



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# Terminology

- **Automation** - The use of technology to perform tasks without human intervention.
- **Battery Swapping** - A method for recharging electric vehicles by exchanging a depleted battery for a fully charged one.
- **CCS (Combined Charging System)** - A standardized method for charging electric vehicles using a physical cable connection.
- **Chicken-and-Egg Dilemma** - A situation where two or more issues exist such that solving one issue depends on solving the others, creating a circular dependency.
- **Decarbonization** - The process of reducing carbon dioxide emissions from various activities, especially fossil fuel consumption.
- **Dominant Design** - A widely accepted standard or approach within a technology field.
- **Electric Roads** - Roads equipped with embedded technology that charges electric vehicles as they drive.
- **HDV (Heavy Duty Vehicles)** - Large vehicles such as trucks used for transporting goods.
- **Incremental Innovations** - Minor improvements or simple adjustments in existing products or processes.
- **Inductive Charging** - Charging electric vehicles wirelessly using electromagnetic fields.
- **MCS (Megawatt Charging Systems)** - A new charging standard for cable charging that is designed for capacities of up to 3.75 mW.
- **Path Dependency** - The idea that decisions and outcomes are heavily influenced by previous choices and events.
- **Pantograph Systems** - A type of charging where a mechanical arm connects the vehicle to an overhead power line.
- **Radical Innovations** - Major breakthroughs that make significant changes in technology or processes, often creating new industries.
- **Socio-Technical Regime** - The interconnected system of technologies, practices, relationships, and institutions that stabilize a particular sector.
- **Socio-Technical System** - A complex network of actors, practices, and standards that interact and depend on each other
- **Technology Clusters** - Groups of related technologies that evolve and advance together, providing mutual benefits and fostering innovation.
- **Twin Transition** - The simultaneous pursuit of electrification and automation within various sectors, aimed at enhancing sustainability and efficiency.

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# 1

## Introduction

### 1.1 Background

In an era marked by an urgent global push towards sustainability, industries are forced to transition from reliance on fossil fuels to adopting greener, more efficient alternatives (Bashir et al., 2024). This shift is pushed by governments worldwide setting more ambitious climate targets and a growing consumer demand for environmentally responsible practices, causing industries to fundamentally redefine their core operations. Simultaneously, a technological revolution is reshaping the landscape, with advancements in digitalization, such as artificial intelligence, robotics, and Internet of Things, profoundly altering operations of businesses (Marr, 2023). This twin transition of decarbonization and digitalization represents a radical overhaul of long-established socio-technical systems - complex networks of actors, practices, and standards. Socio-technical systems are 'locked in' at multiple dimensions, which make them stable and difficult to change (Geels, 2005). Thus, industries traditionally characterized by stability now find themselves at the brink of necessary but difficult change. These industries must navigate a landscape filled with uncertainties where changes of these deeply entrenched systems demands not only technological innovation but also a shift in markets, user practices, norms and values (Turnheim & Nykvist, 2019; Foxon et al., 2010; Geels, 2005).

A sector which experiences this twin transition is the transportation sector, with the electrification trend and the emergence of autonomous vehicles. This shift, highlighted by recent analyses from Deloitte (2022) and McKinsey (2023), is not merely a response to technological advancements but a strategic realignment towards sustainability and efficiency. It is driven by pressing environmental concerns, changing customer preferences and the promise of enhanced operational safety, which marks a significant departure from the industry's historical patterns (Deloitte, 2022; McKinsey, 2023).

The shift towards decarbonization and automation has seen varied levels of progress across different parts of the transportation sector. One sector under more intense pressure is the road haulage industry, the business of transporting goods by road, as it primarily deploys heavy duty vehicles (HDVs). On one hand, these types of vehicles account for more than 35% of the industry's carbon dioxide emission despite constituting less than 8% of vehicles (IEA, 2023), which has placed the industry under intense scrutiny. Consequently, the European Union has set ambitious targets to achieve climate neutrality by 2050 (European Commission, 2019) and 90% carbon reduction of new trucks in 2040 (European Commission, 2023), which put pressure on fast decarbonization. On the other hand, the industry is facing slim margins (Dagens Infrastruktur, 2021) and a pressing

driver shortage, projected to double by 2028 (IRU, 2023), which pushes it towards automation. However, the majority of automation technologies remain in infancy, with most initiatives still in the pilot phase (Boston Consulting Group, 2022a; WEF, 2023). Therefore, the road haulage industry constitutes a compelling context to explore how the twin transition takes place.

Additionally, the complex and multifaceted network of road haulage closely resembles a socio-technical system, integrating both social and technical elements to design and manage organizational systems. This system involves many different actors and technologies that interact and depend on each other, including not only vehicle manufacturers but also carriers transporting goods and infrastructure providers (e.g., roads and fuel stations). Furthermore, significant cooperation and coordination are required among these actors to ensure smooth operations. Consequently, standards (e.g., fuel specifications and pallets) have evolved in road haulage to provide predictability and efficiency. Thus, the electrification and automation transitions of the sector require a ‘system innovation’ – a shift from one socio-technical system to another – where the entire interplay is shifted (Geels, 2005). So, in this twin transition, there are multiple elements that are required to change for a technological transition to take place.

One important bottleneck within the transition of the road haulage industry is the charging infrastructure (IEA, 2023). Currently, the industry relies entirely on cable charging, which requires manual interaction and thus poses a barrier for a future scenario of fully autonomous vehicles. However, all alternative technologies that could facilitate fully autonomous operations without human input remain in an exploratory phase. The dependency on other actors causes reluctance to commit to an immature technology. Vehicle manufacturers are hesitant to alter their production processes without assurances that carriers, i.e. vehicle operators, will purchase these. Conversely, carriers are reluctant to commit to purchasing vehicles equipped with this new technology unless there is already a supporting infrastructure. Similarly, charging providers are reluctant to roll out infrastructure incompatible with the vehicles. This brings challenges to first movers and introduces a "chicken-and-egg" dilemma, where each step toward change depends on the willingness of others to take risks and make investments.

Multiple additional factors intensify this chicken-and-egg dilemma. One such factor is the high cost of deploying public charging stations and how their financial viability is closely tied to high usage throughout their operational lifespan (Karlsson & Grauers, 2023). The expected changes in operational and charging patterns from electrification and automation compounds this challenge further as there are less basis for the investment decision. Another factor that complicates the decision-making process is the few electric trucks on the road, making up only 0.6% of new sales (WEF, 2023), and the compatibility requirements with these trucks. Hence, the ‘chicken-and-egg’ dilemma intensifies from the challenges of long-term investments combined with an uncertain future and limited adoption rates.

As stakeholders navigate this uncertain landscape, the industry also experiences a complex landscape with multiple different charging technologies. Anderson and Tuschman (1990) describe this period as an era of ferment, characterized by significant uncertainty and the absence of a dominant design, which amplifies business risks for all parties. The reluctance of companies to commit to a specific technology during this time, along with the diffusion of competing technologies until one emerges as dominant, has been thoroughly explored in research. Studies indicate that the decision to adopt a technology is influenced not only by rational analysis or cost-benefit considerations but also by a mix of strategic positioning, and psychological, social, and economic factors (Lieberman & Montgomery, 1988; Rogers, 2003). Additionally, the concept of network effects illustrates how a technology’s value increases with its adoption by more users or organizations, creating self-reinforcing mechanisms that can accelerate the adoption rate (Onufrey & Bergeck, 2015). This complexity underscores the importance of understanding both rational and subjective influences on technology adoption and the emergence of standards, highlighting how path dependency can lock in even inferior technologies due to the cumulative advantages of early adoption.

However, much of the existing research on the diffusion and adoption of innovations focuses on how new technologies replace older ones in isolation. As demonstrated, the road haulage industry exemplifies a socio-technical system where innovations do not merely replace existing technologies but demands a shift from one entire system to another. This includes changes in user practices, supporting infrastructure, regulations and policies – all of which are interdependent components of the system. Moreover, the evolution of the road haulage industry is impacted by both the aim towards decarbonization (driving electrification) and the significant opportunities opened by digital technology advancements (driving automation). This twin transition aspect of dual forces diverges from the empirical settings most literature examines. Existing literature has not yet fully explored how the twin transition influences industry transition or its relation to the diffusion patterns of technologies in systems that are ‘locked in’.

## 1.2 Aim and Research Question

The aim of this thesis is to examine the key determinants for technology adoption and diffusion during the early stages of transformation in industries experiencing a twin transition. Through these findings, we intend to expand the literature on technology diffusion by integrating insights from technological transition and twin transition theories, illustrated through a real-world case study of the road haulage industry. Moreover, the thesis aims to provide practical implications for companies to effectively navigate technology adoption in industries undergoing a twin transition.

**Research Question:** *What drives the adoption and diffusion of new technologies during the early stages of twin transition towards electrification and automation?*

### 1.3 Research Setting

To explore our research question, we initially focused on a case study of “TruckCorp”, a newly established carrier in the road haulage industry. The company was founded during the last ten years and aims to revolutionize the transport sector through technological innovation with purchased electric trucks and development of autonomous electric trucks. However, during our initial investigation, it became obvious that the charging technology choice of “TruckCorp” is not an isolated decision. Instead, there is a lot of dependency on the industry response due to the public network alignment, the network effects, and the variance of customer sites.

Therefore, we extended the study focus beyond this single organization to get a more holistic perspective of the problem. In order to accomplish this, we incorporated perspectives from many different industry stakeholders, including vehicle manufacturers, other carriers, charging infrastructure providers, researchers, and charging developers. This broader approach helped us understand the dynamics of charging technologies’ adoption without being delimited to the specific characteristics or experiences of the "TruckCorp".

In addition, our investigation focused on seven charging technologies that hold potential as future standards within the industry: the widely-used cable charging and six emerging alternatives – battery swapping, conductive charging, inductive charging, electric roads, pantograph systems, and robotic arms. These technologies vary in their development maturity, operational requirements, and geographic implementation levels. Through this qualitative study, we aimed to capture the on-going socio-technical transitions influenced by the twin transition in electrification and automation. The gathered insights reflect the views and experiences from industry-wide stakeholders rather than being limited solely to the case company.

### 1.4 Delimitations

The thesis is delimited with several aspects to focus the research and to provide more depth to the analysis. The following delimitations will be applied:

- **Industry focus.** The research will be delimited to road haulage, chosen for its critical environmental footprint and on-going transformation. The decision to exclusively focus on one industry is driven by the intention to achieve a greater depth of analysis than would be possible with a broad, generic approach. The road haulage also consists of a complex stakeholder network, including manufacturers, carriers, regulatory bodies, and technology/infrastructure providers, which makes it a compelling research context for examining system changes and innovation.
- **Geographic focus.** The research is geographically concentrated on Europe, reflecting the

case company's primary operational base. In addition, Europe's stringent regulations and ambitious sustainability targets also provide a compelling context for examining strategic decisions and technology adoption within the road haulage sector.

# 2

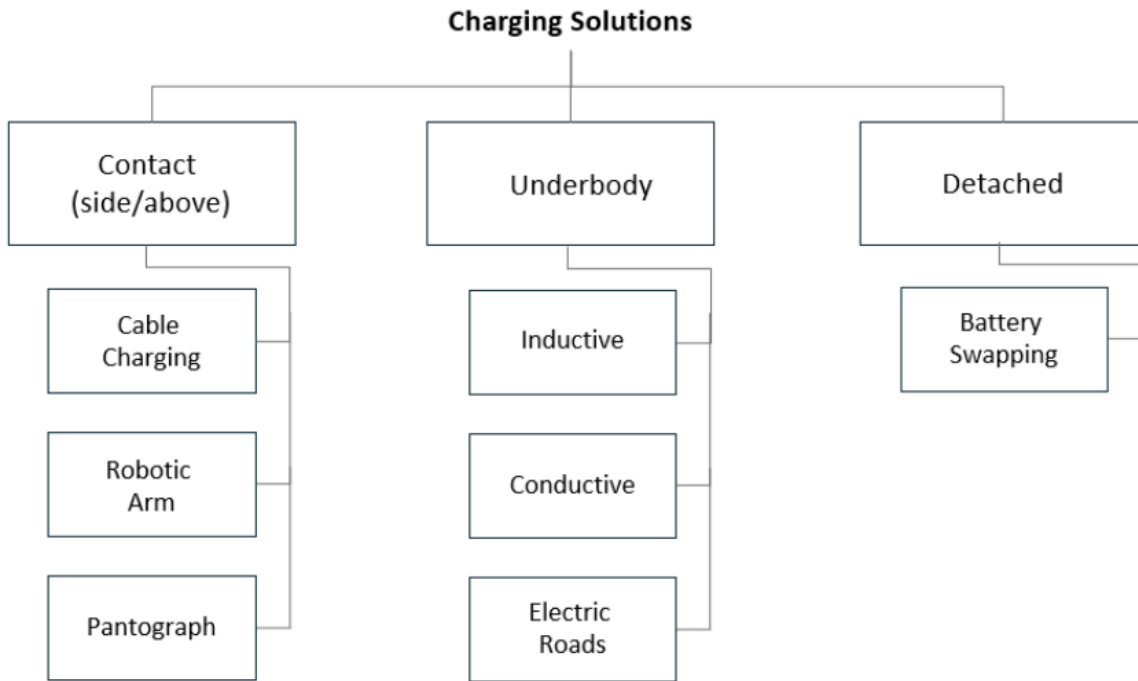
## Theoretical Background

Our theoretical background will start by a description of the different charging technologies to provide an overall understanding and introduction. Secondly, we will shed light on traditional diffusion theory as a starting point to understand how innovation emerges and become more adopted. Finally, concepts within Socio-Technical Transitions are deployed to offer a comprehensive view beyond technological advancements, capturing the complex dynamics and interplay of various actors.

### 2.1 Charging Technologies

The twin transition towards electrification and automation in the road haulage industry leads to several challenges and opportunities for the adoption of and diffusion of new technologies. A central part to addressing these challenges is the charging infrastructure, which is vital to support the widespread adoption of electric and autonomous HDVs. Efficient charging solutions are essential because they directly impact vehicle uptime, operational costs, and the feasibility of integrating new technologies into existing transport systems.

The landscape of charging technologies is diverse, where each solution has its unique set of advantages, limitations, and needs. To navigate this complexity and provide a structured overview, the charging technologies have been categorized into three main buckets based on their charging principle and infrastructural requirement; contact charging, underbody charging and detached charging, as presented in Figure 1 below. Within these categories, there are further sub-buckets, such as electric roads or robotic arms.



**Figure 1:** An overview of the different charging solutions

The sections that follow will explore each of these main categories and their subcategories. This examination will not only outline how these technologies align with the operational needs and strategic objectives of the road haulage industry but will also contrast their capabilities and limitations in the context of the twin transition.

### 2.1.1 Current State of Charging Infrastructure

The thesis is delimited to Europe, which has become a significant player in the electric vehicle market, with a quarter of all global sales in 2022 originating from the continent (Swedish Parliament, 2024). In Sweden, a part of this European initiative, the number of registered electric trucks is increasing steadily. As of October 2023, there are 19,186 light electric trucks and 441 heavy electric trucks. Forecasts by Power Circle (2023) indicate that the number of heavy electric trucks in Sweden is expected to rise to 12,500 by 2030 (Thuresson, 2023).

Despite these advances in vehicle electrification, the development of the necessary charging infrastructure has not kept pace. The European Union has recognized this shortfall and set ambitious targets to expand this infrastructure. They require public charging stations every 60 kilometers along the main transport corridors of the Trans-European Transport Network and every 100 kilometers within the broader network, with the aim of full coverage by 2030 (Swedish Parliament, 2024). Sweden currently has approximately 33,000 charging points and plans to add

230 charging stations from 2022 to the end of 2025 (Closer, 2024). Nevertheless, this expansion still is far from the estimated 3 million charging points needed by 2050 to adequately support the growing fleet of electric vehicles (Boston Consulting Group, 2022b).

Most public charging points currently utilize cable charging methods (Swedish Parliament, 2024). However, with the increase in charging power, there has been a notable shift towards the development of alternative charging methods. This evolution is particularly important as it aligns with advancements in autonomous technology, which aim to transform the charging process into a hands-free operation. Such innovations would enhance vehicle readiness and operational efficiency, aligning with the broader goals of reducing downtime and supporting continuous fleet operation.

### **2.1.2 Contact Charging Systems**

Contact charging are the most common and direct methods of charging electric vehicles. The charging infrastructure includes a separate charging unit which transmits the power through a contact solution, which is placed either on the side of the vehicle or on the roof. This category consists of cable-based systems (such as CCS and MCS), which require manual connection, robotic arms that autonomously plug the charger into the vehicle, and pantographs with adjustable mechanisms that connect from above.

#### **Cable Charging**

Cable charging represents the most traditional form of contact charging and is by far the most used alternative (Leijon & Boström, 2022). This method involves a physical cable connection between the EV and the charging station, which facilitates a direct transfer of electrical power to the vehicle's battery. Despite the development of more modern or advanced charging technologies, cable charging remains a cornerstone due to its simplicity, reliability, and widespread availability.

Within cable charging, there are primarily three types of charging utilized by battery-electric trucks: overnight chargers, Combined Charging Systems (CCS), and Megawatt Charging Systems (MCS). These systems differ in nominal power they deliver, where the overnight chargers have the lowest power and MCS has the highest (Bernard et al., 2022). Historically, CCS has been widely adopted, but as the electric HDV sector has grown, with increasing energy demands, its limitations have become apparent. This has led to initiatives such as the Charging Interface Initiative (CharIN), which has developed new connectors to support market demand for electric trucks with high battery capacities. These new MCS connectors allow for a bi-directional energy flow, which makes it able to provide much higher power (Far et al. 2022). The new Closer report (2024) concludes that the MCS charging can reach up to 3.75MW, which would drastically reduce the required charging time. However, MCS still remains in its nascent stages and is expected to be commercialized in the beginning of 2025 (Closer, 2024).

The transition from CCS to MCS highlights the industry’s response to evolving demands as it is a shift towards more efficient, high-capacity charging solutions that align with the increasing battery capacities of modern electric HDVs. However, this evolution in conductive charging also includes the development of other innovative technologies aimed at further enhancing the efficiency of the charging infrastructure and the compatibility with autonomous flows.



**Figure 2:** Cable charging (created by Dall-E)

### **Robotic Arm**

An emerging contact charging alternative is the robotic arm, which automates the connection process between electric HDVs and charging stations. This technology leverages robotic mechanisms to ensure precise connections, enhancing operational efficiency and supporting the industry’s gradual shift towards automation (Saputra et al., 2023). Additionally, robotic charging is designed to be compatible with various vehicle configurations, which allows for flexibility across different HDV models (Chablat et al., 2022).

The relevance of robotic arm technology increases in scenarios involving autonomous electric trucks, where manual connection methods are impractical due to the absence of drivers. However, the implementation of robotic arms faces significant technical challenges, including the development of sophisticated sensors, precise positioning systems, and comprehensive safety protocols (Saputra et al., 2023).



**Figure 3:** Robotic arm charging (created by Dall-E)

### **Pantographs**

Pantographs charging is another type of contact charging solution. The technology originates from electrical rail transports, but has grown into other vehicle systems, such as buses and potentially trucks. Pantographs are available in both top-down and bottom-up configurations, where the moving part is either on the charging unit (top-down) or the vehicle (bottom-up). This method allows for rapid charging and is flexible enough to support different vehicle types across various infrastructural settings (Prakash et al., 2022).

The high power output capability of pantograph systems, which can reach up to 600 kW, makes them suitable for applications requiring quick energy transfer, such as commercial trucks on fixed routes or extensive journeys (Mathes et al., 2022; Prakash et al., 2022). However, widespread adoption of pantograph charging faces hurdles such as the need for standardized infrastructure, a lot of space, and vehicle-specific modifications to ensure compatibility.



**Figure 4:** Pantograph Charging Technology (created by Dall-E)

### 2.1.3 Underbody Charging Systems

Underbody charging systems eliminate the need for traditional charging units by integrating the charging infrastructure directly into the road network. This innovative approach supports both stationary and dynamic charging options, enabling electric vehicles to charge while stationary or in motion. There are two stationary options, inductive and conductive charging. Furthermore, it is possible to expand on these technologies to offer dynamic charging, which is called electric roads.

#### **Inductive Charging (stationary)**

Inductive charging represents a transformative approach to power electric vehicles, leveraging the principles of electromagnetic induction to transfer energy wirelessly. This method involves two coils: a transmitter coil embedded in the charging station or roadway, and a receiver coil fitted within the vehicle. When the transmitter coil generates an alternating magnetic field, it induces an electric current in the receiver coil, which charges the vehicle's battery without requiring physical contact (Dimitriadou et al., 2023).

Stationary inductive charging systems are designed for scenarios when the vehicle is idle, such as when parked during overnight charging at depots or opportunity charging at designated stations throughout the day. These systems usually consist of a ground pad connected to the power source and a receiver pad mounted on the vehicle's underside. When the vehicle is positioned over the ground pad, the system activates and an electromagnetic field is generated, transferring energy across the air gap to charge the battery. The efficiency and convenience make it a viable alternative to traditional plug-in charging methods (Karthi et al., 2023).



**Figure 5:** Inductive Charging (created by Dall-E)

### **Conductive Charging (stationary)**

While all contact charging technologies are conductive, this part focuses on underbody stationary conductive charging, which is referred to as conductive charging for simplicity throughout the thesis. Such conductive charging offers a solution that enables the transfer of electrical power without direct metal-to-metal contact, but differs from the inductive charging described in the previous section. Once the vehicle is accurately positioned within the working area of the robot, the ground unit's parallel kinematics engage, which establishes a conductive connection with the vehicle which enables charging (Volterio, n.d.). The convenience makes it a candidate for future charging, but the solution faces challenges with standardization as well as high efficiency.



**Figure 6:** Conductive Charging (created by Dall-E)

### **Electric Roads (dynamic)**

Electric roads present an innovative solution by charging vehicles in motion. Electric roads can build upon both the inductive and conductive charging technology presented above, as described in a report by the Swedish Parliament (2024). The report also concluded that electric roads could significantly reduce the required battery range by more than two-thirds if implemented on just 25% of the most trafficked national and European highways. This technology not only enhances vehicle range but also supports a more sustainable transport infrastructure by reducing the frequency and length of charging stops necessary for long-distance travel. However, it is challenging for a single actor to implement this solution due to its infrastructure cost and complexity.



**Figure 7:** Electric Roads (created by Dall-E)

#### **2.1.4 Detached Charging Systems**

Detached charging systems streamline the process of electric vehicle refueling by decoupling the charging of the battery from the vehicle's operation. This approach facilitates the charging process and avoids long charging times without placing excessive demand on the electrical grid. By separating energy delivery from charging, these systems enhance grid efficiency and reduce vehicle downtime, making them particularly advantageous for sectors where time is critical.

#### **Battery Swapping**

One prominent example of a detached charging solution is battery swapping. It provides a quick alternative to conventional charging methods by allowing vehicles to exchange a depleted battery for a fully charged one within minutes. The process is typically automated and occurs at specialized swap stations, which effectively eliminates long charging waits and optimizes vehicle uptime. This makes it a viable alternative for the road haulage sector where operational delays translate directly into financial losses (Amry et al., 2022).

While battery swapping is well-developed in specific regions like China, where robust infrastructure and subsidies support quick and efficient swaps, it is also being explored through pilot projects in European countries like Sweden (Swedish Parliament, 2024). In these systems, the vehicle's ownership is usually separated from the battery's ownership, which reduces upfront costs and increases operational flexibility (Amry et al., 2022).

Despite its potential, the widespread adoption of battery swapping faces significant challenges, particularly the need for standardized battery designs across different vehicle models and manufacturers. Without a unified standard, the efficiency and scalability of swapping stations are compromised, potentially limiting the technology's broader application in global markets.



**Figure 8:** Battery Swapping Technology (created by Dall-E)

## 2.2 Diffusion Patterns

This chapter will explore the diffusion of innovation, focusing on how new technologies can gain traction in the industry. It will cover the adoption dynamics as well as examine the interplay of path dependency and dominant design. This theoretical framework is helpful to understand the complexities of transitioning in a traditionally locked-in industry, providing insights into the factors driving and hindering technological evolution.

### 2.2.1 Adoption Dynamics

In the context of innovations, diffusion refers to the process through which new technologies are embraced and spread out within a society or industry. Korres (2012) defines diffusion as the sequence of adoption lags, which primarily can be determined by how information is spread. Everett Rogers' diffusion of innovation theory (2003) further delves into this phenomenon, providing an established

framework for understanding how new technologies are adopted and spread across different societal systems. The adoption process is influenced by four key elements: characteristics of the innovation itself, communication channels, time, and the social system (Rogers, 2003). Potential adopters are then categorized into given groups based on their readiness to embrace new technologies: innovators, early adopters, early majority, late majority, and laggards.

Grubler (1996) also concludes how innovations do not spread instantaneously. However, instead of mentioning different groups, he concludes how innovation appears to diffuse through a S-shaped temporal pattern. The author also explicitly notes how transport infrastructure does not diffuse in isolation, but in a broader context. The new solution, charging infrastructure in this context, will not be evolved in a vacuum, but have constant interaction with existing practices and technologies.

The adoption of new technologies, particularly in industries as complex and established as road haulage, is often hindered by various barriers. Hosseinpour et al. (2015) investigated barriers to the adoption of electric vehicles and found four main categories: technological, social, economical, and political. These challenges were echoed by Cristino et al. (2021) in their comprehensive literature study based on barriers hindering the adoption of energy-saving technologies.

- **Technological challenges** are significant in the adoption of new technologies, where Butler and Sellbom (2002) found that the largest concern with a new technology is reliability. This factor is important in the road haulage sector, where reliable charging technology and infrastructure directly impacts the range and charging speed for the electric trucks.
- **Socio-cultural barriers** stem from a lack of familiarity with new technologies and a reluctance to depart from traditional practices. Attitude also plays a crucial role in the acceptance and adoption of new innovations (Dwivedi et al., 2017). The road haulage industry's culture, still influenced by traditional large manufacturers and gasoline-based operations, can be slow to embrace new, unproved technologies.
- **Financial considerations** are also crucial, where the high costs associated with new technologies, like charging infrastructure, pose a significant risk for companies. This economic barrier is often cited as a primary concern among businesses considering transitioning to new technological solutions (Stornelli et al., 2021).
- Finally, the **political landscape** can both aid and obstruct the adoption of new technologies. Many governments around the world have introduced subsidies to facilitate the green transition, but the process of standardizing new technologies can be slow. Additionally, powerful interest groups and regulatory complexities can further complicate the process, restraining innovation and slowing down the transition (Cristino et al., 2021).

### 2.2.2 Path Dependency

The concept of path dependency is critical in understanding the complexity of technological evolution. It captures how historical decisions set precedents that shape long-term development and constrain future options. Path dependency suggests that an industry's early decisions and the particular technological trajectory it chooses becomes entrenched, making it increasingly difficult to deviate from (Utterback & Suarez, 1993). The process is not a random sequence of events but a pattern of cumulative choices that gains momentum over time – similar to a snowball rolling downhill. This leads to a preference of traditional alternatives, even over potentially superior options (Grubler, 1996).

Path dependency develops from two main components: persistence and self-reinforcing mechanisms (Onufrey & Bergek, 2015). Persistence refers to the steady pattern of repeated choices or action in relation to technology development, while self-reinforcing mechanisms are the underlying forces or processes that consistently reproduce specific patterns of events, decisions, or activities over time. Within these self-reinforcing mechanisms, Onufrey and Bergek (2015) identify four main types that stand out, which are described below. These mechanisms do not act in isolation but are interconnected and can occur both on the development and the adoption side.

- **Coordination effects.** These refer to how the utility of choosing the same alternative as other actors increases as the interaction can be much more efficient. In the context of charging technologies, coordination effects are seen in how vehicle manufacturers, infrastructure developers, and regulators must collaborate to establish standardized charging protocols and networks.
- **Complementarity effects.** These effects conclude how the success of a technology is related to the development of complementary products. The success of electric and autonomous trucks is linked to the availability and capability of relevant charging infrastructure.
- **Expectation effects.** People are inclined to alter their expectations and preferences as a result of what they expect of others. If potential customers trust that charging will be fast, accessible, and integrated seamlessly with their operations, they are more likely to invest in and adopt it.
- **Investment and learning effects.** This is the accumulation of non-transferrable resources attached to a certain alternative, which makes the alternative more attractive for future adoption or development. These effects are especially relevant if the technology is complicated and requires investments in training. The high upfront costs that will be paid in early technology will also make actors more prone to continue with the selected technology (Onufrey & Bergek, 2015).

Furthermore, the path dependency process can be divided into three phases: preformation, where the initial conditions are set; formation, where a path becomes increasingly established; and lock-in, where a dominant pattern becomes fixed, significantly diminishing flexibility within the industry (Schreyögg et al, 2011). During the lock-in phase, a phenomenon known as 'dominant design' often emerges, marking a critical point when a particular technology becomes the standard within the industry. This dominant design results from a series of strategic decisions that lead to a widely accepted standard, which later influence subsequent technological developments. The effects of being locked into this design, known as lock-in effects, further cement the dominance of this design. Once a technology achieves dominance, economic and strategic factors such as increasing returns to adoption and network externalities make it progressively more challenging for alternative technologies to compete (Arthur, 1989). One such example is the QWERTY keyboard, where, despite knowing how to design more efficient keyboards, it remains difficult to deviate from a well-established trajectory (Utterback & Suarez, 1993).

However, the road to reaching a dominant design is rarely straightforward. Anderson and Tushman (1990) conclude how so-called technological discontinuities (defined as innovations leading to a significant change in performance or price) lead to an era of ferment. During such an era, there is a high degree of uncertainty and experimentation with many different variations. On the contrary, when a domain design has been established, there is often more focus on incremental change. However, the passage from ferment to dominant design is seldom just a technical aspect, but often involves many sociological aspects, where industry associations, regulatory agencies and strategic alliances are impactful (Anderson & Tushman, 1990).

Contrary to the often cited irreversible selection of an individual "winning" technology in literature, Bergek and Onufrey (2014) propose that multiple technologies can coexist over prolonged periods, facilitated by cross-technology learning effects. These effects highlight how advancements in one technological area can enhance developments in another, contributing to a richer, more integrated technological landscape. This concept is closely linked to technology spillover, where innovations in specific technologies, such as improvements in battery efficiency or charging speed, can have benefits for other different but related technologies (Karshenas & Stoneman, 1995). This interconnectedness not only challenges the rigidity of path dependency but also introduces opportunities for more dynamic and adaptive technological evolution within the industry.

### **2.3 Socio-Technical Transitions**

As we tailor the narrative towards road haulage, it becomes evident how the traditional literature on innovation and adoption fails to provide a complete picture. Thus, we draw upon Socio-technical transitions, which include changes in elements such as user practices and institutional structures and the role of complementary technology and infrastructure (Markard et al., 2012).

To navigate the complexity of transition studies, scholars mainly draw upon four frameworks (Markard et al., 2012), where we will rely on the multi-level perspective on socio-technical transitions (Geels, 2002; Geels & Schot 2007). This chosen perspective highlights the shift from one socio-technical system to another by using three levels: niches, regimes and landscapes with interplay and dynamics between them (Geels, 2002). The framework serves as a roadmap for the upcoming section and emphasizes the multifaceted relationships between the different elements at play. However, as the road haulage industry experiences dual forces of change, we need to complement the multi-level perspective with the concept of twin transition.

### **2.3.1 Twin Transition**

The "twin transition" refers to the simultaneous pursuit of electrification and digitalization within various sectors, which is frequently featured in academic literature. This dual focus aims to address global sustainability challenges by reducing carbon emissions through electrification while enhancing efficiency and capabilities through digitalization in parallel (Rehman et al., 2023). In the context of the road haulage sector, the twin transition is particularly relevant as it seeks to integrate advanced digital technologies with electric vehicle development to create more sustainable and efficient transportation systems.

Theoretical frameworks that explore the interdependence of these transitions often discuss the synergistic potential between electrification and digitalization. Digitalization has been recognized for its positive impact on a firm's sustainability and its crucial role in propelling the sector towards climate neutrality (Rehman et al., 2023; Benedetti et al., 2023; Chen et al., 2023). While digitalization facilitates the integration and optimization of electrification technologies, there is a risk that digital advances could outpace decarbonization efforts. Fouquet and Hippe (2022) suggest that without coordinated policies, digitalization might advance in ways that do not necessarily contribute to carbon reduction.

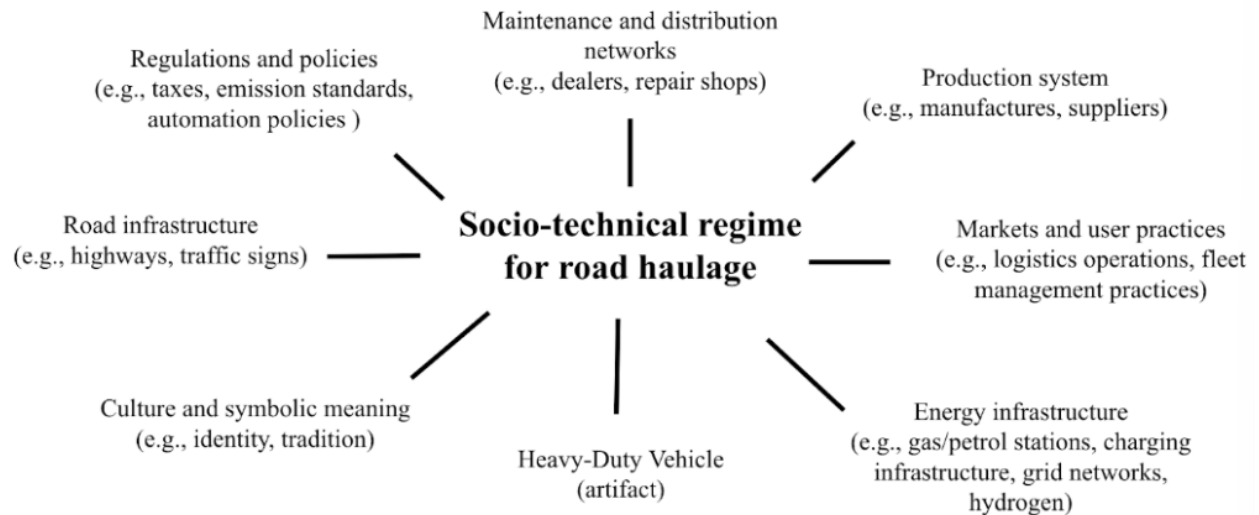
Moreover, there's often a gap between the fast pace of digitalization and the slower adoption of low-carbon energy solutions. This gap suggests that policies are needed to help the less advanced areas catch up (Fouquet & Hippe, 2022). Similarly, multiple other studies stress the importance of designing policies that bring these two areas together effectively (Benedetti et al, 2023; Husain et al., 2022). These policies should facilitate the adoption of new technologies, support infrastructure development, and foster a regulatory environment that encourages investment in both digital and green technologies.

### **2.3.2 Socio-Technical Regime**

A socio-technical regime refers to the complex and interconnected system of technologies, practices, relationships, and institutions that stabilize and influence technological progress within a particular

sector. In the context of road haulage, as illustrated in Figure 9, the twin transition of electrification and automation impacts not only the technological artifacts but also all elements of the regime, including the interlinkages between them (Geels, 2005). These interlinkages of elements contribute to the system’s stability and resistance to change. As a result, emerging technologies face challenges entering the regime due to misalignment with the established norms and practices adapted to the previous technologies (Geels, 2002).

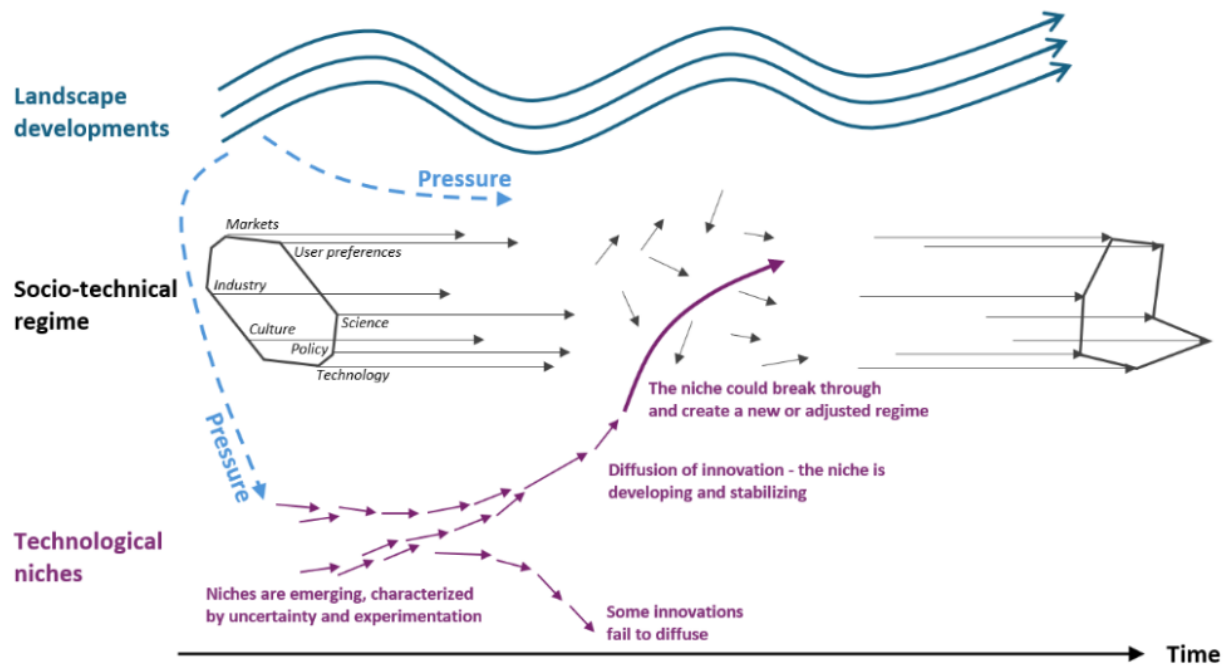
In a socio-technical regime, there are self-reinforcing mechanisms for all actors, i.e., not only for developer and adopter of electric trucks but for charging infrastructure and carriers with user practices as well. Furthermore, the socio-technical regime amplifies the barriers for emerging technologies. Factors such as complementary technologies and infrastructure, government policies, psychological barriers favor the incumbent technology over the emerging technology and stabilize the entire socio-technical regime (Kemp et al., 1998). This stability often leads to the innovation in these systems being incremental rather than radical or disruptive (Geels, 2002). When a socio-technical transition does take place, the elements change through a process of co-evolution and mutual adaptation (Kemp et al., 1998).



**Figure 9:** Socio-technical regime of road haulage, adapted from Geels (2005)

### 2.3.3 Transition Process

The Multi-Level Perspective (MLP) explains socio-technical transitions by framing them within three levels: macro-level landscape developments, meso-level socio-technical regime, and micro-level technological niches as presented in Figure 10. Landscape developments, such as environmental problems and political shifts, exert external pressure on the regime, challenging its stability and potentially fostering new technological opportunities (Geels, 2002; Geels & Schot, 2007).



**Figure 10:** The Multi-Level Perspective, adapted from Geels (2002)





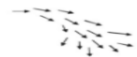
Within this framework, transitions are driven by two key processes: external environmental pressures that challenge the regime and the internal coordination among actors to adapt to these pressures (Smith et al., 2005; Geels & Schot, 2007). The regime's response often involves navigating between maintaining stability and adopting new technologies, balancing influences from both the broader landscape and emerging niches.

Technological niches are critical as they provide a protected space where radical innovations can develop without the immediate pressures of market competition or commercial viability (Geels, 2005; Raven et al., 2012). These niches allow for learning, experimentation, and the development of new standards and norms that diverge from those of the existing regime. These protective places are vital as they provide space for learning activities as well as developing standards and norms that differ from the prevailing socio-technical regime. Despite their deviation from mainstream technology, these innovations can secure a foothold, either within specific geographic, market niches, or through the aid of targeted policy support. As these niches evolve, they may either remain isolated, contributing to the diversity of the technological landscape, or potentially disrupt and transform the prevailing industry regime, especially during periods when the existing system is vulnerable to change (Geels, 2005).

To further understand these dynamics, Geels and Schot (2007) have developed a typology of transition pathways based on the typology of environmental changes by Suarez and Oliva (2005),

which categorizes changes by their pattern, frequency, amplitude, and speed. This typology, detailed in Table 1, helps identify common pathways transitions might follow.

**Table 1:** Type of Environmental Change (based on Suarez & Oliva, 2005; Geels & Schot, 2007)

Typology	Pattern	Frequency	Amplitude	Speed	Scope
Regular		Low	Low	Low	Low
Hyperturbulence		High	Low	High	Low
Specific shock		Low	High	High	Low
Disruptive		Low	High	Low	Low
Avalanche		Low	High	High	High

Geels and Schot expand on this typology to identify common transition pathways of socio-technical regimes where they emphasize the importance of timing and nature of interactions between the levels. The timing of landscape pressures relative to the state of niche innovations determines whether a window of opportunity leads to a breakthrough or closes prematurely. The nature of the interaction between niche and regime, whether reinforcing or disruptive, also critically influences the regime's response. Disruptive developments may push the regime to change, whereas reinforcing developments stabilize it. Depending on the timing and nature, Geels and Schot (2007) outline the four transition pathways as transformation, reconfiguration, technological substitution, and dealignment and realignment.

In summary, the Multi-Level Perspective provides a comprehensive framework for understanding the complex dynamics of socio-technical transitions. By analyzing interactions across landscape, regime, and niche levels, the MLP highlights how external pressures, coupled with internal adaptive responses and innovations within protected niches, drive the evolution of industries. The approach underscores the importance of timing and interaction in shaping transitional pathways and illustrates the potential for radical innovations to reshape existing socio-technical systems. This offer valuable insights into managing technological change.

# 3

## Method

This chapter outlines the methods employed in conducting this thesis, including the research design, data collection methods, selection of interviewees, and the ethical considerations. The aim is to offer transparency regarding the processes and principles guiding the research, facilitating for potential replications and ensuring credibility.

### 3.1 Research Design

Our study utilized a qualitative research methodology to gain a comprehensive understanding of the complex situation within the non-standardized landscape. According to Bryman and Bell (2011), a qualitative approach is ideal when seeking a holistic view of a situation, aligning well with the exploratory nature of this study's research question. This question required an in-depth exploration of the interactions among several factors influencing technology adoption and diffusion. Creswell and Poth (2018) further support the qualitative choice, highlighting its strength in providing depth and context.

We employed a single-case study approach focused on a particular industry. This method is ideal when generating deep knowledge and a comprehensive understanding of a specific topic is required (Bell et al., 2019). The long time-horizon and the under-researched nature of our topic further supported the use of a case study, in line with Denscombe (2018) and Yin (2014), who underscore the value of case studies in exploring new or poorly understood phenomena.

The research began with an exploratory phase involving numerous internal interviews within the case company, focusing on the carrier perspective. This phase helped us to understand the challenge of navigating this complex environment, which clarified the scope and direction for the following phases. It also highlighted the interdependence in the industry and need for taking a broader, external perspective as one actor cannot act in isolation. Therefore, the data collection consisted of external interviews with various industry stakeholders, providing a broader view of the industry dynamics.

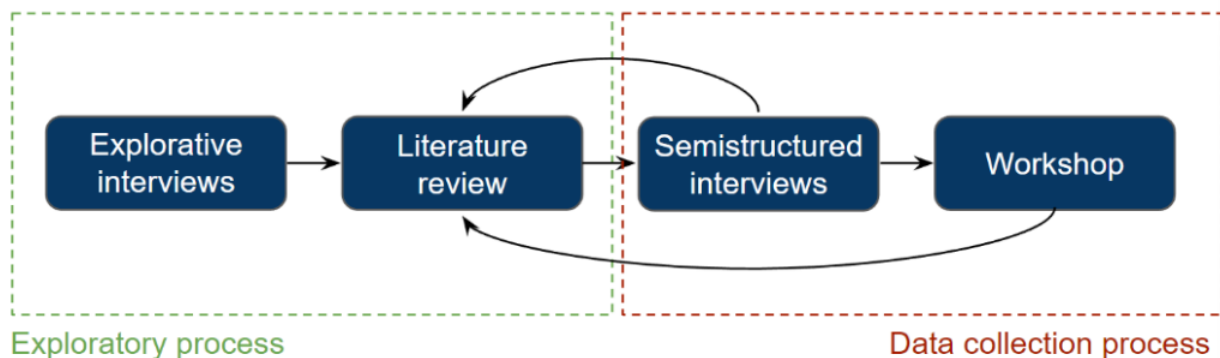
To navigate the study's complexities, we adopted an abductive approach. This preference arose from the recognition that both inductive and deductive strategies, while valuable, may not fully capture the dynamic interplay between theory and empirical findings that our research objectives require. Inductive reasoning allows for theory development from observed data, whereas deductive reasoning tests hypotheses derived from existing theories (Bell et al., 2019). However, the unique

landscape of electrification and automation necessitated a more flexible and iterative process, which is why an abductive research approach was chosen.

This approach enabled us to dynamically integrate theoretical insights with real-time observations from the industry. It facilitated a responsive research process where theories could be adjusted or expanded based on new findings, ensuring that our study could effectively address the uncertainty in the industry (Alvesson & Sköldbberg, 2008). As a result, the research question was iterated throughout the process. In addition, an abductive approach is particularly valuable in areas where existing theories might not fully capture the nuances of new or emerging phenomena (Dubois & Gadde, 2002), making it ideal for our exploration into the technological and regulatory transitions within the road haulage industry.

### 3.2 Research Process

The research process was purposefully structured to explore and refine our understanding of the twin transition in the road haulage industry, focusing initially on electrification and automation from the perspective of a case company, and then expanding to include external views. This multi-phase approach, which is illustrated in Figure 11, allowed for an in-depth exploration of both the internal and external dynamics influencing technology adoption and diffusion in this sector. Each stage informed and refined the subsequent steps, which allowed for a flexible and responsive approach to emerging insights.



**Figure 11:** Overview of the research process

#### 3.2.1 The Exploratory Phase

The research process began with an exploratory phase conducted internally at the case company, an innovative carrier in electric and autonomous road haulage. This phase was critical for gaining an in-depth understanding of the challenges and operational nuances faced by the industry, especially by the carriers. Internal interviews were conducted with a range of departments, including product,

operations, hardware, and human factors, to gather a rich qualitative data. These interviews, which are summarized in Table 2, helped shape the direction of the subsequent phases of research by identifying key themes and areas of interest that required further exploration.

**Table 2:** Overview of initial exploratory interviews

#	Role of respondent	Team / department	Time
1	Product Manager	Platform	30 min
2	VP	Manufacturing	30 min
3	Engineer	Hardware	30 min
4	PhD candidate	Operations	30 min
5	Human Factors Specialist	Autonomous Vehicle	30 min
6	VP	Energy & Charging Infrastructure	15 min
7	Product Director	Autonomous Vehicle	30 min
8	Operations Manager	Operations	40 min
9	Commercialisation Director	Autonomous Vehicle	20 min
10	Head of Supply Chain	Manufacturing	25 min
11	Human Factors Specialist	Autonomous Vehicle	40 min
12	Product Manager	Platform	40 min

Parallel to these exploratory discussions, a comprehensive review of existing literature was undertaken. This helped us contextualize the insights gained from the exploratory interviews within the broader academic and industrial landscapes, ensuring that the study was grounded in a solid theoretical framework while remaining relevant to practical realities. The search process utilized the online library at Chalmers, which included databases such as Scopus, ScienceDirect and Web of Science. Patel and Davidsson (2019) conclude that books provide relevant theories and models, but scientific articles provide a more up-to-date perspective, which was deemed relevant in our case with our forward-looking perspective. The search for relevant articles was based on keywords refined from the exploratory phase, as presented in Table 3 below. Backward searching was also incorporated from sources deemed highly relevant. Finally, additional literature was incorporated based on suggestions from our Chalmers supervisor and also included previous master theses.

**Table 3:** Keywords used during the literature review

<b>Keywords</b>	<i>Autonomous Charging, Decarbonization of Freight, Digital Transformation, Electric Heavy-Duty Vehicles, Electrification of Transport, EV charging, Industry Transitions, System Innovation, Technology Diffusion, Twin Transition</i>
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### 3.2.2 The Data Collection Phase

Building upon the exploratory phase, our data collection process involved conducting in-depth interviews with a broad spectrum of stakeholders across the road haulage industry. This included experts, academics, suppliers, and potential customers, reaching a combined 28 external interviews. Each of the interviews aimed to uncover detailed insights into technology adoption, strategic considerations, and the unique challenges posed by a non-standardized landscape.

The choice of semi-structured interviews as our primary data collection method was based on its flexibility and depth, allowing respondents to elaborate on their responses and discuss complex topics in detail (Bryman & Bell, 2011). In a semi-structured interview, the interviewer also utilizes an interview guide, but is not restricted to those questions and may add follow-up questions or change the order of the questions (Bell et al., 2019). Such a detailed and broad perspective aligns well with the exploratory nature of this research paper, aiming to understand the complex dynamics of technology adoption within road haulage. This format also enabled us to adjust the flow of conversation in real-time, ensuring that clarity and depth were maintained (Patel & Davidsson, 2019).

The interviews began with general questions to understand the respondent's background and their organization's involvement with the different technologies, before moving into more focused discussions on adoption strategies, challenges, and industry dynamics. We placed a strong emphasis on the interviewer-respondent relationship to foster a dialogue conducive to gathering rich qualitative data. Prior to each interview, participants were briefed about the objectives of the thesis to set a clear framework for the discussion. This preparation was crucial in ensuring that participants felt comfortable and prepared to engage in meaningful dialogue about their experiences and perspectives (Patel & Davidson, 2019).

The interview guide was crafted to facilitate a natural progression of discussion topics, starting from broader organizational contexts to more specific technological and strategic insights. This approach was recommended by experts to help set the context before delving into the complexities of the industry (Patel & Davidsson, 2011). Flexibility was maintained throughout the interviews to allow for spontaneous exploration of topics that emerged during the discussions, which was instrumental in capturing the dynamic nature of the industry. Moreover, as the study incorporated multiple different stakeholders, the interview guide was tailored to remain relevant for all interviews.

To ensure a comprehensive perspective, we selected interviewees who represented a diverse cross-section of the industry. Interviews were conducted both in person and online to accommodate geographical diversity and the interview recordings were made with the consent of the participants to facilitate accurate data analysis and review. However, acknowledging potential response biases due to recording, we offered participants the option to opt out of being recorded, as suggested by Jacobsen

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(1993). During each session, one researcher focused on leading the interview while the other took detailed notes, ensuring that all information was accurately captured.

The culmination of this phase was a workshop involving stakeholders from the case company. This workshop was designed to validate and refine the findings from the interviews, fostering a collaborative environment to discuss the collected data and generate collective insights. This setting aimed to integrate multiple viewpoints and facilitate a consensus on strategic and operational considerations for future technological implementations in the sector.

### 3.3 Selection of Interviewees

The selection of interviewees was an essential part of our research process and designed to capture a diverse array of perspectives from the road haulage ecosystem. The diversity in selection ensured that the study included a broad spectrum of insights, from technical experts and industry leaders to end-users and regulatory authorities.

The criteria for selecting interviewees were defined to align with the study's objectives, focusing on stakeholders actively involved in areas relevant to our research. Participants were chosen based on their involvement in significant projects or their role within their respective organizations, ensuring that each interviewee could provide detailed and expert-level input on the topics at hand. Moreover, we prioritized interviewing actors with decision-making power, as they significantly influence diffusion patterns. While actors such as drivers play a central role in the operational flow, they were not targeted as interviewees because they are not heavily involved in making critical decisions.

Below are the different roles or perspectives that were targeted for the interviews.

- **Project coordinators:** Individuals engaged in pioneering projects at the forefront of charging technology provided insights into the latest innovations and their practical applications.
- **Industry sector involvement:** Stakeholders from various segments of the road haulage industry, including vehicle manufacturing, logistics, and infrastructure development, were included to understand different perspectives.
- **Research and development focus:** Technology experts and research professors offered a closer look at upcoming technologies and the trajectory of current innovations.
- **Urban planning and mobility strategy:** Individuals involved in planning and policy provided insights into how urban and mobility strategies are adapting to accommodate new technologies.

The selection process was dynamic, utilizing both snowball and purposive sampling techniques.

Snowball sampling allowed us to extend our network based on recommendations from initial interviewees, which is deemed particularly valuable in accessing well-informed individuals when direct contacts are limited (Bryman & Bell, 2011). Given our limited experience in the field, that made it an appropriate sampling method. Purposive sampling was employed to target specific individuals who could contribute directly to the emerging themes identified during the exploratory phase and literature review. Patton (2015) emphasizes the utility of purposive sampling in qualitative research for its ability to focus on information-rich cases that yield in-depth understanding, strengthening its usage in this thesis.

To further enhance the breadth and depth of our interview pool, we continued to engage with new stakeholders recommended through our network to ensure that our data collection was as comprehensive and representative as possible. Interviews were conducted until data saturation was achieved, following the guidelines suggested by Hennink et al. (2017) for comprehensive thematic coverage. This approach ensured that all relevant perspectives of the topic were explored in detail, providing a robust foundation for the subsequent analysis.

The process was carefully documented and analyzed so that each new interview contributed to the research objectives. This iterative approach to participant selection and data collection ensured that the study remained aligned with the evolving landscape of the industry. All conducted interviews in the data collection phase are presented in Table 4 below.

**Table 4:** Overview of external data collection interviews

#	Category	Organization	Date	Duration
1	Researcher	Chalmers/Rise	2024-02-16	45 min
2	Researcher	Power Circle	2024-02-16	45 min
3	Academia	Chalmers	2024-02-19	65 min
4	Charging Infrastructure	Port of Gothenburg	2024-02-19	70 min
5	Project Coordinator	AFRY	2024-02-20	30 min
6	Researcher	RISE	2024-02-21	40 min
7	Researcher	Lindholmen Science Park	2024-02-22	60 min
8	Academia	Chalmers	2024-02-27	60 min
9	Charging Technology	Halmstad University	2024-02-27	45 min
10	Regulatory Expert	RISE	2024-02-28	30 min
11	Logistics Expert	Ex Chalmers	2024-02-28	30 min
12	Charging Technology	Volterio	2024-02-29	40 min
13	Charging Technology	ABB	2024-02-29	30 min
14	Vehicle Manufacturer	Scania	2024-02-29	40 min
15	Governmental	Göteborgs stad	2024-03-01	30 min
16	Academia	Chalmers	2024-03-01	35 min
17	Governmental	Trafikverket	2024-03-01	30 min
18	Vehicle Manufacturer	Volvo AB	2024-03-04	30 min
19	Vehicle Manufacturer	Scania	2024-03-05	40 min
20	Charging Technology	Ample	2024-03-06	30 min
21	Charging Infrastructure	Port of Gothenburg	2024-03-13	35 min
22	Project Coordinator	Business Region Gothenburg	2024-03-27	35 min
23	Charging Technology	Electreon	2024-03-27	40 min
24	Charging Technology	Rocsys	2024-03-21	30 min
25	Charging Technology	Rocsys	2024-03-27	30 min
26	Charging Technology	Elonroad	2024-04-08	35 min
27	Carrier	DFDS	2024-04-16	35 min
28	Charging Infrastructure	Kempower	2024-04-17	30 min

### 3.4 Data Analysis

After conducting the semi-structured interviews, we transcribed each recorded session to ensure the analysis could be made on accurate representations of the conversations. We used an intelligent transcription method, which means that pauses and filler words were omitted. For the few interviews that were not recorded, detailed notes were taken during the interview sessions and served as the

primary data source. In addition, these notes were complemented with immediate post-interview reflections to capture any other contextual factors, aligning with recommendations by Rubin and Rubin (2012). Here, we also wrote down our main findings for the respective interview to facilitate the upcoming analysis.

The purpose of content analysis is to systematically arrange the collected data in order to draw conclusions from it (Bengtsson, 2016). The approach began with an extensive process of data familiarization, where interview transcriptions, key findings, and notes were read and re-read to gain a deep understanding of the content – a step that Saldaña (2015) identifies as crucial for familiarizing oneself with the data’s depth and breadth. After this, we initiated a systematic coding process, marking segments of text that were particularly relevant to our research question, a method supported by Bengtsson (2016).

During the coding process, we started to group the text segments and key findings into common themes. This thematic development was conducted using both inductive and deductive reasoning, which allowed us to integrate findings directly with our theoretical framework, following the approach suggested by Braun and Clarke (2006). Such an approach was aimed to improve the rigor and trustworthiness of the qualitative analysis by mitigating potential biases (Malterud, 2001). The common themes were then further aggregated and categorized under different headers related to our research question. We also regularly reviewed and refined the themes to ensure they accurately represented the data and were coherent throughout the analysis. This refinement process involved adjusting, combining, and even discarding themes depending on the depth of data supporting them. We filtered out some findings as they were considered too far out of scope or did not pertain to any of our relevant themes. Some examples of these are how many interviews brought up the importance of vehicle-to-grid, but this was not as connected to the specific charging technologies, or how some interviews went outside the scope of the road haulage industry.

The final phase of our analysis involved defining and detailing the themes, examining how they interrelated, and discussing the overall narrative they created in relation to our research question, guided by the recommendations of Patton (2015). Additionally, we assessed the broader implications of our findings through a narrative that connected these themes, following practices outlined by Saldaña (2015).

Finally, to further validate our findings, we conducted a workshop with key industry stakeholders at the case company to review the themes identified. Before the workshop, we identified what perspectives that we believed were the most valuable, which we concluded to be *Operations*, *Commercial*, *Hardware*, *Autonomous Platform*, *Manufacturing* and *Charging*. Then we invited at least one responsible person within all of these practice/perspectives at the case company to participate. The session allowed participants to provide feedback and ensured that our analysis resonated with real-world experiences, enhancing the validity of our research. This collaborative

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approach not only confirmed the relevance of our findings but also enriched our research with practical insights.

### 3.5 Validity, generalizability, and reliability

To evaluate the quality of a qualitative study, Mason (1996) highlights the importance of reliability, validity, and generalizability. This section discusses these concepts in the context of our completed study.

Validity refers to the accuracy with which the study reflects the phenomena it was intended to explore (Bell et al., 2019). In our study, we ensured validity initially through exploratory interviews that helped us understand the problem deeply. We maintained this through regular check-ins with our supervisor at Chalmers and the case company. Additionally, an internal workshop was conducted to validate the findings with stakeholders, ensuring the study addressed relevant questions. Finally, the use of triangulation, involving multiple sources of data, further strengthened the study's validity.

Reliability describes the consistency of the study and the trustworthiness of its results (Bell et al., 2019). While replicating qualitative studies, especially case studies, is challenging, we aimed to enhance reliability by carefully documenting our processes, including the interview guide, criteria for selecting interviewees, and the coding process. This documentation strategy aligns with Bryman and Bell's (2011) recommendations for improving consistency. However, the anonymity of interviewees, necessary for ethical reasons, might limit the ability to replicate or verify the findings directly.

Generalizability is the extent to which findings from the study can be applied to other contexts. Although case studies traditionally face limitations in generalizability, our study aimed to overcome this by anchoring insights in established theories and covering a broad range of industry stakeholders. Despite the case study focus on one industry, the insights are still applicable to similar industries going through the twin transition. Nonetheless, the specific characteristics of the road haulage sector might limit the direct application of findings to vastly different sectors or situations. Finally, the use of purposive and snowball sampling could introduce selection biases, but we attempted to mitigate this by ensuring a diverse range of interview participants.

### 3.6 Ethics

Ethical aspects were considered throughout our study, adhering to the four main principles outlined by Bryman (2018): information, consent, utility, and confidentiality. Every respondent was fully informed about the study's purpose and methods, and their participation was strictly voluntary, with the option to withdraw at any time. We assured participants that the data collected would only be used for academic purposes and maintained strict confidentiality. Given the potential for sensitive information disclosure, especially from the case company, we made sure to anonymize all

personal identifiers to secure the interests of all involved parties.

# 4

## Empirics

We structure the empirics according to the Multi-Level Perspective to capture the wide range of data collected from a diverse range of stakeholders and broad spectrum of perspectives. The holistic perspective is needed to fully grasp the complex ongoing transition and we explore how they relate to the pressures on both micro and macro levels.

### 4.1 Macro Pressure: Impact of Twin Transition

In this section, we delve into the empirical analysis of macro pressures, which we define as landscape developments within the Multi-Level Perspective framework. Landscape developments represent broad, external forces that can enable significant shifts in a regime. By examining these macro-level influences, we aim to understand how they catalyze or impede regime transitions. This will help us identify key drivers of change and their impact on the stability and evolution of the regime.

#### 4.1.1 Electrification as the Primary Transition Focus

The interviews reflected broad support for the goals associated with the twin transition, where both reduced emissions and increased automation are seen as key future requirements. However, it was noted that the two forces, electrification and automation, are not pursued as equally immediate priorities. Electrification is more urgently prioritized due to the pressing demands of environmental regulations, as articulated by a transport expert: *“Companies are much more pressed to get electrification in place than automation”*.

This prioritization stems largely from political and regulatory focus on decarbonization. There are many rigid regulations targeting electrification whereas automation is more seen as an opportunity, primarily enhancing operational efficiency and benefitting private firms. Moreover, the regulations that penalize carbon emission have clear time constraints which contrast with the more flexible timelines for automation. Additionally, the EU has established carbon regulations that force many actors to accelerate their electrification strategies. A vehicle manufacturer representative explained the priority of this challenge: *“We do not have the time. Our race to electrification cannot be delayed at all due to the stringent EU carbon regulation requirements”*. Additionally, a carrier underscored their ambitious targets, with one stating that *“Our aggressive goals to electrify a substantial segment of our fleet by 2030 drive us to intensify our efforts toward electrification”*. Therefore, interviewees considered automation as a secondary priority compared to the much more pressing goal of electrified charging infrastructure.

The development of infrastructure reflects this prioritization, with significant governmental support for the rapid establishment of charging stations to facilitate the transition. For example, the Swedish government prioritizes the establishment of charging stations as this has been a bottleneck of the transition to meet pressure from international regulations. The anticipation for an expansive charging network is also underpinned by European regulatory requirements, which necessitate a widespread deployment of charging stations. One researcher concluded how this is perceived as a clear roadmap to facilitate the electrification transition. A professor highlighted that the development of electrification infrastructure is progressing more rapidly than that of automation. Reflecting on this rapid development, another researcher pointed out that *“The existing electric infrastructure will certainly play a role in the development of systems for autonomous vehicles”*, indicating that the infrastructure for autonomous electric trucks will likely evolve based on the systems established for manually operated electric trucks, rather than replacing them entirely.

Moreover, the transitions between electrification and automation are observed to be notably disjointed. Several interviewees highlighted a significant disconnect and lack of coordination between teams working on electrification and those focusing on automation. This segmentation often results in separate forums with different individuals, which limits collaboration opportunities. As one researcher pointed out, *“Electromobility and automobility are treated as separate domains with different people, resulting in little cooperation.”* This separation is more than just organizational; it reflects a deeper strategic misalignment that directly impacts how technologies are developed and integrated.

The disjointed nature of these transitions impacts the current rollout of charging infrastructure, where limited consideration for automation is evident. Current policy frameworks and infrastructure developments focus primarily on meeting immediate decarbonization goals rather than integrating automation. A traffic planner emphasized, *“We don’t push for an automated perspective in the rollout of charging infrastructure now”* reflecting a policy emphasis on electrification. This approach suggests that while automation is recognized for its potential future benefits, it is currently secondary in terms of policy urgency and resource allocation.

#### **4.1.2 Regulatory Drivers Shaping Industry Adaptation**

While the previous section highlighted how regulatory pressures prioritize electrification over automation, this section delves deeper into the specific regulatory mechanisms that drive industry adaptation. These regulations not only mandate decarbonization but also define the operational boundaries within which industry actors must operate. They significantly influence the development of charging infrastructure, the standards for various charging technologies, and operational patterns within the system, all of which affect technology adoption

Firstly, the regulatory emphasis extends to the development of charging infrastructure, which

is critical for supporting the widespread adoption of electric vehicles. The introduction of the Alternative Fuel Infrastructure Regulation (AFIR), which mandates the deployment of alternative fuels infrastructure across the EU, exemplifies this push. *"Every EU member state needs to comply with these rules—charging stations for heavy-duty vehicles with a minimum output of 350 kW must be deployed every 60 km along the TEN-T network—ensuring that these facilities will be operational as soon as next year throughout the EU,"* explained a group of researchers. Furthermore, policies like 'Klimatklivet', which provides 100% financing for public charging infrastructure, encourage the development of these facilities even in areas where few electric trucks are currently on the roads.

Standardization is another critical aspect of the regulatory focus, aiming to ensure compatibility across the European network. The purpose is to prevent a situation where nearby countries have different solutions for carriers moving goods across borders. This standpoint is emphasized by a researcher *"We cannot build a technology here in Sweden which Europe is not aligned with"*. To facilitate this coherence, standardization bodies work closely with industry actors to establish universal standards both on international level (ISO) and EU level. Interviewees emphasized the critical role of standards, noting that many actors consider them essential for adoption. As a result, developers make significant efforts to ensure that upcoming standards align with their technologies. However, these processes, while essential, are noted for their lengthy durations due to the extensive collaboration required among numerous stakeholders.

Finally, regulations influence operational and charging patterns. For example, the EU mandates a 45-minute rest every 4.5 hours of driving, which charging developers strive to reach full vehicle charging in that time. In the US, union efforts have resulted in drivers not being responsible for connecting chargers, which supports the adoption of autonomous charging solutions. Thus, regulations and policies not only accelerate decarbonization but also directly modify operational and charging practices, notably impacting the adoption of each technology.

### 4.1.3 Large Dependency on Incumbent Vehicle Manufacturers

As the transition to electrification and automation unfolds, incumbent vehicle manufacturers are considered pivotal. While there has been a surge in new entrants developing charging technology, the vehicle manufacturing side remains dominated by established players. Unlike many industry transitions where disruptive new entrants often displace incumbents, leading vehicle manufacturers maintain their dominance in this case. Interviews highlight that these incumbents are instead changing their innovation and investments activities as a result of electrification pressure.

The critical role of vehicle manufacturers was consistently emphasized across the ecosystem, especially in discussions about partnerships. The road haulage industry involves multiple stakeholders who need to collaborate, but power dynamics distinguish the importance of vehicle manufacturers above the rest. Developers of emerging charging technologies particularly stressed the necessity of aligning

with vehicle manufacturers to ensure their products meet the necessary specifications for integration into vehicles. This underscores how new entrants prefer to create partnerships with established manufacturers rather than attempting to replace existing systems. A researcher highlighted the central role of vehicle manufacturing by noting, *“the vehicle is the most expensive part, so the charging developers are fully dependent on the vehicle manufacturer.”* This dependency extends to those developing the charging infrastructure, who must ensure compatibility with the current vehicle fleet. An interviewee in charging infrastructure development confirmed this, stating they simply roll out the technology deployed by vehicle manufacturers.

Furthermore, another group of researchers emphasized the significant influence vehicle manufacturers have in driving standardization processes, underscoring the dependency other actors have on them. It is also noted that both national and EU policymakers often align with the preferences of these manufacturers. This dependency across various levels highlights a concentrated decision-making process, where many actors rely on the directives set by vehicle manufacturers and strive for alignment with them. In addition, this also means that certain actors are not actively trying to influence the charging technology deployed, but rather follow the technological trajectory of incumbent vehicle manufacturers.

#### 4.1.4 Collaborative Dynamics Across the Industry

In addition to a concentrated power and decision making process, there is also noteworthy cooperation between the actors in the system within charging. Even though the vehicle manufacturers hold substantial power, they cannot accomplish the transition by themselves. One technology actor described it as *“Not even the most powerful vehicle manufacturer, such as Toyota, would be able to build an electric road in the city. There is a need for many different actors to coordinate and cooperate.”* The urgent need of decarbonization combined with future policies and regulations also pushes the actors to transition quickly and cooperate. An industrial actor captured this urgency: *“We do not have the time, we have to speed up the process.”* At the same time, most actors acknowledge that they are co-dependant on other actors in the system to transition. A governmental representative described it as *“Academia, industry and government cooperate a lot in this stage, with a lot of information sharing. A lot of stakeholders must be aligned to push for a standard as it is a system change.”* This picture is shared across the industry, with a researcher pointing out *“the entire heavy-duty vehicle industry is characterized by a lot of cooperation, with few dominant actors who are used to working with each other.”*

Moreover, the lack of sufficient charging infrastructure is currently hindering the sales of electric trucks, which are central to the core business of vehicle manufacturers. A vehicle manufacturer noted *“It is a chicken-and-egg-problem, where the technology is ready but the public infrastructure is not.”* Since charging infrastructure serves more as a support to their primary business rather than the main focus, vehicle manufacturers are less protective over trade secrets in this area. This

openness allows them to collaborate with one another, even though they are competitors in the broader automotive market. Therefore, charging experiences a high degree of cooperation and coordination compared to other aspects of the industry. This is underscored by most researchers who pointed towards standards and lobbying groups such as the Charging Interface Initiative (CharIN), and the European Automobile Manufacturers Association (ACEA). Additionally, researchers have observed these coordinated responses in standardization bodies and highlighted the joint ventures leading vehicle manufacturers have within charging. Consequently, the concentrated power dynamics, combined with collaborative nature and coordinated responses, concentrates the decision making process of diffusion in this industry.

## 4.2 Micro Pressure: Diffusion of Charging Technologies

As part of the multi-level perspective on socio-technical transitions, this section explores the micro-level pressures influencing the diffusion of charging technologies within the road haulage industry. While the broader landscape (macro pressures) shapes long-term shifts and sets the stage for systemic change, micro-level factors focus on the specific technological innovations and the immediate challenges they face. Here, we examine the impacts of individual charging technologies and how they interact with existing industry structures, consumer expectations, and regulatory frameworks to either foster or hinder their broader adoption. This helps to understand the technological potential of these innovations as well as the socio-economic and regulatory barriers they must overcome to become integral components of the transportation ecosystem.

A major source of uncertainty during the twin transition in the road haulage industry is the wide range of potential charging technologies. Interviewees noted that, as of today, there is only a single charging technology – cable charging – that has reached maturity and is supported by a well-established infrastructure. However, this does not imply that cable charging represents the optimal future solution. Instead, interviews revealed a consensus that while cable charging’s maturity drives its present dominance, other emerging technologies, though less mature, offer attributes that potentially make them better suited for future industry needs. For instance, certain technologies were described to find their place in niche applications where their unique advantages can be fully leveraged. Despite their promise, each of these technologies faces distinct barriers that hinder their widespread adoption and influence their diffusion across the industry.

Additionally, interviewees pointed out that investments and technological advancements in a single charging technology do not guarantee that it will become the dominant design in the future. Instead, many of these technologies exhibit similarities and form so-called “technology clusters”. Within these clusters, technological spillovers contribute to their collective advancement. This interconnected development fosters accelerated learning and adoption among the grouped technologies.

### 4.2.1 Maturity and Adoption of Charging Solutions

This section explores the landscape of charging technologies within the road haulage industry, emphasizing the current predominance of cable charging and examining the status and potential of emerging alternatives.

**Cable charging** is currently the predominant choice due to its simplicity and cost-effectiveness. It is favored for its ease of integration and reliability. An e-mobility expert noted, *"Cable charging is easy to understand and mature. Many carriers start with [this type of charger] on their depots as it is considered low-hanging fruit."* Moreover, this technology's widespread adoption is supported by its operational similarities to traditional fuel systems, offering a familiar transition path for operators. A researcher highlights how the urgent need of decarbonization of the industry makes the actors unable to wait and, instead, have to adopt the available and mature option.

The other technologies either still remain in an exploratory phase or are only commercialized to address specific operational needs beyond what cable charging can offer. **Pantographs** is described as the most mature alternative technology, where it is fully commercialized in specific niches, such as public transit systems for buses. **Battery swapping** is also commercialized in specialized contexts, where interviewers highlighted its use in China or in industrial machinery. The solution is recognized for its potential to support operations with high utilization rates and extensive travel distances, offering a viable solution for specific logistical scenarios.

**Robotic arms, conductive charging** and **inductive charging** are less mature but have recently become commercialized. Developers emphasize their focus on applications where traditional contact-based methods are less feasible, particularly in environments where human interaction is limited or automation is critical. Inductive charging has also seen a distinct development in recent years, with multiple actors reporting the availability of systems capable of delivering up to 500 kW, a substantial increase from what was possible just a few years ago.

Finally, **the electric road** is considered the most immature technology alternative and is described to remain in an exploratory phase – primarily carried out through pilot projects. The envisioned use case for dynamic charging is optimal where vehicles can charge while in motion, which minimizes downtime and extends operational ranges.

### 4.2.2 Motivations for Alternative Technologies Beyond Maturity

While cable charging currently dominates due to its maturity, the road haulage industry faces evolving demands that increasingly expose the limitations of this technology. As detailed in the previous section, while cable charging offers operational familiarity and a broad existing infrastructure, it does not fully meet the advancing requirements for efficiency, automation compatibility, and system resilience. This section explores how various emerging technologies, despite their current lower

levels of maturity, present compelling advantages that align with future industry directions, which challenges the existing dominance of cable charging.

The interviews reveal a multifaceted approach to technology adoption, where factors such as vehicle uptime, operational efficiency, and future readiness for automation play significant roles. Stakeholders express concerns that traditional cable charging, with its manual operation and risk of physical damage due to moving parts, is seen as a constraint. Additionally, the technology's intensive charging sessions can degrade battery health over time, prompting a shift towards technologies that allow more frequent, yet less intensive, charging sessions.

Most alternative technologies except robotic arms are seen as efficiency improvements, where battery swapping and dynamic charging systems are particularly noted for their potential to minimize vehicle downtime. Battery swapping allows for rapid replacement of depleted batteries, ideal for operations requiring high availability and swift turnaround. Electric roads also minimize downtime and are seen as the future of long-haul transport.

All discussed alternative technologies – robotic arms, pantographs, battery swapping, inductive charging, conductive charging, and electric roads – offer better compatibility with automated operations compared to traditional cable charging. For example, inductive charging and conductive charging are noted for their ability to seamlessly integrate into daily operations, such as during scheduled stops for loading and unloading, facilitating smoother operations without manual intervention. A vehicle manufacturer describes inductive charging as *"a Nirvana solution, especially when we are ready to go for fully autonomous charging,"* highlighting its potential to reduce downtime and enhance the automation readiness of logistics operations.

Finally, the benefits of these alternative technologies extend to improving battery health. Technologies like inductive charging, conductive charging, and pantographs not only reduce downtime but also mitigate the battery wear that often accompanies the deep, infrequent charging cycles of traditional systems. By enabling more frequent but less intense charging sessions, these technologies help maintain battery condition over longer periods, enhancing overall vehicle efficiency and reducing maintenance costs. Similarly, battery swapping supports the use of smaller, more efficient batteries, which can be tailored to specific operational needs. Battery swapping also separates the process of charging a battery and delivering the energy, which one technology developer described as *"very helpful where there are problems with energy delivery from the grid to the infrastructure"*.

### **4.2.3 Barriers to Alternative Charging Technologies**

While diverse charging technologies each offer unique benefits tailored to specific operational needs, the transition away from the dominant cable charging also gives rise to multiple barriers. These barriers include technical and infrastructural demands, as well as regulatory and ecosystem

complexities that influence the adoption and scalability of alternative technologies. Several interviewees even highlighted that cable charging will most likely remain as a backup if an actor would try to adapt to a more immature technology as a result of these barriers.

The most significant barrier to **battery swapping** technology is the need for standardization. Without a universal battery standard, the practicality of establishing a widespread battery swapping infrastructure is limited. Additionally, implementing this technology requires a coordinated ecosystem where specialized service providers or energy companies must take over the responsibility for owning and managing the batteries. An e-mobility expert concluded *“The battery is the most expensive component of the vehicle and that is a differentiation component – not something you want to standardize as a vehicle manufacturer. Swedish vehicle manufacturers shake their heads on this solution.”* This statement was also reflected in the interviews with the vehicle manufacturers, who concluded that they cannot see this in the public infrastructure in the foreseeable future. Furthermore, the high initial costs of setting up swapping stations are frequently mentioned as a substantial barrier.

One of the highlighted barriers to adopting **robotic arm** charging technology is the complexity of the robots required to perform what is essentially a simple task. Stakeholders pointed out that the investment in sophisticated robotic systems might not be justified for just connecting a charger to a vehicle. Additionally, the technology must also be compatible with a wide range of vehicle designs and charging standards.

**Pantograph charging** has become less necessary as battery technology advances, allowing buses to operate all day without needing intermediate charging. This shift was emphasized by a logistics professor who noted the diminishing need for pantograph stations. Additionally, the physical requirements for pantograph infrastructure are substantial, as pointed out by a technology developer, with considerable space needed to accommodate the setup.

**Inductive charging** technology faces significant variability in development progress among different technology developers. Some developers struggle with issues such as magnetic field interference and energy efficiency, which are critical for the safe and effective deployment of this technology. Although certain advancements have been made to overcome these issues among some developers, inconsistency remains across the industry. Similarly, the primary challenge for **conductive charging** lies in its infancy stage, which brings uncertainties related to long-term durability and reliability.

**Electric roads** face considerable infrastructural barriers and require the collaboration of multiple stakeholders, including traffic authorities, haulage contractors, grid developers, vehicle manufacturers, and municipalities. Moreover, a professor highlighted that the low traffic flow on potential routes makes the business model for dynamic charging systems complicated and economically challenging. The same professor also emphasized the very high risk of committing to a potentially inefficient

standard, drawing a parallel to Sweden’s adoption of the 16 Hz railway system instead of the more efficient 50 Hz.

#### 4.2.4 Summary of Charging Technology Findings

Following the detailed insights of different charging technologies in the road haulage industry, the table below provides a more concise summary of the key findings.

**Table 5:** Summary of findings related to charging technologies

Technology	Maturity	Benefits	Barriers
Cable	Mature, broad industry focus	Familiarity, cost-effectiveness	Not future-proof, limited by manual operation
Robotic arm	Early-stage contracts, targeting autonomous flows	Autonomous charging, safety, efficiency, easily integrated	High cost, limited operational upside
Pantographs	Mature, commercialized in niche areas (buses)	Autonomous charging	Require significant space
Battery swapping	Commercialized in adjacent niche areas, only pilot projects in road haulage industry	Reduce vehicle downtime, flexible energy delivery, smaller batteries	High infrastructure cost, standardization issues, ecosystem coordination
Inductive	Developing, early-stage contracts	Space-efficient, convenient, aligns with autonomous flow	Energy efficiency, standardization, inconsistency among actors
Conductive	Limited early developed	Space-efficient, convenient, aligns with autonomous flow	Immaturity, long-term reliability
Electric Roads	Pilot projects	Continuous operation, minimal downtime, smaller batteries	High cost, complex infrastructure, ecosystem coordination

#### 4.2.5 Spillover Effects from Cable Charging to Adjacent Technologies

While the charging technologies may appear as distinct options, interviews reveal a significant degree of interconnection between them. This gives rise to technology clusters, which showcases how advancements in one technology can benefit the development of others. Consequently, although cable charging is currently the only mature option, it provides a foundation that promotes the enhancement and rapid progression of other emerging technologies.

Interviewees highlight how all technologies except battery swapping build on the same underlying technology as the cable charging, using the same protocols and hardware components. This gives room for compatibility possibilities in both adoption and technology development, where one

academic expert highlighted how advancements in one technology can easily benefit its clustered counterparts due to these shared components. Moreover, one technology developer explained it more practically: *“We build everything [for the conductive technology] on the basis of what is already there. The only difference is the connector that is optimized for the application that we plug on the car’s underbody and not to the side.”*. This adaptability across technologies underscores the foundational interconnections that facilitate broader technology adoption within the cluster.

The infrastructure side of the technology cluster further exemplifies this interconnection. An independent cable charging developer emphasized their system’s flexibility, stating, *“We’re super flexible. Since the power generation and delivery are separate in our systems, transitioning to, for example, inductive solutions [from cable charging] would be rather straightforward.”* This separation of power generation and delivery highlights how infrastructure can be designed to support multiple charging technologies, reducing barriers to adoption and enhancing the flexibility to pivot between technologies as market dynamics evolve.

Further exploring these connections, electric roads align closely with their stationary counterparts. This alignment leverages foundational advancements made in stationary systems to facilitate a smoother transition to dynamic applications in the future. One technology expert clearly stated, *“As a user, there is no difference between our stationary and dynamic [inductive] solution - you are compatible with both. However, the process of developing dynamic electric roads is much more complex compared to the much easier stationary solution.”* This illustrates a unified development trajectory where initial investments in stationary technology can catalyze advancements in dynamic charging.

Contrastingly, battery swapping is depicted as following a separate developmental path. This technology diverges significantly as it requires a different system where battery production and management are externalized, often involving third parties or specialized service providers. Multiple participants highlighted that this divergence introduces significant barriers to adoption, originating from the need to standardize across different operational frameworks and vehicle models. An academic expert elaborated on these challenges, noting that such divergent paths encounter greater adoption barriers due to shifts across multiple operational dimensions, necessitating distinct approaches to integration and standardization.

Finally, interviews revealed that while the initial cost of physical charging units is substantial, it often represents less than half the total investment needed. The majority of expenses are instead in establishing the necessary grid connections and infrastructure groundwork. This serves as a mitigation factor to a potential lock-in, as the majority of the cost will not be a sunk cost for other adjacent technologies.

#### 4.2.6 Room for Niche Applications

Another factor that prevents one mature solution from dominating the entire market, apart from the technology spillover, is how interviews describe the existence and continued likelihood of private niches. Several interviews highlight how they anticipate multiple viable technologies coexisting within the market, where each is serving or will be serving distinct operational needs and regional preferences. For instance, many highlighted battery swapping has gained traction in regions like China, where governmental subsidies can support the technology's expansion. Similarly, in the United States, robotic arm charging has found a unique application due to union mandates that relieve drivers from the responsibility of connecting chargers. These examples illustrate how various technologies can find their place in private niches in the market. One technology developer described this as straightforward as *"We will absolutely see multiple different technologies. You will see one market for traditional cable charging, one market for inductive charging, and one for battery swapping."*

This phenomenon is further emphasized by the fact that private charging, such as in home depots, is expected to keep a substantial part of the market. A researcher described it as *"Most actors have built up their own infrastructure in their terminals, some to secure price and supply and others to own the process."* This means that multiple other technologies different from the public can find a place in the market as a niche application.

#### 4.2.7 Strategic Flexibility as a Response to Technology Shifts

Interviews highlighted how flexibility is vital when stakeholders try to navigate the uncertainty surrounding the adoption of new charging technologies. While all actors conclude that the mature cable charging has a dominant position with its established infrastructure, the landscape is far from static. Moreover, the interconnectedness of the industry causes many actors to focus on flexible strategies, ensuring they are ready to pivot when market conditions shift.

Vehicle manufacturers are considered particularly important in this dynamic environment. Many of these vehicle manufacturers are expanding beyond focusing on a single technology, and instead explore multiple charging solutions to remain competitive and responsive to future customer demands. One vehicle manufacturer explained it as *"We cannot afford to focus on only one or the other, we need to consider both what is the standard today and potential future solutions."* The same actor also highlighted the value of partnership and joint ventures, where they explore less mature charging technologies. Another vehicle manufacturer focuses on a modular vehicle design, specifically structured to accommodate various types of charging systems. This modularity ensures that as new charging technologies become viable, they can be integrated into the vehicles without requiring complete redesigns, thus facilitating quicker adaptation to market changes.

This strategic flexibility is extended to the charging developers. For example, one developer mentioned how they have separated the power generation and distribution which allows for swift transitions between different distribution methods. Additionally, the separation ensures that innovation activities in power generation are applicable for other distribution methods, which prevents lock-in effects. Another example of the actor's flexibility is how many electric road developers are now expanding their offering to also include stationary charging technology as the latter is easier to commercialize. Such strategies are highlighted to enhance an organization's agility, minimizing the risks associated with technological lock-in and maximizing responsiveness to new opportunities.

# 5

## Discussion

### 5.1 Macro Pressure: Electrification Paving the Way for Automation

Our discussion begins by addressing the macro pressure, which compels the regime to adapt and paves the way for niche innovations. This macro pressure is the driving force that requires change, containing the micro pressures.

Initially, we illustrate how the twin transitions of electrification and automation should be viewed as two distinct sequential processes rather than occurring simultaneously. Subsequently, we explore the dynamics and implications of the initial electrification transition. Building on this, we examine the boundaries this initial phase imposes on the subsequent transition to automation. We conclude this section by analyzing how the regime's configuration and its response to macro pressure influence technology diffusion. This analysis also sets the stage for the following section, which delves into the micro pressures.

#### 5.1.1 Two Separate Sequential Transitions

While much of the existing literature portrays multiple transitions as simultaneous shifts within socio-technical systems, our findings suggest a more detailed story. In the twin transition of the road haulage industry, electrification is clearly prioritized over automation. This emphasis largely stems from the urgent demands of environmental regulations and the pressing need for sustainability. Public policy is a key factor guiding technology adoption, as it incentivizes sustainability-related goals, pushing organizations to prioritize electrification technologies to meet regulatory requirements. Such regulations, particularly strict EU carbon reduction mandates, not only demand emission cuts but also set clear and ambitious targets for various industry participants. This differs from views like those of Fouquet and Hippe (2022), who observed that digitalization might advance without sufficient decarbonization. In our case, the road haulage sector clearly prioritizes electrification, potentially paving the way for later integration of automation technologies, rather than the opposite.

The technological characteristics of electrification and its relative maturity compared to automation also guide adoption. Electrification technologies are more developed and market-ready, while automation faces significant technical and societal challenges. The investment trends within the sector reflect this focus, with more resources allocated towards developing strong electrification capabilities. This also aligns with market readiness and technological maturity, where electrification

technologies are more developed compared to automation that still faces significant technical and societal challenges. As a result, investments and infrastructure are currently focused on electrification. Therefore, and as previously discussed in our theoretical framework, the landscape pressure is primarily originating from electrification, with automation expected to follow as a separate and subsequent transition phase.

### 5.1.2 Maintained Core Structure in Electrification Transition

This section explores how the socio-technical regime – the established network of relationships, practices, technologies, and user expectations – adapts to the pressures from the prioritization of electrification over autonomous transitions, blending insights from both literature and empirical findings.

As illustrated, the electrification transition places significant adaptation pressure on the regime, recognized and responded to by regime actors. Electrification, while significantly altering the existing system and posing adoption challenges, is a gradual process influenced by technological advances, supportive policies, and evolving consumer demands, rather than an abrupt shock. This type of change can be categorized as an *'Disruptive'* landscape development (Suarez & Oliva, 2005). With this type of change, Geels and Schot (2007) describe two transitions types depending on the maturity of niche innovations and whether incumbent actors respond to the pressure and evolve.

Empirical findings from our study reveal that in the electrification of road haulage, niche-innovations were not sufficiently mature when pressure arose. Additionally, incumbent actors have adjusted their investment activities to align with the pressure, focusing on electrification. This behavior aligns with what Geels and Schot (2007) term as a *'Transformation Path'*. Therefore, this transition stands in contrast to most literature on disruptive technologies, which often illustrates how new entrants replace incumbents unable to overcome inertia. As regime actors adjust their innovation activities in response to landscape pressure, the regime evolves through a gradual process of incremental adjustments and strategic reorientations, rather than complete replacement. This adaptation is evidenced by the substantial investments made by vehicle manufacturers and carriers in electric trucks, demonstrating the regime's evolution from its existing structure. These actor's emphasis on strategic shifts towards electrification further underscore their commitment to adapt to the landscape pressure. Consequently, the industry's fundamental architecture is expected to persist as the regime continues to evolve through cumulative adjustments (Geels & Schot, 2007).

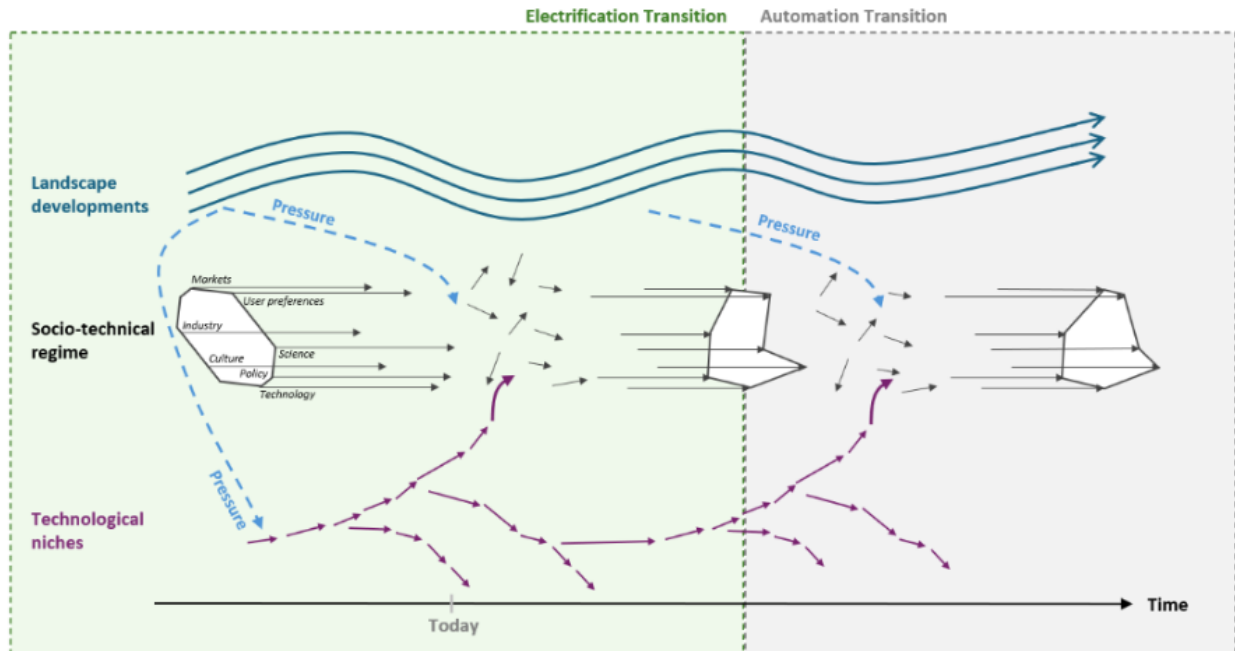
The socio-technical systems' high degree of integration and reliance on cooperation further complicates the potential for new competitors to enter and displace incumbents, as highlighted by Simoens et al. (2022). Empirical findings underscore this point, showing that entrants of new charging technologies depend on their compatibility with existing vehicle manufacturers' products. Moreover, the regime actors are generally committed to preserving existing user practices and

infrastructure investments. Consequently, the regime is likely to maintain the fundamental structure, evolving gradually through continuous adjustments rather than radical overhauls. This gradual evolution impacts technology adoption patterns, favoring technologies aligned with existing practices and infrastructures over radical innovations.

### 5.1.3 Constraints on Subsequent Autonomous Transition

In the transition within the road haulage industry, the shift towards electrification before the widespread implementation of automation signifies more than just a sequential change. It sets a trajectory that could potentially shape, or even restrict, the integration of autonomous technologies. Interview insights suggest that the strategic course and infrastructural advancements are predominantly shaped by regulatory pressures and immediate sustainability objectives. This singular focus on electrification meets current needs, but does not necessarily integrate considerations for future autonomous applications. This may create a path dependency (Utterback & Suarez, 1993) where the infrastructure that is rolled out does not account for the specific technological requirements or operational flows that fully autonomous trucks may demand.

Just as the transition to electrification evolved from the traditional fueling regime, the autonomous transition is expected to build upon the foundations established by electrification efforts. Initially, the industry was deeply rooted in a traditional fuel system, developing a socio-technical regime tailored to these conventional methods. This historical context set clear limitations on the potential changes during the electrification transition. Similarly, as the socio-technical regime now adapts due to the current shift towards electrification, it will likely become further entrenched, naturally evolving to support and maintain the status quo of electrification, without automation considerations. As illustrated in Figure 12, after the electrification transition, the socio-technical regime will reach a configuration that is likely to establish limitations on how the regime can later evolve under the influence of automation. Such an evolution could impose resistance or add complexity to the seamless incorporation of autonomous trucks into the existing framework. This scenario resembles how the concept of a dominant design impedes future technological transitions, as articulated by Utterback and Suarez (1993), who argue that once a particular technology becomes entrenched, it sets a path dependency that limits the scope of subsequent innovations.



**Figure 12:** Illustration of sequential transition, based on Geels (2002)

Moreover, the highlighted separation between the teams working on electrification and those focusing on automation could amplify these challenges. The lack of coordination and shared vision may result in missed opportunities to design infrastructure that is flexible enough to cater to both electric and autonomous technologies. Bergek and Onufrey (2014) discuss coordination effects as essential in facilitating technological integration within industries, emphasizing that without coordinated efforts, technological transitions are difficult to implement. Consequently, technological and organizational silos are critical factors constraining the subsequent transition to automation because they hinder the development of integrated infrastructure solutions.

Finally, the policymakers, who are considered the main drivers of the electrification transition, are described to not be as invested in the automation transition. Thus, the intervention of policymakers to solve the chicken-and-egg dilemma through extensive subsidies and targets for charging infrastructure is not expected to be as forceful when autonomous vehicles become commercially available. This dynamic complicates the potential for drastic shifts towards automation-focused technologies, as organizations will have already committed significant resources, developed competencies, and made investments in the existing electrification infrastructure.

#### 5.1.4 Regime Configuration Influence on Technology Diffusion

This section explores how the regime configuration within the road haulage industry influences the diffusion patterns of alternative technologies. Compared to traditional literature on adoption

patterns, this industry reflects a more extensive coordination and collaboration aspect.

Our empirical findings emphasize the critical role of incumbent vehicle manufacturers, where new entrants in charging technology seek partnerships rather than attempting to displace them. Additionally, policy makers and standardization efforts are described to align their efforts with the vehicle manufacturers, which create a concentrated power dynamic. However, despite this dominance, vehicle manufacturers are still described to prioritize collaboration with other stakeholders to achieve the transition. Hence, the empirical findings reveal a collaborative dynamic where key stakeholders jointly steer the technological trajectory.

The collaborative nature of this regime encourages strategic alignment that both accelerates infrastructure development and reduces industry-wide uncertainty. Stakeholders, including vehicle manufacturers, standardization bodies, and industry associations like CharIN and ACEA, synchronize their efforts to focus on collective goals, which streamlines the technology adoption process. This departure from the typical path-dependent model, characterized by multiple isolated decisions, and involves fewer but more decisive actions that significantly influence technology adoption and diffusion. The concentrated decision-making power and collaborative dynamics facilitate swift transitions and enable the industry to address and overcome significant lock-in effects.

However, while this collective approach facilitates rapid adaptations and the integration of adjacent technologies, it also raises challenges for the introduction of radical innovations. The structure's inherent focus on incremental improvements and maintaining compatibility with existing systems restricts the ability to embrace transformative changes. Therefore, while the regime effectively supports the adoption of technologies that are closely aligned with current systems, it presents substantial barriers to more disruptive or radical innovations that deviate from the established path.

## 5.2 Micro Pressure: Multiple Potential Breakthroughs

The chicken-and-egg dilemma and high uncertainty in the road haulage industry present significant challenges for actors when deciding which technological paths to pursue. Traditional literature suggests that companies facing similar challenges may delay decisions and remain in status quo (Suarez & Oliva, 2005). However, our findings suggest a more nuanced scenario where the pressing regulations force actors to electrify. Furthermore, the presence of technology clusters and the flexibility of these clusters provide a strategic cushion against these uncertainties. This cushion mitigates the risk associated with early-stage investments in immature technologies as the clusters allow for simultaneous advancements across multiple technologies.

Additionally, our research indicates that, due to varied operational conditions in the industry, there are niches within private settings or specialized applications where alternative technologies can innovate and develop, potentially competing with established solutions. Even if some charging

technologies do not become viable for widespread adoption, it is beneficial for industry actors to explore a wide range of options to identify and capitalize on such niche applications.

### 5.2.1 Only One Mature Option Today

In the landscape of charging technologies for road haulage, traditional cable charging stands out as the only mature option, extensively adopted due to its established infrastructure and operational familiarity. Previous studies often illustrate how dominant designs can lead to technological lock-in, where a particular technology becomes entrenched, making it difficult for alternative technologies to gain traction (Bergek & Onufrey, 2014). This lock-in is evident in our case with cable charging, which has become the standard due to its compatibility with existing vehicle designs and refueling practices. The urgency associated with the electrification transition intensifies lock-in effects as there is no time to wait for immature technologies to develop. Policies such as ‘*Klimatklivet*’ and ‘*AFIR*’ directive accelerate the current roll-out which favors more mature technologies. Despite this, there is a recognition among industry stakeholders that cable charging might not represent the optimal long-term solution. This well reflects the literature’s conclusion on how a traditional alternative can be preferred over potentially superior options (Grubler, 1996).

The empirical section highlights how most other technologies, such as inductive, conductive charging or electric roads are still early in their development. Most projects are in the pilot phase where some innovators are willing to try and experiment with new charging solutions. This well resembles Roger’s (2003) categorization of adoption groups and Grubler’s (1996) description of S-shaped diffusion curves, where these immature technologies have yet to take off.

Cable charging’s dominance is also reinforced by several self-reinforcing mechanisms identified in existing literature, such as expectation effects that drive ongoing investments towards this established technology (Onufrey & Bergek, 2015). These investments and the resulting learning effects make cable charging increasingly cost-effective and efficient, demonstrating economies of scale and continuous improvements. Furthermore, the technology benefits from complementary effects, such as compatibility with existing vehicle designs, and coordination effects, where stakeholder efforts are synchronized, which enhances the lock-in.

### 5.2.2 Technology Cluster Prevent Future Lock-in Effects

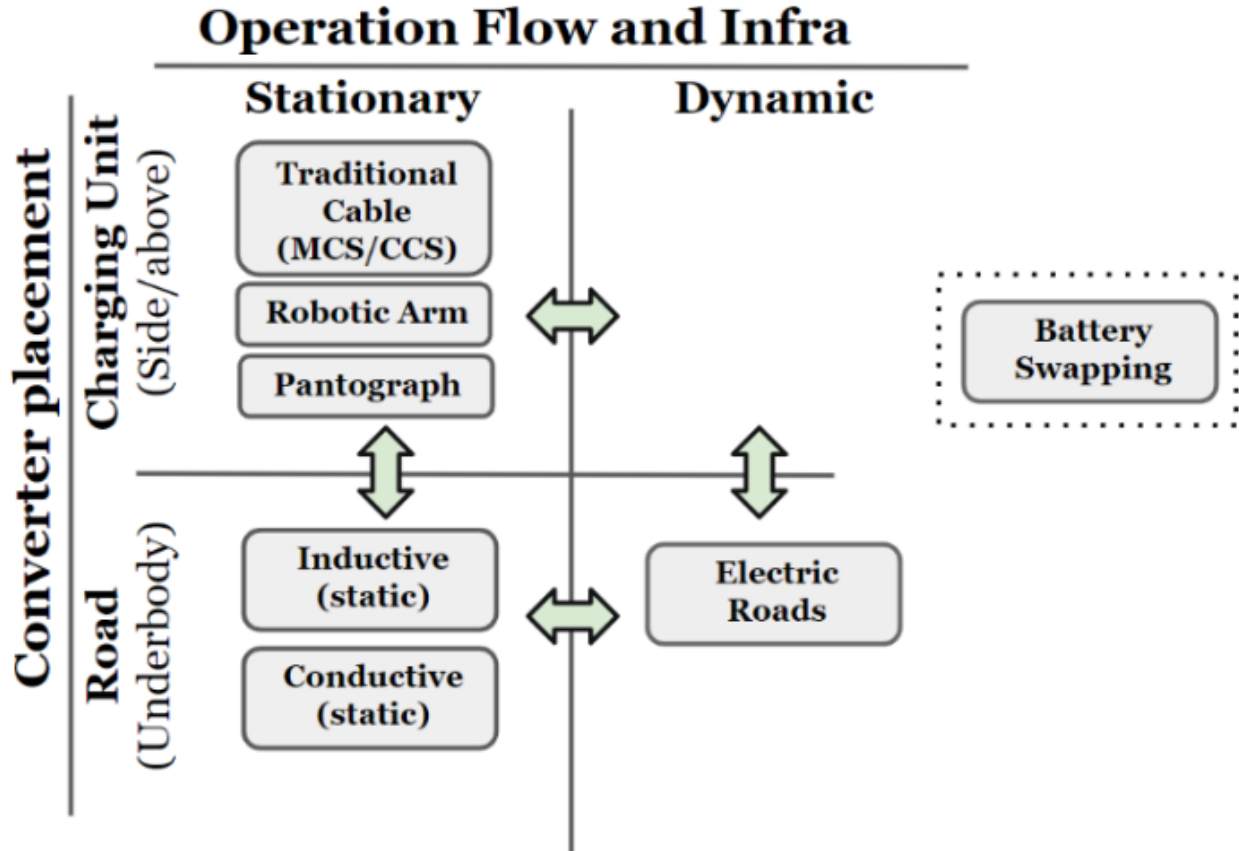
The discussion in the previous sections highlighted significant lock-in effects that favor cable charging systems. These effects align with both historical adoption patterns and established theoretical perspectives within the field. However, our findings suggest the presence of mitigating factors in the current ecosystem that are often overlooked in the literature.

The relationship between traditional cable charging and all alternative technologies except battery

swapping exemplifies what can be termed as 'technology clusters'. These clusters are founded on shared components and underlying principles that facilitate technological spillovers, similar to those Karshenas and Stoneman (1995) describe, or the cross-technology learning effects noted by Bergek and Onufrey (2014). Improvements in one technology thus benefit adjacent technologies within the same cluster. These effects ensure that adjacent technologies benefit not just from direct improvements, but also from increased collaboration and coordination opportunities within the cluster. Thus, the technology clusters are crucial as they enable the diffusion of innovations through shared infrastructure and incremental improvements, guiding technology adoption by reducing the risks associated with transitioning to new technologies.

The empirical findings further emphasized the synergies within the cluster. These synergies ensure that advancements in power capabilities or efficiencies within the stationary versions have direct implications for dynamic charging, electric roads. This facilitates alignment of vehicle configurations for future dynamic compatibility, showcasing coordination and complementary effects as described by Bergek and Onufrey (2014). As a result of these dynamics, developers are adopting a diversified focus that not only enhances current technologies but also paves the way for future innovations.

These dynamics are visualized in Figure 13, presented as a 2x2 matrix categorizing charging technologies based on their operational flow (stationary or dynamic) and converter placement (side/above vs. road/underbody). This matrix layout helps illustrate the potential for future transitions between different charging technologies. It is important to note that all technologies on the matrix are a part of the same clusters benefitting from the same technology spillover effects, but this layout captures other differences between them. Moreover, the matrix does not assign a unique technology to each quadrant; rather, some quadrants contain multiple technologies, showcasing the diversity within each category.



**Figure 13:** Adjacent Charging Technologies Within the Cluster.

The left side of the matrix encompasses stationary technologies where the vehicle is charged at fixed points, while the right side covers dynamic charging technologies, allowing vehicles to charge while in motion. The other axis divides the technologies based on whether the charging unit is integrated into the road or as a separate unit, which changes the position of the charging relative to the vehicle. The upper left quadrant combines traditional contact methods such as cable charging with robotic arms and pantographs, reflecting their reliance on physical connections to transfer power and operate within a stationary context. Below them, we see underbody methods like stationary inductive and conductive systems, which remove the need for a standalone charging unit and, thus, reduces wear, space and maintenance associated with above-ground mechanical connectors. Electric roads are placed in the bottom-right quadrant. However, the dynamic-side/above quadrant is empty as there were no identified road haulage charging alternatives which operate dynamically with an above-ground physical charging converter.

Transitions between adjacent quadrants, such as from the stationary-side/above to the stationary-underbody or from stationary-underbody to dynamic-underbody, are relatively straightforward because they share either a common operation flow or interface method. However,

diagonal transitions, such as moving from the stationary-side/above directly to dynamic-underbody, present substantial challenges. These movements require simultaneous changes in both the operational flow and the interface when transitioning from a static, physical connection to a dynamic, contactless system, which entail significant technical barriers and infrastructural investments.

As battery swapping is not a part of the cluster due to its distinct nature, it is placed outside the matrix. Unlike the gradual transitions within and between the quadrants of the matrix, battery swapping involves a completely different approach with separate systems for battery management and standardization. It also requires extensive changes to vehicle design, charging infrastructure, and logistic operations, which makes it fundamentally different from other types of charging technologies. This placement underscores its isolation from the spillover and learning effects that benefit the technologies within the matrix.

The matrix not only helps in visualizing possible transitions but also helps underline how these interconnections can drive a broader technological evolution across the charging spectrum. The ability to transition smoothly within clusters provides a mechanism to counteract potential lock-in effects by facilitating flexibility in technological adoption and adaptation. This flexibility is critical as it allows stakeholders to shift focus or adapt strategies in response to emerging technologies or changing market conditions without being burdened by previous investments. Thus, while cable charging current dominance might indicate a linear trajectory, the clustering implies a more complex, intertwined path of technological evolution with multiple possible future avenues. Therefore, the technological characteristics of these clusters and their inherent flexibility are key factors that guide technology adoption.

Finally, the empirical data highlights another critical aspect that mitigate the lock-in effect. The interviews conclude how the majority of the expenses in electric vehicle (EV) charging technology development are not tied to the charging units themselves, but to the associated grid connection and infrastructure. This cost distribution significantly reduces the lock-in effect, making it less economically challenging to switch between different charging technologies. Since the underlying infrastructure – such as the electric grid and power distribution systems – accounts for the bulk of the investment and is compatible with multiple types of charging units, stakeholders can more readily adopt new technologies or upgrade existing systems. This flexibility in the use of infrastructure facilitates economic feasibility and encourages the adoption of innovative charging solutions without the need for extensive or costly modifications to the foundational grid setups.

In conclusion, this section highlights how technology clusters mitigate lock-in effects, which impacts adoption patterns. Shared components and principles within these clusters facilitate technological spillovers and cross-technology learning, primarily benefiting adjacent technologies over battery swapping and electric roads. This flexibility allows the industry to adapt to emerging innovations, supporting a dynamic and resilient technological landscape in the road haulage sector.

### 5.2.3 Niches Allow for Technology Development

Within the road haulage industry, our empirical findings present the existence of diverse niches, each characterized by unique operational needs or regional policies. These distinct requirements align with earlier literature of niche innovation where specialized technological adaptations can challenge and potentially transform the dominant technological regime (Geels & Schot, 2007).

Niches can act as protective spaces for more radical innovations, where they are sheltered from the prevailing regime's selection environment. Reflecting back to Figure 13, this means that battery swapping cannot completely be ruled out just because it does not share technological similarities with other charging technologies. These technological niches are crucial because they allow innovations to develop without immediate pressure to conform to the dominant system, guiding technology adoption by providing a safe space for experimentation and maturation. Thus, it is possible with a potential parallel evolution where the innovation within niches does not necessarily have to compete directly with the established cable charging regime but may gradually accumulate the capacity to provoke a regime shift. This resonates with the multi-level perspective framework where niche innovations can destabilize and replace existing regimes.

However, these private niches still do not provide the coordination and complementary effects that are required in the larger public system, which makes it more challenging for niche-innovations to break through the regime.

## 5.3 Implications For Practitioners

Our study presents several key implications for practitioners in the road haulage industry. To navigate the uncertainties of technological transitions, practitioners are advised to adopt flexible strategies and focus on technologies adjacent to existing cable charging to capitalize on cross-technology learning effects. Additionally, they should leverage the cooperative dynamics by engaging in various groups to gain insights into progress and market sentiment, which could indicate future developments.

Achieving strategic flexibility varies across different actors in the system. Large vehicle manufacturers with long production lead times may benefit from adopting modular strategies or explore multiple solutions to leverage economies of scale. In contrast, smaller manufacturers with less scale should focus on experimenting with at least one solution, allowing them to understand the change process and build necessary capabilities while simultaneously closely monitoring market dynamics. Charging technology developers can increase their flexibility by separating power distribution from generation, a move that protects investments across various distribution methods. Infrastructure providers, such as Vattenfall In-Charge, should select site locations that accommodate multiple charging technologies and ensure these sites are capable of being retrofitted in the future. Additionally, practitioners are encouraged to engage in pilot projects, leveraging subsidies and grants to facilitate

learning and adaptability while exploring innovative technologies

Furthermore, all road haulage practitioners should prioritize technologies adjacent to cable charging. Firstly, battery swapping, while innovative, faces clear adoption barriers due to its unique requirements and should be monitored rather than actively pursued. Secondly, electric roads, although promising, face more obstacles than inductive/conductive charging, which are more integrated with the current systems. Actors should, instead, focus on these adjacent technologies to reduce transition hurdles. Vehicle manufacturers can implement low hanging fruit adjustments to support this, for example by changing battery placement to be ready for underbody inductive/conductive charging.

Finally, actors across the ecosystem should actively participate in standardization bodies, associations, and other groups that are shaping the future of charging infrastructure. Engaging in these forums helps all stakeholders remain informed about technological advancements and market trends, which reduces uncertainty about future developments. The need for coordinated efforts makes establishing standards essential for widespread technology adoption. Therefore, it is crucial for charging developers to engage in standardization processes to ensure that emerging standards are closely aligned with their technologies. Similarly, vehicle manufacturers should participate to minimize the need for retrofitting as new technologies are adopted.

# 6

## Conclusion

### 6.1 Summary of Findings

The research aimed to provide theoretical insights into technology adoption and strategic responses during the early stages of industry transformation involving twin transitions. Our findings contribute to expanding the traditional literature on diffusion and technological transitions by highlighting unique dynamics in this sector.

Our findings indicate that public policy plays a crucial role in guiding technology adoption. Regulatory pressures, especially those focused on reducing carbon emissions, have prioritized electrification over automation. This means that the twin transition in the road haulage industry does not happen in parallel, but sequentially. This initial electrification focus establishes a foundational infrastructure that future automation technologies will likely build upon, rather than replace. This sequential approach creates boundaries on the scope and pace of the subsequent automation advancements.

The study showcase how the typology of the initial transition of electrification impact the industry dynamics, which in turn impact technology adoption. Unlike most studies that focus on transitions already completed, this approach provides a real-time perspective. The identification of a gradual transformation, with key actors and core structures remaining intact, suggests that the automation transition will evolve from a similar system as today. This favors technologies aligned with the existing regime over radical changes.

As key actors and core structures remain intact, the current dynamics of the industry are pivotal in shaping future adoption patterns. Coordination among key stakeholders and the strategic adaptability of companies emerge as dynamics with significant implications for adoption trends. Key actors - primarily vehicle manufacturers, due to other actors' compatibility requirements with the vehicle (the most expensive part) - collaborate and coordinate in multiple ways, such as through industry associations, lobbying groups and standardization bodies. This coordination streamlines the technology adoption process by aligning multiple key actors on a unified path. Additionally, the adaptable strategies of vehicle manufacturers and charging technology developers allow the industry to swiftly respond to evolving regulatory and market demands, ensuring that new technologies can be integrated with existing systems. The coordination and adaptability of actors facilitate swift transitions and mitigate severe lock-in effects, suggesting that a shift away from the current dominance of cable is feasible.

While the coordination and adaptability of actors support rapid changes and help mitigate lock-in effects, they also pose challenges for more radical technology adoption that deviate from the interests of key players. Moreover, the current adaptable strategies primarily support adjacent technologies, and not the radical ones. However, niche markets may offer the necessary space for these radical changes, allowing innovative solutions to be developed and refined in specialized, less competitive environments before they are adopted more broadly in the industry.

Transitioning from the themes of strategic adaptability and extensive coordination, technology clusters represent another pivotal element in shaping the technology adoption. These clusters, which are centered around shared charging protocols and hardware components, facilitate technological spillovers and cross-technology learning. This interconnectedness means that advancements in cable charging could enhance the capabilities of adjacent technologies, increasing the likelihood of adopting new solutions in the future. Such dynamics challenge the status quo by encouraging the exploration of non-traditional pathways and promoting a broader array of viable technologies. However, others, like battery swapping, may still face significant adoption barriers due to their unique operational and infrastructural requirements.

Moreover, the integrated nature of these clusters not only ensures compatibility among diverse technologies but also encourages firms to experiment with new technologies with less financial risk. Investments in emerging technologies are not viewed as sunk costs because the improvements and innovations can be applied across the technology spectrum, thus reducing lock-in effects. This strategic investment framework helps mitigate the financial risks associated with adopting new technologies, facilitating a more dynamic and adaptable industry response to emerging challenges and opportunities.

Overall, our study of the road haulage industry illustrates the complex and intertwined nature of the technology adoption process, incorporating the perspectives of twin transitions and technological transitions. We demonstrate that factors such as regulatory pressure, technological similarities, power dynamics, industry evolution, and alignment with existing systems significantly influence the adoption and diffusion of new technologies. Additionally, this thesis provides practical implications for practitioners navigating these transitions amidst uncertainty.

## **6.2 Limitations and Future Research**

The research captures a specific moment within the ongoing transitions, which may affect the applicability of the findings as industry standards, technological developments, and regulations continue to evolve. The study primarily relies on qualitative interviews, which, while offering in-depth perspectives, may not encompass the entire spectrum of industry viewpoints. This method may also introduce biases based on the subjective experiences of the interviewees and the selection of participants, which can affect the broader applicability of the results. Additionally, the complexity

of the transitions means that some factors and diverse stakeholder perspectives might not have been fully explored.

Future studies could expand on this work by employing a mixed-methods approach to combine the richness of qualitative data with the robustness of quantitative analysis, or by extending the research to different regions and contexts to enhance generalizability. Further exploration into how companies strategize and respond to these technological changes would also be valuable, particularly through examining the dynamics of co-opetition, where companies simultaneously cooperate and compete.

Additionally, there is also a significant opportunity to delve deeper into the impacts of specific policies on technology adoption. Analyzing how different regulatory environments influence corporate strategies and the deployment of new technologies could provide clearer insights into the complex relationship with policy and technologies. Furthermore, a detailed examination of battery development would add depth to understanding diffusion patterns and motivations. Since charging infrastructure is closely tied to battery advancements in terms of cost, size, and capabilities, exploring this dimension could significantly enhance our understanding of charging technology adoption.

# 7

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# A

## Interview Guide

### Background

- Describe your background in [x] shortly
- Describe your role within the organization

### Charging Technologies

- What charging technologies do you see as most relevant for HDVs?
  - For autonomous HDVs?
- Do you believe that an established charging infrastructure will be rolled out before the commercialization of autonomous trucks? What impact will this have on charging for autonomous trucks?

### Adoption

- What factors do you believe are driving the adoption of charging technologies for HDVs?
- How does the industry tackle the challenges of a non-standardized landscape for charging technologies?

### Cooperation

- How does cooperation across the industry regarding charging work at the moment?
  - How important would you say such collaboration is in situations like this with a lack of established standards?
  - What are the main challenges in this cooperation?
- How do policies and economic incentives impact the development of charging technologies for HDVs?

- Which actors are the most powerful?

### **Standards**

- Can you describe the typical process for how a technology becomes standardized within the industry? What are the key stages and who are the main influencers?
- Are there any regulatory challenges or barriers for the [technology] to become standard?
- How important would you say that the role of standardization is for the success of [technology]?

### **Other**

- Is there anything else you would like to highlight that would be relevant for our thesis?

### **Specific for charging developers/infrastructure developers**

- Can you describe the current state of [technology] in the context of electric and autonomous vehicles?
- Do you think multiple different technologies will work in parallel? Why/why not?
- What are the main advantages and limitations of [technology] compared to other charging technologies? Have there been any recent advancements to address some of these challenges?
- What are the main technological challenges preventing mass adoption e.g., effect, price, density/size?
- Which vehicles are the technology mostly targeting at the moment?
- Which logistics flow are the technology mostly targeting at the moment?
- Can [technology] charging be integrated into existing infrastructure, or does it require completely new setups?
- What are key considerations for companies when integrating [technology] into their operations?
- Can you describe the ecosystem required to support [technology], including key partners and stakeholders?

### **Specific for vehicle manufacturers**

- How do you view charging technology in terms of business case improvement? Is it merely a necessity, or do you see it as a strategic opportunity for differentiation and value creation?
- Across the spectrum of charging technologies (inductive, conductive, battery swapping, etc.), what challenges do you anticipate in their development and implementation?
- How do different charging technologies fit into your overall strategy for electric and autonomous vehicles?
- Can you discuss any strategic partnerships or collaborations your company has entered into to advance charging technologies or infrastructure?

### **Specific for governmental**

- Describe your role in the development of charging infrastructure?
  - What are the bottlenecks in this development?
- How do you see the future ratio of depot vs public charging?
  - Do you rather see an established standard for the road haulage or multiple parallel technologies, where private actors own their infrastructure?



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