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Digital Hub-to-Hub Operations in Autonomous Trucking

An identification of digital interfaces within the hub-to-hub model

Master's thesis in Quality and operations management

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Abstract

As the transportation industry navigates various operational challenges, the hub-to-hub model using autonomous trucks has emerged as a transformative approach to streamline logistics and enhance operational efficiency. Despite the potential of this technology, there is a significant gap in understanding the specific digital interfaces and stakeholder roles crucial for its successful implementation. This thesis addresses this gap by identifying critical digital interfaces and key stakeholders that are essential for successful hub operations in autonomous trucking systems. The literature review comprises a detailed analysis across four main areas: autonomous road freight transportation, business network perspectives, supply chain interfaces, and lessons learned from adjacent industries. This comprehensive review establishes a foundational understanding of the necessary technological frameworks and stakeholder interactions that support autonomous trucking operations.

The study further delineates the evolution of potential future scenarios that could unfold within the industry, focusing on the shift from conventional trucking to autonomous trucking ecosystems. It explores the emergence of new stakeholder roles and the evolution of existing ones, emphasizing the integration of advanced digital interfaces to improve communication and operational effectiveness. Through this analysis, the thesis predicts two main future scenarios: a decentralized network characterized by integrated operations in a decentralized landscape and a centralized network that promotes centralization and extensive stakeholder cooperation. High-value use cases, encompassing enhanced pre-trip inspection, slot reservation, and gate management, are analyzed to showcase how the identified digital interfaces can be applied to real-world operations. These cases highlight the critical need for standardized digital interfaces to facilitate high-quality, real-time data exchange and overcome prevalent logistical bottlenecks.

Conclusively, this thesis not only maps out the strategic advancements necessary for the implementation of autonomous trucks in the hub-to-hub model but also provides actionable insights for industry stakeholders. It underscores the importance of technological adaptation and strategic stakeholder collaboration in realizing the full potential of autonomous trucking. By doing so, it lays a strong foundation for future research and development in the field, contributing valuable knowledge for the impending technological shifts.

Keywords: Hub-to-hub model, autonomous trucking, autonomous road freight, hub operation, stakeholder involvement, future scenario, high-value use case, digital interface, information entity, data exchange.

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Lydia Lewerentz, Gothenburg, June 2024
Anna Qian Rudin, Gothenburg, June 2024

Terminology

Autonomous truck: An autonomous truck functions as a self-driving vehicle, operating independently without human intervention, leveraging advanced technologies like Radar, Lidar, and Satellite Systems for navigation.

Controlled outdoor environment: An outdoor private area featuring clearly defined boundaries that provides the site owner with the authority to regulate access, entailing limited public traffic within this environment.

Ecosystem: Interconnected network of stakeholders that collectively influence and shape the dynamics of that particular industry.

Hub: A hub is a central point or node within a network where various activities, operations, or connections converge and are coordinated. Hubs tend to be transmodal locations, i.e., transfer within the same type of mode.

Hub-to-hub model: The hub-to-hub model involves freight transportation through central points or nodes collection and distribution of goods traffic.

Intermodal: Transportation of goods using multiple transportation modes, such as trucks, ships, trains, or planes, without the requirement to manage the cargo itself when altering modes.

Network: An interconnected system of entities or nodes that interact and communicate with one another to exchange services, information, or resources.

Operational Design Domain: The specific conditions under which an autonomous system is designed and intended to operate safely, including elements such as traffic, geography, environmental conditions, road conditions, and physical limits.

Original Equipment Manufacturer: A company that produces products or components that are used as parts in another company's end product.

Swap body trailer: Type of cargo container designed to easily be transferred between different trucks.

Trailer: A load-carrier designed to be towed behind a truck or other vehicle, used for transporting different types of goods.

Transportation Management System: A software solution that facilitates planning, executing, and optimizing goods transportation, ensuring compliance of shipments as part of an overarching logistics system.

Yard Management System: A software solution tailored to oversee and track trailer movement within yard and dock areas of different types of logistics centers.

List of Abbreviations

Below is the list of abbreviations that have been used throughout this thesis listed in alphabetical order:

AD	Autonomous Driving
API	Application Programming Interface
AT	Autonomous Truck
AV	Autonomous Vehicle
ATO	Autonomous Transport Operator
B2B	Business-to-Business
BoL	Bill of Lading
CLM	Collaborative Logistics Management
CVSA	Commercial Vehicle Safety Alliance
DDT	Dynamic Driving Task
DSRC	Dynamic Short-Range Communication
EDI	Electronic Data Interchange
ELD	Electronic Logging Device
ETA	Estimated Time of Arrival
ICT	Information and Communication Technology
INA	Industrial Network Approach
IoT	Internet of Things
ITS	Intelligent Transport System
LEA	Law Enforcement Authorities
LSP	Logistics Service Provider
OEM	Original Equipment Manufacturer
ODD	Operational Design Domain
OEDR	Object and Event Detection and Response
RFID	Radio Frequency Identification
SSC	Standards Scheduling Consortium
TMS	Transportation Management System
YMS	Yard Management System
V2I	Vehicle-to-Interface
3PL	Third-party logistics provider

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1

Introduction

In the introductory chapter, the background of this research study will be presented to contextualize the subject matter. Furthermore, the research aim, scope, and questions will be provided along with delimitations to the study.

1.1 Background

In contemporary supply chains, the predominant mode of freight transportation is by road (De Moor et al., 2023), representing a total value of approximately $12.9 trillion in the United States of America (Bureau of Transportation Statistics, 2023). By 2050, projections show that long-distance truckload miles are likely to increase by 69%, accompanied by a 30% rise in employment within the long-haul trucking sector in the United States (Della Rosa, 2022). Accommodating this growing demand will exert immense strain on the trucking industry, not least on the presently pressured workforce (Deloitte, 2021). As hundreds of thousands of drivers retire over the coming decade, the demand for drivers is simultaneously anticipated to soar, inevitably resulting in a shortage of labor (Della Rosa, 2022). Historically, the trucking industry has faced problems with employee retention and struggled to recruit qualified staff for the demanding job (Semuels, 2023). The issue of high turnover rates could be attributed to an aging workforce, low wages, and detrimental health effects characterizing long-haul trucking (Goodman, 2022). Combined with the expected deficit of truck drivers, these challenges pose a threat to the projected expansions of the logistics and transportation industry (Ji-Hyland & Allen, 2022).

To address the shortage of truck drivers, autonomous trucking technologies have emerged as a prominent solution. Autonomous trucking is defined as freight transportation using a tractor-trailer operating and navigating through a combination of AI technology, GPS systems, and software without human guidance (Urwin, 2024). There are six levels of driving automation systems for on-road motor vehicles, distinguished by the level of driver assistance technology advancements (SAE, 2021.). SAE level four trucks, highly automated vehicles capable of executing all driving tasks under specific circumstances, are currently operating within certain states in the United States. The Southwest is at the forefront of autonomously navigating predetermined and mapped routes with safety drivers (Ramey, 2023).

Autonomous trucks (ATs) represent a sizable opportunity for productivity gains and increases in system capacity by enabling operations without the restrictions of human drivers around the clock (Deloitte, 2021). Slowik and Sharpe (2018) state that by eliminating risks related to human errors such as driver fatigue, self-driving trucks are considered to improve safety and reduce the likelihood of accidents. Furthermore, the environmental benefits of autonomous road freight include improved fuel economy and reduction of emissions (Sindi & Woodman, 2021), while also incentivizing the use of clean trucks for local driving (Viscelli, 2018). Additionally, operational efficiency will be increased with autonomous trucks through the reduction of truck downtime and possibilities for real-time planning (Slowik & Sharpe, 2018).

When considering the nature and maturity of autonomous driving (AD) technology, several prerequisites must be met to ensure its successful implementation. The Sun Belt region in the United States is identified as the prime location for testing and deploying autonomous trucking (Collie et al., 2022). Favorable factors include warm weather, high freight volume, supportive legislation, and extensive limited-access highway corridors, creating an ideal environment for autonomous trucking operations. The weather conditions, as well as the flat land in the region, provide favorable circumstances for implementing autonomous driving technology (Muller & Rajwani-Dharsi, 2023). Additionally, the business-favorable policies in states like Texas have allowed the Sun Belt region to become a pioneer in the testing and deployment of the technology (Muller & Rajwani-Dharsi, 2023).

In recent times, the deployment of autonomous trucks on highways, known as the hub-to-hub model, has drawn considerable attention within the industry. Hubs may be defined as centralized nodes for consolidating and distributing the goods traffic from several scattered pick-up points as part of a wider freight network (The Geography of Transport Systems, n.d.). Hubs act as key transmodal points and coordinate between different legs of the overall journey, enabling more efficient transportation of freight between origins and destinations. The hub-to-hub model relies on the deployment of autonomous trucks that operate on highways, known as the middle mile, around the clock (Hope, 2023). These autonomous vehicles (AVs) will work in parallel with human drivers, who operate the first and last mile (Della Rosa, 2022). Human drivers will transport loads from various origins to the starting hub. There, an autonomous truck will take over control of the load and transport it to the next hub. Lastly, human drivers will navigate local roads to deliver the loads to the final customer. A hub represents the specific site where a swap body trailer seamlessly transitions from one truck to another, eliminating the need for unloading and reloading processes (Pudasaini & Shahandashti, 2021). This enhances supply chain efficiency and enables drivers to transition to local short-haul transports, thereby addressing the shortage of long-haul drivers (Slowik & Sharpe, 2018).

According to Dalmeijer and Van Hentenryck (2021), the freight transportation industry is expected to be profoundly transformed by the implementation of autonomous trucks, following rapid technological advancements. Whether changes to existing infrastructure or the addition of new facilities will be necessary to accommodate these emerging technologies is yet to be determined (Pudasaini & Shahandashti, 2021). Escherle et al. (2023) state that the degree of digitalization at hubs determines the amount of manual tasks required. As several hub tasks are conducted manually today, digitalization enables opportunities for reduced costs, improved efficiency as well as service levels within the trucking industry (Pernestål et al., 2021). The potential impact of autonomous truck deployment on the current serviceability and hub processes calls for further investigation. Establishing a robust network of transfer hubs is essential to facilitate the deployment of level four autonomous trucks, necessitating a strategic investment in both infrastructure and technology (Dalmeijer & Van Hentenryck, 2021). Given that current hub processes depend on a driver's presence (Escherle et al., 2023), it is crucial to explore how automated trucks can be integrated into future hub operations. This exploration should particularly focus on stakeholder involvement to define roles and responsibilities for the evolving industry structure, as well as develop digital interfaces to optimize data exchange.

1.2 Aim, scope and research questions

This study aims to identify digital interfaces crucial for hub operations within the hub-to-hub model. This includes outlining key stakeholders likely to participate in the future transportation ecosystem facilitated by autonomous trucking, focusing primarily on the Sunbelt region of the United States. Furthermore, the study identifies three high-value use cases for hub operations, identifying the digital interfaces, involved stakeholders, information entities, and challenges for each use case. In this context, high-value use cases denote specific applications where data exchange could yield significant benefits in achieving certain objectives. These use cases typically involve pivotal activities or functions directly impacting an operation's overall performance, productivity, or success.

The scope of this thesis investigates the future landscape of the hub-to-hub model adapted for level four autonomous trucking solutions. As the autonomous trucking industry is still evolving, this study will construct scenarios for the anticipated trajectory of hub-to-hub transportation development. These scenarios constitute the foundation upon which the analysis of digital interfaces is based. The scope is tailored to fulfill the research aim, focusing solely on hub operations for long-haul transportation using autonomous trucks. Given the primary focus on hub operations, the study will delve into three specific high-value use cases where digital interfaces play a crucial role. These use cases were chosen based on insights gathered from the interviews, underscoring their paramount importance in streamlining the efficiency of hub operations and consequently, the overall throughput. Furthermore, the hub operations are investigated in partnership with a single case company that has opted to stay anonymous.

To achieve the study's aim, four research questions have been formulated according to the following:

- RQ1: What are the key stakeholders and their roles in operational hubs for autonomous trucks in the hub-to-hub model?
- RQ2: How will the scenarios of hub-to-hub transportation evolve in the future?

- RQ3: What are the high-value use cases where the standardization of digital interfaces is crucial in operational hubs for autonomous trucks in the hub-to-hub model?
- RQ4: What are the prospective key stakeholders and information entities that must be involved in future digital interfaces for the high-value use cases?

1.3 Delimitations

The study is delimited to investigating road freight transportation, thus excluding the examination of private or public transport modes. Additionally, it is limited in scope to exclude trucks transporting dangerous goods, given the specialized regulations and procedures associated with these operations. Furthermore, aspects concerning short-haul transportation, including movement within controlled outdoor environments, will be disregarded from the research. Similarly, all operations outside the hub and its associated activities will be disregarded from the scope. The study will concentrate on hubs exclusively involving swap body trailers. The processes of unloading and loading cargo in trailers at the hubs will be delimited from this study, as will considerations regarding fixed-body trailers. The focus of the case study will specifically exclude cybersecurity considerations, as this is regarded as another research topic on its own. Lastly, no considerations will be made to the cost breakdown structure related to ownership roles in the hub network.

2

Literature review

In this chapter, the literature review that underpins the study will be presented. Different aspects of autonomous road freight transportation will be provided, highlighting central concepts of autonomous driving technology. Additionally, different perspectives on business networks will be explored, mainly surrounding the two views of ownership and non-ownership models. This includes the potential future emergence of a network operator as well as projections for the development of a smart transportation network. Furthermore, supply chain interfaces will be examined, encompassing both physical and digital interfaces within logistics systems, to understand how goods and data are exchanged. Finally, use cases from two adjacent industries will be described, offering insights that may be applied to the autonomous trucking industry.

2.1 Autonomous road freight transportation

The following section will delve into fundamental concepts and components essential for understanding autonomous road freight transportation, including different levels of driving automation and the subsystem components that constitute this technology.

2.1.1 Driving automation

Autonomy is according to ISO standard 8373:2021 characterized as the ability to execute intended tasks by relying on the current state and sensing capabilities, without the need for human intervention (International Organization for Standardization [ISO], 2021). The level of autonomy within a specific application can be assessed based on the effectiveness of decision-making and the degree to which it requires human intervention. The most commonly used taxonomy and definitions related to driving automation are the six levels of driving automation for on-road motor vehicles proposed by SAE International (2021), distinguished by the level of driver assistance technology advancements. These range from Level 0, where there is no driving automation in place, to Level 5, referring to full driving automation of the vehicle. Level 4 autonomous trucks are currently operating within certain states in the United States, where automated vehicles are capable of executing all driving tasks under specific circumstances (Ramey, 2023). The Southwest is at the forefront of autonomously navigating predetermined and mapped routes with safety drivers, aiming to remove these within the foreseeable future.

To fully comprehend the levels of automation, one must first grasp some essential concepts related to driving automation. The Dynamic Driving Task (DDT) denotes the act of driving the vehicle, with distinctions among levels pertaining to the degree to which the autonomous driving system assumes control of the DDT. Another significant concept is the Operational Design Domain (ODD), depicting the operational conditions under which the automated driving system is intended to function. This encompasses parameters such as road- or environmental characteristics, time of delay, and weather conditions necessary for the function of autonomous vehicles. Lastly, the notion of Object and Event Detection and Response (OEDR) embodies the driving system's ability to monitor its surroundings and react accordingly to any situations that may occur along the transportation journey. This function may be fulfilled either by an autonomous driving system or a human driver.

Autonomous driving cannot be classified as a single technology as it encompasses complex integration on several interdependent subsystems (Liu et al., 2020). The system architecture may be divided into three main parts: algorithms, client systems, and a cloud platform. Algorithms for autonomous driving encompass capabilities for complex reasoning such as sensing, perception, and decision-making. Sensing enables the extraction of important information from sensor data, perception enables vehicle localization and understanding of the vehicle's surroundings, and decision-making facilitates actions to fulfill assigned tasks or reach target destinations. To ensure safety and reliability, data from numerous sensors must be gathered, including GPS/IMU, LiDAR, Cameras, Radar, and Sonar. These sophisticated devices will need continuous inspection and maintenance, beyond the current procedures of manually driven trucks (Pudasaini & Shahandashti, 2021).

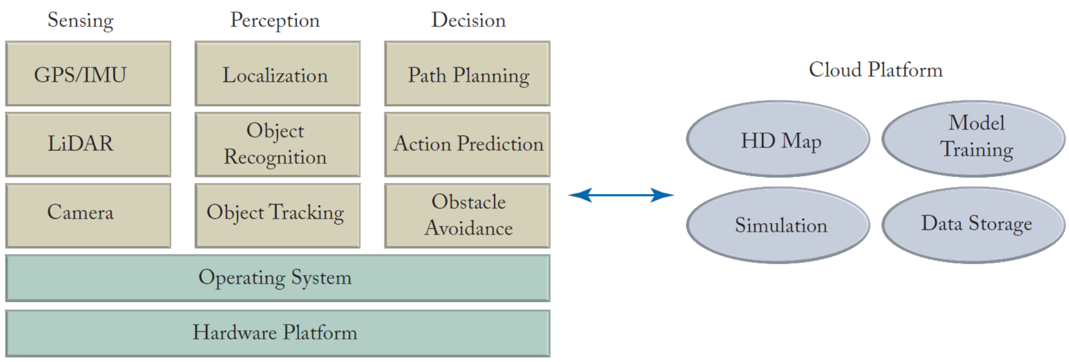

Figure 2.1: Autonomous driving system components (Liu et al., 2020).

Furthermore, client systems integrate hardware and the operating system to meet real-time and reliability requirements while incorporating the algorithms (Liu et al., 2020). Lastly, the cloud platform supports autonomous vehicles (AVs) with offline computing and storage capabilities. Thereby, the cloud platform allows algorithm testing, high-definition (HD) map updates, as well as model training for enhanced recognition, tracking, and decision-making. An overview of the autonomous driving system components is illustrated in Figure 2.1.

2.2 Business network perspective

Scholarly discourse advocates for an expanded conceptualization of business models, in general transitioning from a singular company-centric view to one that embraces an ecosystem perspective (Leminen et al., 2015). There is a compelling need to shift focus from solely concentrating on individual firms towards adopting a more holistic network perspective regarding business models (Lind & Melander, 2023). In business markets, the dynamic interplay between companies' relationships forms network structures, highlighting the interconnected nature of the ecosystem. Over an extended period, truck manufacturers, alternatively referred to as Truck OEMs, have played a central role in road transportation. However, the emergence of autonomous trucking has created a novel relationship dynamic between truck OEMs and software platform providers (Fritschy & Spinler, 2019). Given the disruptive potential of autonomous trucks, significant transformations will occur in the trucking and logistics industry in the coming years, necessitating the development of new capabilities and partnerships.

A business model may be defined as an articulation of the rationale, supported by data and other evidence, that underpins a value proposition for customers, alongside a practicable framework delineating revenue streams and associated costs for the company delivering this value (Teece, 2010; Kindström & Kowalkowski, 2015). Similarly, Magretta (2002) states that business models serve as narratives capturing a company's underlying business logic, acting as "stories of the business". Typically, business models comprise three core components: value proposition, value creation, and value capture of the company's offerings (Zott et al., 2011; Monios & Bergqvist, 2020; Chen et al., 2021; Tongur & Engwall, 2014; Teece, 2010), with adaptions to accommodate increasing levels of technological complexity (Nair & Blomqvist, 2021).

Building on the findings by Teece (2010), Monios and Bergqvist (2020) emphasize that the viability of a business model as a source of competitive advantages depends on its level of differentiation as well as the difficulty of replication by incumbent rivals and prospective new entrants. However, safeguarding one's business model against competitive threats may prove challenging, as its distinctive elements are bound to eventually become transparent (Monios & Bergqvist, 2020). As a potential way forward, successful business models can in practice be shared by competitors (Teece, 2010), consequently resulting in strategic considerations becoming of paramount importance (Zott et al., 2011). While companies might possess the capability to mimic a novel business model, they might refrain from doing so if such replication risks perceived competition with their current customer base (Monios & Bergqvist, 2020).

Furthermore, there are various business models for describing and analyzing network-like collaborative structures. Several authors highlight the Industrial Network Approach (INA) as a perspective on business-to-business (B2B) markets from an industrial network standpoint (Lind & Melander, 2023; Jacobsson et al., 2017). A foundational premise of this approach is that the business market encompasses inter-firm relationships, which form network-like structures as connections between these relationships are developed. These business relationships usually involve a multitude of individuals and impose a significant impact on the involved businesses. As previously stated, the scope of business models must expand beyond the sole attributes of individual firms to encompass the notion of networked companies as complementary or overlapping entities (Lind & Melander, 2023). Thus, the growing significance of business models seems evident, with underpinning arguments advocating for a transition from a company-centric focus to a network-level focus within business models (Jocevski et al., 2020).

A network business model may be delineated as a business model scenario where single firms are unable to govern all activities and resources needed for the development, production, and marketing of technology-based services (Palo & Tähtinen, 2011). Network business models find relevance within the transportation sector, where numerous actors participate in the transport ecosystem (Vural et al., 2020; Ghanbari et al., 2017). Recently, network business models have received attention related to the transportation area. Monios and Bergqvist (2020) elaborate on the transformative impact of technological advancements connected to electric autonomous vehicles (EAVs), potentially eroding incumbent players' competitive advantage and paving the way for the evolution of new business models. Ghanbari et al. (2017) employ the concept of Intelligent Transport Systems (ITS) to demonstrate collaborative efforts among actors through the implementation of Information and Communications Technology (ICT). Similarly, Jacobsson et al. (2020) underscore the significance of automated information sharing between stakeholders involved in the transport system. In this envisioned transport paradigm, intelligent software and information technology are anticipated to be central components for driving market dynamics (Lind & Melander, 2023).

2.2.1 Network business models

When delving into network business models from an ownership perspective, one can segment these into two distinct categories: traditional ownership models and non-ownership models.

2.2.1.1 Traditional ownership models

A traditional ownership model refers to the current business model employed within the road freight industry, where physical products like trucks are sold in transactions involving large single payments, which generate substantial one-time income for the manufacturer and entail significant investment costs for the buyer (Lind & Melander, 2023; Leiting et al., 2022; Agarwal et al., 2022; Engholm et al., 2020; Pallaro et al., 2017). Usually, this revolves around manufacturers primarily selling trucks to transport providers. These transport providers span from local owner-operators to large third-party logistics providers (3PLs), offering elementary transport services or comprehensive logistics management solutions to shippers (Monios & Bergqvist, 2020; Schucht, 2023). The authors state that manufacturers have already extended beyond this model by diversifying their offerings to include both sales and leasing options, along with additional after-sales services and actively involving users during the design phase. However, the fundamental value generation remains rooted in truck technology, prompting competition among manufacturers in this regard (Monois & Bergqvist, 2020).

2.2.1.2 Non-ownership models

The freight transport industry is expected to be significantly transformed, largely due to a likely reduction of ownership-based business models in favor of non-ownership models, a change attributable to the risks associated with technology becoming obsolete (Monios & Bergqvist, 2020; Fritschy & Spinler, 2019). This is mainly attributed to the requirement for large investments as well as advanced software capabilities being fundamental to running the network transport system.

A non-ownership business model refers to a concept where transportation is delivered as an on-demand service, where customers who formerly bought the autonomous trucks instead opt for other arrangements such as leasing the vehicles from the service providers or manufacturers (Monios & Bergqvist, 2019). Thereby, the fixed costs associated with vehicle ownership are transferred to variable costs related to transport usage for the customers (Malik et al., 2022; Teece & Linden, 2017). This mimics the business models employed for digital products, where data is frequently leveraged to enable flexible and innovative pricing strategies through results-based contracts (Agarwal et al., 2022). As-a-service models inspired by the provision of digital products are increasingly used for physical products such as trucks, reflecting an ongoing transformation in traditional business models (Agarwal et al., 2022; Teece & Linden, 2017; Buerkle et al., 2023). According to Monios and Bergqvist (2020), non-ownership models are expected to increase for road freight transportation, including leasing tractor units to operators or implementing service provisions charged based on the distance traveled in kilometers. This transition from product-centric to service-oriented models would entail a significant change in the sector's business practices.

In a similar vein, Fritschy and Spinler (2019) assume that the future strategy of OEMs will be to keep ownership of autonomous truck fleets in-house and instead offer capacity as a service to their customers. In this context, truck OEMs take on the role of mobility service providers, with offers such as selling transportation capacity to logistics service providers (LSPs) or even operating as distributors or freight forwarders themselves. Consequently, the authors believe that industry consolidation will take place where fewer actors own larger fleets of autonomous trucks, which also aligns with the perceived industry trend for consolidation (Fritschy & Spinler, 2019). However, what should be noted is that OEMs must exercise caution since by providing capacity as a service, they will be in direct competition with existing customers purchasing autonomous trucks.

In the subsequent sections, we undertake an examination of two distinct non-ownership models: the "Network Operator Emerges" model and the "Smart Network" paradigm.

Network operator emerges

The value network's distribution of dependency is expected to undergo a shift as cooperation, partnership establishments, and alliance formations emerge as pivotal enablers of autonomous truck technologies (Fritschy & Spinler, 2019). As conventional business models reliant on manufacturers selling trucks to different operators may conceivably become obsolete (Konrad & Wangler, 2018), the emergence of a new network operator is anticipated to oversee this service (Monios & Bergqvist, 2020; Lind & Melander, 2023; Brunetti et al., 2024). With the diminishing value of truck technology and the software component becoming the primary source of value generation, new entrants may seize market opportunities without having to purchase physical assets, opting instead to rent these from an array of competing asset suppliers (Monios & Bergqvist, 2020). The transport service provided by a new network operator could exist in parallel with conventional business models of buying, leasing, or renting from owners or operators.

The network operator is a role and not any particular actor, instead, it could be taken on by an array of parties ranging from existing transport operators or manufacturers or a completely novel actor type (Monios & Bergqvist, 2020; Lind & Melander, 2023). Furthermore, the ownership structure of the truck itself remains uncertain. Monios and Bergqvist (2020) presume that it would fall under the network operator's responsibility, potentially in a business set-up incorporating a separate yet wholly owned asset manager. A crucial component enabling the provision of network-wide transportation services is the software system for planning the flows (Monios & Bergqvist, 2020; Brunetti et al., 2024). While many logistics providers already possess the IT systems for this purpose, there is an opportunity for an IT specialist like Uber, Google, or Amazon to gain an advantage in this area over time (Monios & Bergqvist, 2020).

Moreover, the role of truck manufacturers is expected to change with the emergence of a network operator. While truck OEMs rely on different industry players to provide autonomous driving technologies, they will probably assume a leading role in coordinating and integrating the diverse stakeholders involved (Monios & Bergqvist, 2020). Lind and Melander (2023) hypothesize a sequential course of events, where the truck OEMs initially could take on the network operator role as they have broad expertise in truck technologies and relationship management with customers. Similarly, Monios and Bergqvist (2020) state that truck manufacturers might become future network operators, either running the network themselves or partnering with an external operator. However, this dynamic interplay is anticipated to shift as the industry landscape develops and the ecosystem requires the network operator to acquire different collaborative partners and heavy resources in IT capabilities. Emerging technologies such as automation and connectivity, combined with the involvement of new players possessing expertise in big data and the Internet of Things (IoT), will render the network more open than before, expanding opportunities for interaction and enabling new actors not yet seen on the market to shape the development (Lind & Melander, 2023).

The network operator role marks the onset of a potential market concentration, as it requires substantial financial resources and thus, limits entry to large companies with sufficient assets (Monios & Bergqvist, 2020). What remains to be resolved is whether existing players will compete for this role or leave room for new entrants to set the stage. However, once established, the network operator will benefit from enhanced data quality and IT infrastructure transforming the trucking industry. As the market progresses, the dominant player is expected to have superiority in software design and technology, possess large financial resources, and wield significant data and information assets (Monios & Bergqvist, 2020).

Smart network

Following the emergence of a new network operator, the overall transport system could potentially evolve into a fully smart network in the future (Monios & Bergqvist, 2020). In a smart network, information technology is viewed as the main driver of value generation, orchestrating and overseeing the logistical flows. Such advancements are anticipated to materialize in a more distant future when autonomous trucks roam the entire road transportation network. The establishment of a fully smart network is characterized by automated transport planning, dynamic real-time decision-making, and facilitated in-hub operators through the use of the IoT. Kellerman (2018) shares this view, emphasizing that the critical components of automated mobility extend beyond the vehicles and their physical routes to include traffic control and information management. The significance of these elements is expected to increase further with the development of smart networks.

As this transition unfolds, IT skills become essential, potentially granting IT actors greater influence on the market and possibly enabling them to assume a leading role and directly procure or rent assets from OEMs (Monios & Bergqvist, 2020). The authors emphasize the importance of data when transitioning toward a smart network, where the network operator and shippers are connected through extensive data sharing, essential for real-time network planning and the IoT. However, this transition will more possibly occur in the far-off future, since it requires widespread adoption of software capabilities along with changes to the current transportation infrastructure.

2.3 Supply chain interfaces

Supply chain interfaces are points where trading partners exchange physical goods or information, allowing parties to interact with one another to achieve a successful transfer of these entities (Stefansson & Russel, 2008). Gadde et al. (2003) highlight the significance of facilitating interfaces, as it enables the involved parties to streamline essential operations that extend beyond ownership boundaries, thereby presenting valuable opportunities. Arnäs (2007) underscores that within an interorganizational relationship, the interfaces involving two or more individuals or information systems possess unique attributes, requiring specific descriptions for each. Proper design and architecture of these interfaces are crucial to ensure an alignment of these attributes (Stefansson & Russel, 2008). Failure to do so jeopardizes the effectiveness and success of the inter-organizational relationship. The authors further emphasize the growing significance of comprehending these procedures within the transportation industry, driven by the rising trend to outsource transportation and logistics services. While this trend presents an opportunity for buyers and sellers to enhance the efficiency of moving their information and goods, it also introduces complexities and potential bottlenecks, typically occurring at the interfaces where exchanges take place.

The collaborative logistics management (CLM) model is a framework for determining the roles of various stakeholders within contemporary logistics configurations (Stefansson, 2006). Furthermore, the model also encompasses the exchange of information and materials among the stakeholders, interface attributes, and the architecture of information systems. In line with the CLM model, interface characteristics may be divided into two distinct groups (Stefansson & Russel, 2008):

- *Physical interfaces*: These refer to the point of contact where finished goods are handed over from one ready location to another, such as from shipper to carrier, LSP to carrier, or carrier to receiver.
- *Information interfaces*: These are where information or data, encompassing the content exchanged between involved parties, merges and facilitates effective communication among stakeholders.

Information interfaces encompass several types of attributes. This study focuses specifically on digital data and information attributes considered most relevant, collectively termed "digital interfaces". In the following section, the distinctive characteristics inherent to digital interfaces will be explained. Furthermore, vehicular communication and application programming interfaces are further described as these are essential components in the future development of the hub-to-hub model.

2.3.1 Digital interfaces

A digital interface is where information or data, encompassing the content exchanged between involved parties, merges and facilitates effective communication among stakeholders (Stefansson & Russel, 2008). In a digital interface, information or data can seamlessly combine, exchange, or be unidirectionally shared. Effective interfaces are essential for fostering the exchange of crucial information and promoting smooth collaboration among companies, equally crucial for optimizing autonomous road transportation flows. Establishing standards becomes imperative to ensure precise and seamless transmission of information and data across organizational boundaries.

To achieve seamless integration and coordination of both intra- and inter-organizational business processes, interoperable information systems are required (Jacobsson et al., 2020). Interoperability enables an automatic exchange of high-quality information among diverse systems, networks, and Information and Communication Technology (ICT) platforms, fostering real-time communication. In freight transportation, interoperable information systems encompass ICT applications across domains like transport management, supply chain execution, and fleet management, enhancing collaboration among involved actors. Ensuring high-quality and real-time availability of data is crucial, as it significantly influences the accuracy and effectiveness of decision-making (Stefansson & Russel, 2008). Digital interfaces prove ineffective if the data or message is incomprehensive or erroneous. In the transportation industry, such interfaces hold paramount importance for stakeholders like shippers, ensuring appropriate service levels and satisfactory performance toward customers.

Digital interfaces serve as the medium through which information and data crucial for effective communication among stakeholders are exchanged. In this context, establishing standards for seamless transmission of data becomes imperative, ensuring interoperability among diverse systems and networks. Interoperable information systems facilitate real-time communication and collaboration, particularly in domains like transport and supply chain management. Meanwhile, vehicular communications, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) technologies, enable vehicles to interact with one another and with road infrastructure, enhancing transportation safety and reliability. However, achieving effective communication within ITS requires prioritizing data privacy and security. Standardizing systems globally is essential to enable seamless integration and collaboration across the market, necessitating investment in infrastructure renewal. By leveraging technologies such as Dynamic Short-Range Communication (DSRC), which circumvents issues associated with third-party cellular networks and traditional Wi-Fi methods, vehicular communications can operate efficiently, ensuring reliable data exchange without latency issues or data congestion. Thus, the synergy between digital interfaces and vehicular communications is vital for optimizing autonomous road transportation flows and enhancing overall transportation safety and efficiency. Therefore, the concept of vehicular communications is elaborated on in the following.

2.3.1.1 Vehicular communications

Muhammed Uzair (2022) highlights that AVs utilize distinct vehicular networks to communicate with one another, leveraging their high speed, brief communication windows, and dynamically shifting configurations. Emerging ITS are preparing to leverage vehicular communication data to revolutionize traffic management (Arena & Pau, 2019). This advancement will empower vehicles to seamlessly interact with road infrastructure, significantly enhancing the reliability of self-driving capabilities on highways. However, achieving effective communication within an ITS requires prioritizing the privacy and confidentiality of data. Vehicle manufacturers are required to diligently comply with established security protocols and operational guidelines to ensure the integrity of the system, as emphasized by Arena and Pau (2019).

Vehicle-to-Infrastructure enables traveling motor vehicles to connect with the road infrastructure (Arena & Pau, 2019). This communication provides travelers with real-time information about road conditions, traffic congestion, accidents, construction sites, and parking space availability, facilitated by the usage of sensors. The data is transmitted via an ad-hoc network to facilitate wireless, bidirectional communication. Communicating data between the vehicle and infrastructure allows for dynamically adjusting the speed limits. This adjustment, coupled with real-time communication, optimizes traffic flow by adapting speeds as needed, thereby improving fuel efficiency and offering more precise arrival time estimates. Ultimately, as highlighted by Arena and Pau (2019), it enhances traffic supervision and management systems, while also fostering better communication between drivers and customers.

This interconnection forms an ad-hoc network between the entities, ultimately enhancing transportation safety and reliability by mitigating traffic accidents and congestion (Uzair, 2022). However, Arena and Pau (2019) emphasize that each company relies on exclusive and privately owned technologies, limiting communication and collaboration between systems in vehicles from other manufacturers. Thus, establishing a globally standardized system is imperative to enable seamless integration between entities and applications across the market. This requires funding to renew most parts of existing infrastructure.

2.3.1.2 Application Programming Interface

An Application Programming Interface (API) serves as a mechanism for exchanging data and content among diverse software applications (Penubarthi, 2018). Ofoeda (2019) emphasizes how APIs facilitate the seamless interconnection of individuals, applications, and systems, thus establishing a fundamental framework within the digital ecosystem. This interconnectedness is aimed at connecting businesses, fostering value creation, and promoting the advancement of capabilities.

To safeguard communication transactions, APIs play a crucial role by facilitating secure interactions in B2B contexts (Munsch & Munsch, 2020). Moreover, Penubarthi (2018) underscores the pivotal role of APIs in enabling the exchange of transactional data and application logic among external partners, thereby enhancing B2B integration. This capability enhances interoperability by sharing and swapping real-time data and information entities between companies, fostering visibility and improving workflow among the involved parties.

APIs play a pivotal role within the software ecosystem, which has emerged as a preferred method for developing extensive software solutions built upon a unified technology foundation (Ofoeda, 2019). APIs enable access to data for other applications without the need for developers to create functionalities from scratch; instead, they can integrate existing functionalities provided by APIs (Meng et al., 2017). These interfaces serve as the backbone of communication between systems and are essential to the operation of IoT devices and cloud operating systems. However, Meng et al. (2017) emphasize that an API's success hinges on the effectiveness of its documentation in meeting the informational needs of software developers. This underscores the importance of maintaining high-quality standards, such as completeness and clarity, in API documentation, emphasizing the necessity for the involvement of communication professionals' expertise.

2.4 Use cases from adjacent industries

Given that the field of autonomous road transportation within the hub-to-hub model is relatively unexplored, this section draws valuable insights from similar sectors in transportation. In this section, the division of roles among stakeholders and the evolution of business networks in the aviation and intermodal railway sectors are examined. The objective is to uncover valuable strategies that can be applied to the advancement of the hub-to-hub model in autonomous road transportation. Insights from the aviation industry are gathered to demonstrate the potential division of roles among the involved stakeholders as well as different contractual arrangements for hub utilization, which will inform the development of future scenarios for the autonomous trucking industry in Chapter 5. Furthermore, parallels are drawn to the intermodal railway industry, underscoring the similarities and potential synergies with the autonomous road freight's hub-to-hub model. Key parallels include ownership structures for hub or terminal operations, suggesting possible analogous arrangements in autonomous trucking. This also emphasizes the critical role of network operators and the necessity for seamless stakeholder collaboration across these sectors.

2.4.1 Aviation

Although the aviation industry encompasses a wide range of stakeholders, it can be segmented into consumers and producers (Gran et al., 2008). Passengers and freight companies constitute the consumer sector, while airports, airlines, aircraft manufacturers, regulatory agencies, and aviation service providers operate as producers. Despite both serving consumers, airports, and airlines have distinct responsibilities: airports manage ground infrastructure related to travel, while airlines provide transportation services. These two entities are highly dependent on each other, sharing a common objective of providing high-quality service marked by punctuality, reliability, and excellence. Regardless of how the collaboration is structured, the two parties collectively meet the demand for air traffic in a profitable, efficient, and sustainable manner. Collaboration among airlines through strategic alliances is a common phenomenon within the aviation industry and a result of heightened competition.

The majority of airports are either state-owned or privately operated entities, serving as vital links between the three primary players in the air transport system: the airport, airlines, and passengers (Gran et al., 2008). Airports provide all essential infrastructure to facilitate the transition of passengers and cargo from land-based to air-based transportation modes, while also enabling airlines to conduct their business by overseeing essential tasks such as aircraft take-offs and landings. The success of a regional airport highly depends on its geographical position and its proximity to the city center (Gran et al., 2008).

Traditionally, airports offer airlines exclusive and non-exclusive leasing contracts (Sabel, 2004). Airlines with limited flight operations may opt for non-exclusive arrangements. Under this arrangement, facilities are shared among two or more airlines, each utilizing them during designated time slots. The authors further highlight that such arrangements prove economically advantageous for individual airlines, as lease costs are divided among participants, promoting cost-effectiveness.

2.4.2 Intermodal railway transportation

The hub-to-hub model shares similarities with the intermodal railway network, which primarily utilizes rail and barge transport for long-distance haulage. In the intermodal system, freight typically begins its journey with a truck transporting it to an intermodal terminal, where trailers, containers, or swap bodies are grouped together to load onto trains (Monios & Bergqvist, 2019). These trains traverse the middle segment of the journey, transporting the goods to another terminal within the network. Finally, the goods are offloaded and transferred to trucks for the last leg of their journey, completing the intermodal process.

Rail infrastructure ownership varies depending on geographical location, with either private or public entities holding control (Laurnio et al., 2015). In the United States and Canada, the rail networks are primarily owned and operated by private freight companies. This model entails separate rail companies managing tracks, terminals, and services (Bergqvist & Monios, 2019). In contrast, in numerous other countries, it is customary for public entities, such as the national rail company, to manage and operate a single vertically integrated network (Laurino et al., 2015). The ownership and management structure of intermodal railway terminals vary based on regulatory approaches. These facilities may be operated either by public or private operators.

While autonomous trucks travel on public roads, the ownership model of terminals remains uncertain. Monios and Bergqvist (2019) emphasize the potential benefits of future terminals being open-access, similar to public rail networks, allowing multiple system suppliers to utilize them. However, the authors suggest that a blend of ownership models is probable, mirroring the diversity seen in the intermodal railway transport system. Large operators are likely to establish their own networks and operate exclusive terminals, alongside a scattering of open-access terminals providing broader coverage. Similarly to the intermodal railway system, where some operators oversee both services and terminals while others focus on specific segments, the structure of autonomous vehicle terminals and their associated services might mirror this arrangement. These terminals and services could either integrate into the comprehensive transport offerings of AV providers or exist as independent entities, potentially leading to various integrated or segmented models within the industry (Monios & Bergqvist, 2019).

The evolving market dynamics of the hub-to-hub model are thought to resemble the intermodal railway business model, where several major operators provide middle-mile services connecting terminals via regular road networks (Monios & Bergqvist, 2019). The authors further emphasize that likened to the role seen in the intermodal railway business model, network operators are anticipated to play a crucial role in enabling AV services between terminals, seamlessly integrating them into traditional road networks. Additionally, they underscore that the economies of scale within this network will stem from providing a comprehensive and interconnected infrastructure.

The future landscape of network operators in the hub-to-hub model remains uncertain, encompassing questions about their quantity, scale, and the entities driving them. The United States leads globally in the number of network operators within intermodal railway networks, as highlighted by Laurino et al. (2015). It is possible that the role may be operated by new players, like manufacturers, currently not engaged in this sector (Monios & Bergqvist, 2019). Initially, it's anticipated that network operators may primarily be transport specialists, leveraging their asset ownership for competitive advantage. However, over time, this role is poised to mature, with a shift towards developing competitive advantages in data networking by utilizing real-time customer data for automated flow planning. Such a transition could disrupt existing business roles within the network.

Similar to the intermodal network, successful hub-to-hub operations necessitate robust collaboration among stakeholders, including shippers, hauliers, 3PLs, and logistics software operators (Monios & Bergqvist, 2019). Achieving seamless collaboration requires integrated systems between stakeholders, typically consolidated at a terminal adjacent to a logistics platform, merging various logistics components like transportation, distribution, and processing. Additionally, the authors emphasize that cargo flow management may mirror intermodal railway operations, where cargo space can be sold directly to shippers or through intermediaries like 3PLs or freight forwarders.

Jacobsson et al. (2017) performed a study on intermodal freight transportation, aiming to outline what information entities are needed for improved access management between hub companies, referring to ports, intermodal freight terminals, and hauliers. The studied objectives were two different road hauliers, one intermodal freight terminal operator, one port operator in addition to one information system supplier.

The result highlights shortcomings in the exchange of information among stakeholders, with a lack of notice before trucks arrive at the hubs. Its primary discovery is a thorough assembly of identified information attributes, systematically presented within an analytical framework. Among the crucial information attributes identified are actual pick-up time, occupancy rate, hub loading point, hub unloading point, and queuing status. These findings may be applied to similar operations within hubs for autonomous trucking when relevant.

3

Methodology

In the following chapter, the research methodology is presented. The chapter provides an understanding of the research strategy as well as outlines the anticipated data collection methods for this study.

3.1 Research strategy

Bell et al. (2019) define qualitative research as a strategy that centers on words during both data collection and analysis, in contrast to quantitative research, which places emphasis on numbers throughout these processes. To acquire the necessary information and address the research question at hand, this study employed a qualitative approach, aiming to provide detailed descriptions of complex issues. Quantitative methods involving the collection and analysis of statistical data were not applicable to the study's character, given the constraints related to the nuances that emerge. A qualitative research study can be conducted in various ways including cross-sectional design, comparative design, longitudinal design, and case study design (Bell et al., 2019).

This research was done by conducting a case study. Bell et al. (2019) define a case study as a detailed and intensive analysis of a single case, which is a common approach in business research. This research entailed a single-organization case study, chosen for its suitability to the study's objectives since it is currently operating autonomous trucks within the Sunbelt region. As the selected organization stands out as a pioneer in the segment, it offered sufficient data for comprehensive analysis. The company has chosen to remain anonymous.

This thesis contributes to understanding the autonomous road freight industry in the context of the hub-to-hub model, by providing new knowledge that may complement existing theories. As Bell et al. (2019) underscore, qualitative research interviews prioritize capturing interviewees' perspectives. Hence, the conducted interviews in this thesis aim at gaining a deeper understanding of hub-to-hub transportation from an industry viewpoint, identifying common themes and challenges that correspond to the research inquiries.

3.2 Data collection

The collected data consist of both primary and secondary data, where the former will derive from interviews with a selection of relevant case company employees. Secondary data was gathered using different internal and external sources, including case company documentation, Chalmers Library, Google Scholar, and public websites.

3.2.1 Interviews

Primary interview data was sampled using two different methods in a consecutive order. First, a purposive sampling strategy was applied to outline key individuals as a starting point. Bell et al. (2019) describe purposive sampling as a non-probability type of sampling, meaning that the sample data is carefully chosen based on certain criteria rather than randomly. According to the authors, purposive sampling entails the selection of study participants to be guided by the research questions in a way that allows them to be addressed effectively. Second, a snowball sampling strategy was employed based on references from the prior sampled subjects. Bell et al. (2019) state that another sampling approach commonly precedes snowball sampling, as the concept entails researchers using initial contacts who are knowledgeable of the research topic to establish further connections. This is to gain a deeper understanding of the research matter at hand (Bell et al., 2019). In this study, snowball sampling was utilized to draw on the emerging findings of conducted interviews in the first round.

During the study's course, two rounds of interviews were held, aiming to first outline general themes connected to the research questions and then delve deeper into relevant areas. In Appendix A.1, interview questions from round one are presented, aiming to address research questions one and two. Moreover, Appendix A.2 further includes the questions from the second interview round, which aimed to answer research questions three and four. Each interview template was used for its respective rounds to ensure a uniform process. Exceptions were made only for the enhanced pre-trip inspection, where expert knowledge was sought from a select few interviewees. According to Bell et al. (2019), the advisable sample size may vary between qualitative interview studies, however, the authors state that a rule of thumb is to conduct around 20-30 interviews to ensure the research's acceptability. To ensure the conviction of this study's outcome, 21 interviews were conducted with key stakeholders such as participants from the case company, research institutes, related industries, and other subject matter experts.

The subjects of interest possess different roles at the case company and other interesting organizations such as research institutes, university, and port management. Moreover, interviews with sampled participants were semi-structured in nature. Consequently, this entailed that the questions followed a general interview guide while allowing freedom to vary the sequence and addition of follow-up questions during the interviews (Bell et al., 2019). This guide was pre-tested with stakeholders at the case company and adjustments were made according to gathered feedback.

Interviews were recorded with the interviewee's consent and interpretation was supported by additional notes taken during the session.

Table 3.1: Summary of conducted interviews.

Interview participants				
ID	Type	Professional title	Date	Duration
CC1	Case company	Head of Operations	2024-02-06 & 2024-03-01	60 m
CC2	Case company	Digital Strategy Development	2024-02-29 & 2024-04-11	60 m
CC3	Case company	Head of Business Development	2024-02-28	60 m
CC4	Case company	Commercial Project Manager	2024-03-01	60 m
CC5	Case company	Corporate Development	2024-03-05	60 m
CC6	Case company	Digitalization Project Manager	2024-03-06 & 2024-04-10	60 m
CC7	Case company	Head of Strategy	2024-04-03	60 m
CC8	Case company	Head of Safety	2024-04-09	60 m
CC9	Case company	Head of Uptime	2024-04-16	60 m
UR1	University researcher	Professor in Supply & Operations Management	2024-02-27	60 m
UR2	University researcher	Professor & advisor in Transport Logistics	2024-03-06	60 m
UR3	University researcher	Professor in Supply & Operations Management	2024-03-13	60 m
UR4	University researcher	Professor in Service Management & Logistics	2024-03-14	60 m
UR4	University researcher	Professor in Maritime Transport Logistics	2024-03-19 & 2024-03-26	60 m

Continuation of Table 3.1				
ID	Type	Professional title	Date	Duration
RI1	Research institute	Senior researcher on autonomous transportation	2024-03-11	60 m
PM1	Port Management	Business Development	2024-04-08	60 m
LE1	Texas Department of Public Safety	Chair of CVSA board	2024-04-11	60 m

3.2.2 Literature review

The literature review consists of secondary data, which was collected continuously throughout the study to enable a greater understanding of the research topic. According to Blomkvist and Hallin (2015), the literature review's purpose is to catalog and review previously published knowledge in the research field. The literature review of this study is categorized into four main areas: Autonomous road freight transportation, Business network perspective, Supply chain interfaces, and Use cases from adjacent industries. Complimentary literature was gathered based on indications from the interviews that were conducted. Blomkvist and Hallin (2015) further state that clearly defined search terms are essential for effectively navigating findings during the literature review. Research databases that were used for finding applicable literature are Chalmers Library, Scopus, Web of Science, and Google Scholar, further complemented by Google searches for topic-related business articles. Examples of search words include; Hub-to-Hub model, Autonomous truck hub, Hub operations, Terminal operations, Autonomous vehicle transportation, Autonomous road freight, Autonomous long-haul transportation, etc. Findings from the literature review were used collectively with those from the interview rounds to answer the research question, complementing one another to fill the knowledge gaps.

3.2.3 Documentation

In addition to interviews and a thorough review of existing literature, documentation of the case company was reviewed to enhance the understanding of the subject area. As emphasized by Bell et al. (2019), organizational documents provide background information about the company and its history, which is of particular importance in case studies. The author further elaborates on documentation's role in building up a chronological timeline and documentation of the company's strategic evolution. This becomes particularly important when seeking to increase the understanding of the present status of autonomous trucking hubs and the envisioned future state.

3.3 Data analysis

The case study undergoes analysis via a qualitative data analysis approach. Thematic analysis, as outlined by Bell et al. (2019), is the chosen methodology for this study. This method seeks to identify, analyze, and interpret significant themes or patterns within qualitative data, as outlined by Braun and Clarke (2017). Bell et al. (2019) emphasize that repetition emerges as a prevalent criterion for discerning patterns in data; however, it is crucial to ensure its relevance to the research question.

Thematic analysis unfolds in six sequential phases, as outlined by Braun and Clarke (2006). Initially, one familiarizes oneself with the data, underscoring the significance of iteratively engaging with it to uncover patterns and meanings. In this thesis, all interviews were recorded, with permission from the interviewee. Consequently, these recordings were transcribed and revisited, and the insights gained from the interviews were expanded upon through detailed note-taking. In the process of thematic data analysis, the second phase involves creating initial codes to capture data points that intrigue the analyst (Braun & Clarke, 2006). In this study, this step entailed identifying and highlighting potential patterns and data segments from individual transcripts. In the third phase, the pursuit of themes progresses through the organization of diverse codes into prospective thematic groupings. This process involves gathering all highlighted potential patterns within an Excel sheet and categorizing them based on the initial themes they were perceived to align with. As per the guidelines of Braun and Clarke (2006), tables and mind maps were employed to visually organize these codes into cohesive theme clusters.

The fourth step entails reviewing themes, aiming to enhance the clarity and precision of the generated themes (Braun & Clarke, 2006). In this report, this process involved iterating through all the themes multiple times to ensure thorough refinement. Following this, the themes were labeled, marking the fifth step as per Braun and Clarke's framework (2006), encompassing identified roles, stakeholders, future scenarios, and high-value use cases. Subsequently, the final step involves generating the report, with the outcomes detailed in the results section of this document.

3.4 Research quality

Research quality is pivotal in scholarly work as it underpins the trustworthiness and rigor of the study's methodology and outcomes. This thesis adheres to established criteria to meet the high standards required for academic research. In the following section, the quality of the research conducted will be assessed, focusing specifically on reliability and validity as critical criteria for qualitative analysis, as suggested by Bell et al. (2019). Given the qualitative nature of this study, these two criteria are considered particularly pertinent.

Bell et al. (2019) define validity as the research's conclusion integrity. Golafshani (2003) further elaborates on validity by discussing its dual aspects: the accuracy of measurement and the extent to which the measurement truly assesses the intended variable. According to Bell et al. (2019), there are four types of validity — measurement, internal, external, and ecological — with internal and external validity being most relevant to qualitative research and therefore, discussed more in detail for this thesis. Specifically, internal validity pertains to the correspondence between the observations and the outcomes of the study, ensuring that any causal relationships observed are genuine. This was addressed by conducting diverse and independent interviews to gather a broad spectrum of data. Additionally, external validity relates to the generalizability of the research findings (Bell et al., 2019). To enhance external validity, this study did not limit participants to a single case company but included a variety of industry experts and researchers, thereby broadening the applicability of the findings across different contexts.

Regarding reliability, Bell et al. (2019) highlight its importance in terms of the repeatability of a study. The authors state that achieving exact repeatability is challenging in qualitative research due to the dynamic nature of social settings, making it nearly impossible to replicate the research under identical conditions. However, Bell et al. (2019) elaborate by suggesting that internal reliability can be attained by consensus among multiple researchers. Golafshani (2003) supports this view, advocating for triangulation, which means validating the findings through multiple separate sources, as a robust method to ensure reliability. This study implemented this approach by cross-verifying findings through several interviews and integrating them with the literature review to support the claims made.

Lastly, ethical considerations are paramount throughout the research process (Bell et al., 2019). This was ensured throughout the interview rounds, by informing participants about the purpose of the research and assuring their anonymity and confidentiality. Informed consent was obtained from all participants, ensuring that they were participating voluntarily and had the right to withdraw their statements at any time without any consequences.

4

Results

The following chapter is based on the conducted interviews involving personnel from the case company and external stakeholders, encompassing a total of 21 interviews. The interview material has been organized into three primary sections: Stakeholder involvement in the future hub-to-hub model, identified high-value use cases, and their respective supply chain interfaces. In the initial section, the chapter presents the collected data concerning the future landscape of the hub-to-hub model, encompassing the identification of key actors and their respective roles within this framework. The subsequent section builds upon the findings of the previous section, which identifies two distinct future scenarios: the decentralized and centralized network models. The section presents three high-value use cases essential for ensuring efficient operation in both scenarios identified. Additionally, the section outlines the supply chain interfaces associated with each identified high-value use case within the two scenarios under consideration.

4.1 Stakeholder involvement

In the forthcoming section, the results gathered for research question *"What are the key stakeholders and their roles in operational hubs for autonomous trucks in the hub-to-hub model?"* will be presented, detailing potential future roles within the hub-to-hub model and the corresponding stakeholders. Furthermore, the section will highlight high-value use cases, pinpointing specific processes where data exchange could yield significant benefits in achieving particular objectives within the hubs. Lastly, the chapter will explore diverse viewpoints on the potential future structure and configuration of the industry, particularly concerning the extent of facility sharing.

Based on the initial round of interviews, it is important to distinguish between the terms "stakeholders" and "roles", which often differ in terminology and application. A role is defined as a specific responsibility assigned to an individual or group within a system, process, or organization. This study identifies not only existing industry roles but also four prospective future roles, which include the hub owner, hub operator, autonomous transport operator (ATO), and network operator. On the other hand, a stakeholder refers to any individual or group that assumes these roles, responsible for carrying out the associated duties. The potential stakeholders suitable for each of these future roles have been summarized in detailed tables for clarity, found in subsections.

4.1.1 Autonomous truck provider

During the interviews, six participants provided insights into the role of autonomous truck providers (CC1, CC2, CC4, CC5, CC6 & UR1). These providers are essentially companies that offer self-driving trucks. For instance, they could be truck OEMs collaborating with autonomous driving technology providers, specialized subsidiaries, or specialized integrator companies. Concerning truck manufacturers, CC2, CC6, and UR1 stated that they would provide autonomous trucks themselves through leasing or similar models. CC2 elaborated by stating that *"Truck OEMs are transcending traditional roles of asset sellers. Instead, they are taking a step up the value chain through increased ownership and prioritizing more comprehensive service solutions such as leasing models"*. Additionally, the interviewee emphasized that this shift would necessitate dealing with the challenges of becoming more asset-heavy. Moreover, CC1, CC4, and CC5 emphasized that specialized companies or divisions within larger corporate groups, dedicated to developing autonomous driving solutions for commercial trucks either by themselves or through collaboration, will continue to be the primary autonomous truck providers. These companies generally function at the intersection between conventional truck manufacturers and virtual driver technology providers. Regardless of the organizational layout, it seems evident that truck manufacturers and their respective subsidiaries are competing against each other in commercializing the use of autonomous trucks.

4.1.2 Autonomous driving technology provider

An autonomous driving (AD) technology provider is a key stakeholder specializing in the development and supply of technology and systems essential for enabling vehicles to operate autonomously, without the need for human intervention. Examples of players in this field include emerging companies such as Kodiak, Aurora, and Waymo. According to CC1, AD technology providers are *"those that create the autonomous software to put in the tractors, who are also responsible for approving the routes between the hubs and throughout the entire network"*. This underscores their critical role in approving the ODD for each journey and accessing the autonomous freight network. Whether there will be a few or numerous AD technology providers dominating the autonomous trucking market remains uncertain. However, CC2 suggested that multiple virtual drivers will likely collaborate with different truck manufacturers or subsidiaries, leading to a fragmented market with various coexisting actors. In addition to software development, AD technology providers may also play a part in hub operations. CC3 proposed that these companies could provide specialized equipment for AVs, such as inspection tools. Furthermore, some AD technology providers have taken steps to establish trucking hubs for pilot testing themselves, as mentioned by CC5. These facilities are operated in-house, indicating a proactive approach to testing and refining autonomous trucking solutions.

4.1.3 Hub owner

Concerning the role of the *hub owner*, seven different types of stakeholders were mentioned in the interviews as suitable candidates for assuming this role in a future hub-to-hub network (CC1, CC2, CC3, CC4, CC5, CC6, UR1 & UR2), highlighted in Table 4.1. The hub ownership encompasses the physical assets including necessary infrastructure for accommodating the trucks in-between journey legs such as the hub facilities themselves. This could also cover specialized equipment for autonomous trucks and fuel capabilities. According to the majority of first-round interview participants, autonomous truck providers (CC1, CC5, CC6, UR1 & UR2) and real-estate companies (CC1, CC3, CC4, CC5 & CC6) were deemed most appropriate considering a number of factors.

Table 4.1: Potential stakeholders for the role of the hub owner.

Hub owner	
Stakeholder	Number of times mentioned
Autonomous truck provider	5 (CC1, CC5, CC6, UR1, UR2)
Real-estate companies	5 (CC1, CC3, CC4, CC5, CC6)
Logistics provider	3 (CC1, CC2, CC6)
Large shippers	3 (C1, CC2, CC6)
Carriers	2 (CC1, CC5)
Other property owners	2 (CC1, CC5)
Autonomous driving technology providers	1 (CC5)

Due to their extensive product and technology knowledge, several interviewees proposed AT providers as probable to become hub owners (CC1, CC5, CC6, UR1 & UR2). UR2 further elaborated on this by explaining that the lagging homologation process of autonomous trucks is one major reason. Currently, the AV is type-approved as one unit, meaning that each replacement of a single component requires new permits from the relevant authorities. The limitations imposed by a lack of industry-wide regulation and standardization entail the AT provider initially having to participate in inspections and maintenance of ATs at hubs until the concept of autonomous trucking is commoditized (UR2). Hence, as concluded by UR2, the AT provider will play a major role in establishing hubs and associated operational processes. This is supported by the statements made by CC1 and CC6 who highlighted that this will be especially relevant when looking at more remote locations, far off from existing terminals and other facilities proximate to highways. Furthermore, CC1 emphasized a scenario where AT providers act as both hub owners and -operators, running all operations by themselves when strategically justifiable.

On the other hand, both CC3 and CC4 made a clear division between the provision of real estate and in-hub operations, where CC3 stated that real estate is easier to consolidate ownership of as few actors already possess these long-term physical assets. In addition, CC5 believed that the hub owner would either be the same player as the one operating the facilities, including a range of actors such as the AD technology providers, or a real estate company that subcontracts in-hub operations.

Similarly, CC6 stated that real-estate companies or logistics providers (like DHL or DB Schenker) and large shippers (like IKEA, Amazon, or PepsiCo) could leverage their networks and develop current infrastructure to become accustomed to hub operations. This view aligns with the statements of CC2, who claimed that *"there will be two configurations; one where a major logistics company owns and operates the hubs, and another where large shippers operating much logistics themselves will have their own hub facilities"*. These configurations were also emphasized by CC1, who stated that viable options would be for AT providers to partner with large shippers who act as hub owners and lease the property to them, or large logistics companies could establish hubs themselves.

Moreover, CC1 and CC5 mentioned carriers as well as other property owners as potential new hub owner-operators. Other property owners refer to truck stop operators, gas stations, and leasing and maintenance players with wide-ranging geographical coverage, possessing pre-existing infrastructure that could be leveraged when establishing a network of hubs. Although the opinions on whoever might become the future hub owner(s) differ between interview participants, a common theme is that this actor likely will benefit from having an existing infrastructure to build upon along with an understanding of the technology that enables autonomous trucking.

4.1.4 Hub operator

When examining the role of the *hub operator* within a future hub-to-hub network, nine distinct potential stakeholders were identified during the interviews (CC1, CC2, CC3, CC4, CC5, CC6, UR1 & UR2), summarized in Table 4.2. The hub operator is the actor responsible for owning, managing, and overseeing the operations within the hub. This role is highly dependent on which stakeholder owns the hub. CC2 emphasized the possibility of organizing the future network into geographical macro-regions within the United States, wherein smaller networks could emerge, potentially with one dominant player overseeing all hub operations in specific areas. Several interviewees envision parallels with other industries, such as railways and airports, regarding the sharing of terminals and the division of ownership within the evolving hub-to-hub network (CC5, CC3 & CC1).

There is a strong consensus among experts (CC2, CC3, CC5, CC6 & UR2) that regardless of the hub owner, specific tasks and procedures within hub operations will likely be subcontracted or outsourced. CC6 illustrated that a particular operator might handle gate operations and planning. Furthermore, CC5 emphasized that if a real estate company owns the hub, they are likely to outsource or collaborate with subcontractors to manage hub operations.

If the AT provider possesses its own hubs, it is believed that the stakeholder will manage the operations internally to streamline processes within a decentralized network (CC1, UR2). On the contrary, CC6 suggests that the AT provider could still serve as the hub operator even if another actor owns the property. As emphasized by UR2, the absence of industry regulations and standardization necessitates the AT provider's involvement in inspections and maintenance, underscoring their

Table 4.2: Potential stakeholders for the role of the hub operator.

Hub operator	
Stakeholder	Number of times mentioned
Subcontractors	4 (CC2, CC3, CC5, UR2)
Autonomous truck provider	3 (CC1, CC6, UR2)
Logistics provider	2 (CC2, CC6)
Large shippers	2 (CC2, UR2)
AD technology providers	2 (CC1, CC5)
New specialized operators	1 (CC3)
Real-estate company	1 (CC1)
Carriers	1 (CC5)
Other property owners	1 (CC5)

importance in hub operations. It is further argued that if the hub is owned by established logistics players (CC2, CC6) or large shippers (CC2, UR2) who possess both a network of customers and real estate they will likely develop internal operational expertise. Furthermore, as AD technology providers have already begun establishing hubs for pilot testing, CC1 and CC5 suggest that these stakeholders will likely persist in operating their own hubs.

CC3 proposed the emergence of specialized companies dedicated to managing the hub operations. These companies would focus on tasks such as resource management, regulatory compliance, and optimizing hub infrastructure. Currently, no such dedicated stakeholder exists. However, CC3 envisioned that they would combine the expertise of port terminal operators, who excel at receiving and storing containers but face challenges with gate management and queues, and truck terminal operators, who are adept at handling fast-paced operations. CC1 and CC5 additionally assert that when a hub owner adapts their land and infrastructure for autonomous trucking, they can transition into specialized hub operators. This may encompass real estate companies (CC1), carriers (CC5), and other property owners (CC5).

4.1.5 Autonomous transport operator

When discussing the role of the *autonomous transport operator*, interviews identified four potential stakeholders (CC1, CC2, CC3, CC4, CC5, CC6, UR1 & UR2), outlined in Table 4.3. The consensus among the majority of experts suggests that the autonomous truck provider is most likely to fulfill this role (CC1, CC2, CC3, CC4, CC5, CC6 & UR2). Additionally, CC5 highlighted that within the next decade, the autonomous truck provider is anticipated to adopt operational models similar to current large industry carriers (such as Schneider, Daimler, and Knight-Swift). Their position as manufacturers and financial stability will facilitate the acquisition of a significant fleet of autonomous trucks and the provision of related services (CC5).

CC2 and UR1 elaborated on the notion that if a logistics provider were to own, manage, and operate the transportation within the hubs, they could serve as in-

Table 4.3: Potential stakeholders for the role of the autonomous transport operator.

Autonomous transport operator	
Stakeholder	Number of times mentioned
Autonomous truck provider	7 (CC1, CC2, CC3, CC4, CC5, CC6, UR2)
Logistics provider	2 (UR1, CC2)
Smaller carriers (through platform)	1 (CC2)

termediaries between the customer or shipper and the subcontracted autonomous transport (AT) provider. Additionally, CC2 envisioned the persistence of current industry players, suggesting that smaller carriers might consolidate their capacity by utilizing aggregation platforms or by undergoing significant expansion through hyperscaling. Conversely, UR2 observed that individual truck owners are likely to diminish as the industry transitions toward a completely new logistics system. UR2 anticipates the rise of multiple decentralized networks where autonomous truck providers operate their own fleets, driven by limited sharing of hub facilities. CC1 expands on this concept, asserting that the ATO will assume ownership and operational control of the entire transportation infrastructure, encompassing both vehicles and hubs.

4.1.6 Logistic software provider

When exploring the role of a *logistics software provider* within the hub-to-hub model, several critical aspects were identified (CC1, CC2, CC3, CC4, CC6 & UR2). Such a provider specializes in developing digital solutions tailored to optimize and streamline various aspects of transportation and logistics processes within and between hubs. Their software typically facilitates functions like route planning, scheduling, fleet management, real-time tracking, and data analytics. This enables efficient coordination and execution of shipments within the hub-to-hub network. CC2 highlights the importance of the role by stating, *"The logistics software providers act as a facilitator. The hub is a bottleneck if you do not have traceability of the goods and the flow, as you then won't be able to optimize. The role of the logistics software provider is to facilitate the flow of goods and information in the best possible way"*.

UR2 underscored the need for logistics software to develop a comprehensive logistics system, illustrating the flow of goods from origin to destination. A Transport Management System (TMS) is highlighted as a crucial component of the hub software (CC1, CC3, CC4, CC6 & UR2). Such a system is where transport planning and booking take place and allows the involved stakeholders to connect with one another (CC1, CC6 & UR2). UR2 anticipated that the development of autonomous freight transportation would lead to a significant transformation in the TMS market, necessitating the adaption of decision-making frameworks to align with emerging planning software. CC3 underscored that TMS providers (like Blue Yonder, Oracle, or Manhattan Associates) are actively refining processes tailored for intelligent terminals, signaling an ongoing evolution. However, CC4 identified existing gaps in functionality within current TMS platforms, suggesting the potential emergence of new entrants to address these deficiencies.

Additionally, there was a consensus on the necessity of a Yard Management System (YMS) for effective in-hub management (CC1, CC6). Furthermore, UR2 emphasized the criticality of real-time management systems, stressing the need to effectively monitor and control vehicle transportation in real-time. This emphasizes the importance of continuous tracking and management to ensure smooth and efficient operations within the hub-to-hub logistics framework.

There was a consensus among experts that utilizing off-the-shelf solutions, with certain customizations, is an effective approach (CC1, CC3 & CC6). CC1 emphasized the imperative of new system development to enhance hub scheduling, focusing on key applications like slot allocation, load management, real-time information retrieval, and the scheduling of ETAs for incoming trucks. Additionally, CC3 pointed out the limited capacity of autonomous truck providers to internally develop such software solutions. As a potential remedy, CC6 emphasized the potential for collaboration between autonomous truck providers and logistics software providers to develop advanced solutions surpassing current offerings collaboratively. CC2 further underscored the possibility of a consortium forming between major hub operators and a software provider to jointly create such a system.

4.1.7 Network operator

Delving into the role of the *network operator*, the interviewees pointed out eight types of stakeholders as probable candidates. These are summarized in Table 4.4. Some participants predicted the emergence of a network operator without being asked, while others were questioned specifically to elaborate on this role even if not mentioned priorly. The network operator role entails being the orchestrator of a network of AT hubs, bridging the gap between involved stakeholders within the broader transportation ecosystem to ensure a smooth movement of goods between nodes. Alternative terms used to describe its function include "ecosystem integrator", "ecosystem orchestrator", and "footprint integrator", however, this report will employ the term network operator throughout.

Table 4.4: Potential stakeholders for the role of the network operator.

Network operator	
Stakeholder	Number of times mentioned
Large shipper	4 (CC1, CC2, CC5, UR2)
Autonomous truck provider	3 (CC3, CC4, CC6)
New platform provider	2 (CC5, UR2)
Logistics software provider	1 (CC6)
Large tech company	1 (UR1)
AD technology providers	1 (CC1)
Smaller carriers (through platform)	1 (CC2)
Other property owners	1 (CC1)

As the network operator role emerges alongside establishing an ecosystem of players within the hub-to-hub model, there is currently no definitive stakeholder considered most appropriate for this role. Instead, speculations point toward an array of different stakeholders possessing relevant capabilities. Firstly, the AT provider was mentioned as a potential new network operator (CC3, CC4 & CC6). Integration of the virtual driver, customers, and hub owner-operator is necessary for ensuring seamless collaboration and requires the network operator to maintain strong relationships with various players. CC3 emphasized the contemporary influence of the AT provider in this regard by stating that *"at the intersection of technology and service provision, [AT providers] play a critical role, seamlessly integrating with both customers and AD technology providers, positioning [themselves] as the facilitator of efficient integration across the autonomous trucking ecosystem"*. Aligning with this view is CC4, who explained that the AT provider acts as a spider in the web, handling a major part of transport planning and communication between various stakeholders.

In contrast, other interviewees advocated for another arrangement where a large shipper would act as the network operator, utilizing their existing platform portals (CC1, CC2, CC5 & UR2). CC2 and UR2 both explained that such a player could fundamentally reshape the landscape of transportation logistics, influencing the flow of goods and consequently shaping the overall network dynamics. CC2 further emphasizes this in the statement that *"their dominance allows them to dictate demand, essentially orchestrating the network's configuration. However, the emergence of a dedicated network operator within the next decade is unlikely"*. Linked to this concept is an alternative pathway underscored by CC1 and CC6, suggesting that ATOs might forge strategic alliances with major shippers and leverage their preexisting network infrastructures, potentially even integrating fully into their operations. The opportunity to form partnerships within the ecosystem was also highlighted by CC1, who envisioned other property owners like truck stop or leasing companies with established networks for conventional trucks could venture into the market without acquiring new property.

Moreover, CC6 emphasized the potential of logistic software providers to become network operators, drawing upon their software capabilities for connecting ATOs with customers. This would entail further development of current logistics systems to accommodate the increased complexity of autonomous trucking, likely in collaboration with hub operators and ATOs. Additionally, a couple of interview participants predicted the emergence of an entirely new platform provider taking on the network operator role. Both CC2 and CC5 elaborated on the predictions of a new platform provider matching demand and supply, explaining that this stakeholder would enable smaller transport operators to aggregate their capacity through an aggregation platform, similar to Uber for robotaxis or Convoy for conventional trucking. Conversely, UR1 believed that a large tech company such as Google or Microsoft is more likely to become the future network operator due to its inherent experience with platform development.

Based on the current industry layout, interview findings indicated one configuration where a few dominant players act as local hub orchestrators rather than seeing an overarching network operator (CC1, CC2, CC5, & UR2). CC1 believes that AD technology providers can have an impact as network operators in the near term, orchestrating various decentralized networks. The rationale stems from the crucial function of AD software providers in accessing hub networks, as they bear responsibility for approving driving routes and ODDs for ATs. Adding onto this, CC1 asserts that *"initially, multiple network operators will emerge, gradually consolidating into fewer dominant players"*, suggesting that the transport industry's evolution will unfold through successive stages rather than as a singular transformation. Furthermore, UR2 stated that *"the pioneer in establishing the initial hub network will likely withhold access to the hubs for competitors, recognizing the significant competitive edge it provides"*, highlighting the expected unwillingness of first movers to share facilities with external stakeholders. The control wielded by whoever oversees the future network was demonstrated by CC2, who stated that *"for example, if [X] manages transportation between hubs and [X] oversees hub operations, they can influence which competitors are permitted to operate within that network"*, highlighting a potential desire for control across the industry.

Conclusively, CC5 opined that larger actors operating within a decentralized network might exist in parallel with smaller players who connect to an aggregation platform. The commercialization of autonomous road transportation is expected to change the way things are done today, which UR2 emphasized by underscoring that *"A new industry will arise in the wake of this evolution, marked by immune system reactions from conventional trucking companies. Competition will primarily unfold between ATOs and traditional logistics firms, rather than among ATOs vying for the same market space"*. Regardless of whether decentralized and centralized network configurations will coexist side-by-side or one scenario will dominate the other, the interviews point toward the emergence of one or several network operator(s), potentially impacting the trucking industry's development significantly.

4.1.8 Law enforcement authorities

The regulatory landscape of the industry and its progress were examined in an interview with a chair of the Commercial Vehicle Safety Alliance (CVSA) (LE1). In the interview, it was emphasized that the United States lacks federal regulations specifically tailored for commercial autonomous freight vehicles. Consequently, regulations vary from state to state. UR2 further emphasized this by highlighting the authorities' lag in developing appropriate policies to address autonomous vehicles, struggling to keep pace with the industry's rapid development.

The sole federal requirement applicable to AV developers is the National Highway Traffic Safety Administration's general order concerning the reporting of crashes and incidents (LE1). However, there is an anticipation of forthcoming regulations. Yet, it is recognized that progress might be hindered due to the country being in an election cycle. Additionally, there is an emphasis on how the results of the election could influence future regulations and the industry landscape.

LE1 emphasized Texas's recognition of the safety and economic benefits associated with automated fleet vehicles. Consequently, Texas leads the nation in commercial freight traffic testing and operations, positioning itself significantly ahead in terms of experience, vehicle interaction, and the establishment of best practices. However, it is noted that creating a regulatory and enforcement structure requires a nationwide effort. Operating as an autonomous vehicle fleet or developer in the state is relatively straightforward: one must register their truck, certify their system's compliance with road rules, and ensure continuous camera operation during operations. As asserted by LE1, *"If you meet these basic requirements, there is nothing preventing you from operating as an autonomous fleet within Texas"*. LE1 anticipates that most sunbelt states will follow Texas's development.

In contrast to Texas' regulatory scheme, California's framework is notably more detailed and stringent, with certain bans on commercial AV testing (LE1). It was further noted that these regulations have hindered the industry's westward expansion in the nation, although this trend could shift. LE1 illustrated this spectrum by stating, *"You look at Texas on one end of the spectrum and California on the other, and if you look across the sunbelt, you'll see states falling somewhere between"*.

Ensuring a fairly uniform and consistent regulatory landscape nationwide is imperative for companies and the development of the industry, providing assurance that rules remain consistent when crossing state borders (LE1). LE1 additionally acknowledged that establishing suitable infrastructure for this advancement will take time stating that *"companies are currently in the process of building out their infrastructure, with each focusing on their specific operational design domains and within their own operating areas"*.

Multiple experts agree that authorities will play a pivotal role in the industry's future, particularly in controlling and auditing (CC1, CC2, CC4 & LE1). CC2 believed that certain new actors connected to the authorities would be developed in connection to this. LE1 elaborated that third-party companies facilitating communication between authorities and autonomous trucking firms have emerged. Third-party providers (like Drivewyze or PrePass Alliance) have established platforms for autonomous trucking firms to upload enhanced pre-trip inspection information. This allows authorities to receive the necessary data and certify that autonomous trucks on the road have successfully passed the inspection. LE1 describes this system as, *"providing certainty on the data we need daily to grant an automatic bypass for these vehicles"*. However, the adoption of these systems varies by state, emphasizing the challenges of communicating within those states (LE1). This further underscores the importance of developing infrastructure and robust communication networks, which are crucial for the industry's advancement.

4.2 Future scenarios for hub-to-hub transportation

In the following section, the results gathered for the research question *"How will the scenarios of hub-to-hub transportation evolve in the future?"* will be presented. When envisioning the future landscape of hub-to-hub transportation, several experts highlighted the potential for decentralized networks (CC1, CC3, CC5, CC6, UR2 & UR2). They emphasized a tendency to oppose facility sharing, noting that hub operators who have developed these networks may resist allowing other operators into their hubs due to the competitive advantage provided by the infrastructure establishment (CC1, UR2 & UR4). CC5 and CC6 further underscored that initially, multiple players will operate their own decentralized networks, although this dynamic might evolve as the industry progresses. The importance of customers being informed about which hubs are part of the network and the extent of coverage provided by the transport provider when purchasing the service was also highlighted by CC3.

UR4 also emphasized the technological hurdles to integration, pointing out companies' resistance to adopting new software systems when they already have their own, as well as the challenge of sharing information among themselves, which is crucial in a collaborative or centralized network. Moreover, it was noted that numerous actors in the United States rely on outdated Electronic Data Interchange (EDI) technology, posing an integration obstacle among them (CC6). Additionally, CC6 stressed that the hub's location will likely determine whether it remains private or becomes shared among multiple entities, highlighting that a hub required in a rural area, for instance, is likely to remain decentralized.

While some interviewees emphasized the concept of a decentralized network, others highlighted the advantages of a centralized network (CC1, CC2, CC5 & CC6). Some drew parallels with rail setups or airports where multiple carriers operate with various slot times and multiple operators traverse the system (CC1, CC5). CC1 suggested, *"From a cost efficiency standpoint, an airport-style setup seems to make sense, allowing multiple autonomous companies to utilize their yards and gates and share costs"*. Nevertheless, CC1 pointed out that possessing only a limited number of slots constrains the potential to broaden each ATO's market share. On the other hand, owning a network of hubs involves risks and significant investment expenses which must be accounted for (CC1). Moreover, CC2 believes that while a centralized network scenario is likely to be the predominant model, the decentralized scenario will serve as an essential intermediate phase prior to a wide adoption of the hub-to-hub model.

CC2 also stressed the possibility of a major player taking charge of all hub operations in particular regions, effectively dividing the nation into micro-regions and fostering a centralized network approach within these areas. This could lead to a scenario where a few dominant players serve as local orchestrators. CC6 shares the perspective that the industry will evolve to become more consolidated, with large corporations assuming responsibility for merging transportation. However, it was observed that this trend is anticipated to be especially prominent in popular locations (CC6), further underlining the consensus among numerous experts that there will be a mixture of centralized and decentralized networks (CC1, CC5 & CC6).

In summary, there is a range of perspectives concerning the future structure of the industry. This includes the potential for decentralized or isolated networks, where facilities are reserved solely for individual transport operators, as well as a centralized network model where multiple operators share a common hub. There is also the possibility of a hybrid approach combining elements of both. While the future industry configuration remains uncertain and is expected to evolve in the coming decades, significant changes will certainly occur. These potential developments will be further analyzed in the forthcoming discussion chapter.

4.3 Identification of high-value use cases

In the following section, the results gathered during the initial round of interviews for the research question *"What are the high-value use cases where the standardization of digital interfaces is crucial in operational hubs for autonomous trucks in the hub-to-hub model?"* are described. High-value use cases denote specific applications where data exchange could yield significant benefits in attaining particular objectives. These use cases typically involve pivotal activities or functions that directly impact an operation's overall performance, productivity, or success. While a total of eight distinct high-value use cases were identified in Table 4.5, this report will primarily focus on three of them. The selection criteria were primarily based on the frequency of mention and subsequent discussion with case company representatives, ensuring their relevance. For each selected use case, interview participants were tasked with providing a brief description of its contents and objectives, as well as outlining the stakeholders they deemed necessary to involve, along with key challenges and potential solutions. The subsequent section presents these findings in detail.

Table 4.5: Summary of high-value use cases mentioned in the interviews.

High-value use cases	
High-value use case	Number of times mentioned
Enhanced pre-trip inspection	6 (CC1, CC2, CC4, CC5, CC6, UR2)
Slot reservation	6 (CC1, CC2, CC3, CC4, CC5, CC6)
Gate in flow	3 (CC1, CC2, CC5)
Information sharing	2 (CC1, CC4)
Real-time terminal conditions	1 (CC3)
Route optimization capabilities	1 (CC3)
Trailer (de)coupling	1 (RI1)
Truck launch	1 (CC4)

One of the most mentioned high-value use cases is the enhanced pre-trip inspection, which was mentioned by six of the interviewees (CC1, CC2, CC4, CC5, CC6 & UR2). CC1 described the enhanced pre-trip inspection as a mandatory procedure outlined by law enforcement entities (like the DOT). The term "enhanced" pertains to the unique features of autonomous vehicles (CC2). This inspection encompasses ensuring both the vehicle and trailer are in optimal condition for departure (CC2, CC4). Consequently, safety (CC1, CC2, CC4 & CC5), traceability (CC2, UR2), and reliability (CC2, CC4) stands as the primary objective of this process. Furthermore, CC5 underscored that the inspection typically spans 60-90 minutes, encompassing numerous steps, thereby advocating for automation to expedite operations. Hence, an additional aim of the process is minimizing time (CC4, CC5 & CC6).

The consensus among experts suggests that the hub operator will likely incorporate this service into its operations in some capacity in the future (CC1, CC2, CC4 & CC5). CC1 emphasized that while the hub operator will oversee the inspection, it could potentially be subcontracted to a specialized actor in the future. UR2 further elaborated, *"The process can not be outsourced presently, this may become possible in the future, as it can not be modularized until the complexity is reduced to a low level"*. Moreover, CC2 indicated that it might take time before autonomous technology providers permit other actors to conduct inspections due to market immaturity and concerns over reputational risks in case of errors. CC1 also suggested the possibility of ATOs assigning employees to hubs for critical activities, even in shared facilities, to ensure the timely completion of the process.

The second most mentioned high-value use case was the slot reservation, which was also brought up by six interviewees (CC1, CC2, CC3, CC4, CC5 & CC6). When asked to describe the slot reservation system, all participants briefly explained it as the notion of reserving slot appointments in advance for the arrival and departure of autonomous trucks. Expanding on this, CC5 and CC6 underscored the system's significance in mitigating hub queue issues, particularly in addressing cascading transportation delays. CC3 drew parallels to slot reservation systems utilized at airports and maritime ports, highlighting their significant role in increasing efficiency and maximizing vehicle uptime. There is a consensus among the interview participants regarding that the goal of the use case is to enhance efficiency. CC2 and CC4 stressed the importance of lead-time and cost reduction for minimizing turnaround time and eliminating queues. Meanwhile, CC1, CC3, and CC6 emphasized the significance of optimizing operations, including synchronizing with different actors and increasing customer satisfaction. CC5 suggested that the slot reservation system aims to streamline operations and improve market dynamics.

In terms of stakeholders involved in the slot reservation, it was unanimously agreed that effective communication between the hub operator and the ATO is crucial. Additionally, CC1, CC2, CC3, and CC4 highlighted the pivotal role of the AD technology provider in ensuring seamless communication between on-road autonomous trucks and slot reservation software. Furthermore, interviewees emphasized the importance of collaboration with logistics software providers, including TMS and YMS developers, as essential partners for enabling this use case (CC2, CC3, CC4, CC5, & CC6). These digital capabilities were recognized as vital foundations for facilitating an efficient slot reservation process. CC5 emphasized the potential of a platform provider to centralize slot availability planning and optimize hub throughput by matching incoming freight from various transport operators. It was also noted that customers play a key role in providing timely and accurate information on their loads to service providers (CC6).

The third high-value use case involves the flow of vehicles into the hubs, as emphasized by three interviewees (CC1, CC2 & CC3). This process entails autonomous trucks passing through gates to access hub facilities. The objective is to streamline gate operations by eliminating redundancies and bottlenecks, as noted by CC1. This encompasses managing vehicle access and bookings to ensure compliance with facility protocols (CC5), a task demanding robust security measures (CC2). CC2 further underscored the contemporary reliance on physical documentation provided by drivers to validate bookings and cargo details. Efficiency (CC1), traceability (CC5), and security (CC1, CC2) were brought up as key goals of the process. Additionally, verifying paperwork and ensuring the correct pairing of trailers with booked shipments were mentioned as objectives (CC1, CC5).

The primary stakeholder in this scenario is the hub operator (CC1, CC2 & CC5), with CC5 pointing out that the operator or potential subcontractors would handle information reception, likely integrating it into their yard management systems. Consequently, software providers and ATOs are crucial players (CC2). A notable challenge highlighted is the bottleneck caused by manual trailer inspections before entering hubs (CC1). To address this, CC1 suggested implementing automated camera systems and trailer scanning technologies (e.g., RFID tags or QR codes) to alleviate pressure on the process. Nonetheless, CC5 stressed the significant cost hurdle associated with such implementations, suggesting that the technology is not the challenge of this process.

4.4 Digital interfaces and their characterization

To address the fourth research question, *"What are the prospective key stakeholders and information entities that must be involved in future digital interfaces for the high-value use cases?"*, seven interviews were conducted in the second interview round to characterize key elements of the high-value use cases. During these interviews, participants were tasked with describing the key stakeholders involved, information entities, potential standards, and challenges for each respective use case under both scenarios.

This section will explore the findings related to the high-value use cases in the following order: enhanced pre-trip inspection, slot reservation, and gate in-and-out flow. The results for each use case are summarized in three exhaustive tables, highlighting the key stakeholders and information entities involved. Additionally, associated information regarding existing or emerging standards, as well as challenges connected to the digital interfaces, will be provided.

4.4.1 Enhanced pre-trip inspection

Three interviews were conducted exclusively with experts in the field to delve deeper into the enhanced pre-trip inspection process. These interviews followed the same structure as those conducted for other use cases but allocated more time to explore the intricacies specific to the enhanced pre-trip inspection, particularly distinguishing it from inspections for conventional trucks. The findings from each scenario are summarized and categorized in Table 4.6.

In the context of enhanced pre-trip inspections within the decentralized scenario, interviews with CC7, CC8, and CC9 identified six crucial digital interfaces. These interfaces involve various stakeholders: the ATO, the hub operator, the logistics software provider, a third-party intermediary, and law enforcement authorities (LEA). Firstly, all three interviewees emphasized the significance of a digital interface between the ATO and the logistics software provider. CC8 provided further insight into the involvement of the logistics software provider, explaining that three separate systems are integrated into this interface by the hub operator: the TMS, the YMS, and the electronic logging device (ELD).

Additionally, a digital interface was identified between the AD technology provider and the ATO (CC8, CC9). CC9 stated that the AD technology provider will interact with the ATO's TMS. However, the extent of interaction between the virtual driver and the TMS remains uncertain. This could be likened to a control tower overseeing the virtual driver's operations. The amount of information that is exchanged between the stakeholders depends on the nature of their collaboration, and whether they are integrated into the other's systems. Furthermore, CC8 elaborated on the opportunity for the ATO to utilize its partnership with the AD technology provider to delegate tasks such as the enhanced pre-trip inspection.

Another digital interface was identified between the ATO and a third-party intermediary, serving as a middle link between the ATO and LEA (CC8, CC9). The

Table 4.6: Summarized findings on the enhanced pre-trip inspection.

Enhanced pre-trip inspection		
Category	Decentralized network	Centralized network
Key stakeholders	Hub operator LEA Third-party intermediaries AD technology provider Logistics software provider Autonomous transport operator	Hub operator LEA Third-party intermediaries AD software provider Logistics software provider Autonomous transport operator Subcontracted inspector
Information entities	Arrival time Departure time Slot information Truck & trailer information Inspection status (pass/fail) Failure information Hub conditions Equipment utilization	Arrival time Departure time Slot information Truck & trailer information Inspection status (pass/fail) Failure information Hub conditions Equipment utilization Audit information
Standards	Existing: N/A Emerging: CVSA standards	Existing: N/A Emerging: CVSA standards
Challenges	Driver accountability Lack of established standards Industry immaturity Scaling-up inspections	Pre-existing relationships Trust & verification Uncertainty

third-party intermediary's responsibility was noted by CC8 to encompass facilitating bypasses for trucks, ensuring an approved inspection status. This function bears similarities to, albeit less intricate than, the current role of such companies in conventional trucking (CC8). Additionally, both CC8 and CC9 elaborated on the interface between LEA and the third-party intermediary, enabling the exchange of information regarding AV inspections. Through the third-party intermediary's platform, LEA gain access to data concerning vehicle inspections. This resonates with the earlier statements made by LE1 as presented in the results. Moreover, CC8 and CC9 provided further insights into a digital interface between the ATO and LEA, directly linking these stakeholders. Communication occurs on an ad-hoc basis rather than continuously, as LEA might request information on previous inspection outcomes as part of a protocol compliance check.

In the decentralized scenario, the hub operator and ATO roles are unified within the same stakeholder as previously described. A digital interface that has been highlighted is that between the ATO and the hub operator, categorizing this interface as internal (CC7, CC8 & CC9). CC9 underscored the importance of establishing clear internal communications to mitigate the risk of oversight and make tasks more actionable. Furthermore, distinct internal capabilities of the hub operator were delineated, with a focus on safety and security, operations, and repair and maintenance teams as integral functions of the enhanced pre-trip inspection (CC9). This perspective highlighted the operations team's role as a key internal stakeholder overseeing truck missions, while the safety and security team serves as troubleshooters, coordinating measures for optimizing truck operability with the repair and maintenance team. Similarly, though with less granularity, CC8 underscored the central role of the stakeholder serving as both the ATO and hub operator within the decentralized network, acting as the cohesive link between other ecosystem players.

Looking at the centralized network scenario, seven distinct types of digital interfaces were identified for enhanced pre-trip inspection (CC7, CC8 & CC9). On a high level, six of these interfaces are identical to those presented in the decentralized scenario, however, a significant contrast lies in the expanded number of stakeholders involved in each role. As emphasized by CC8 and CC9, multiple transport operators will conduct inspections within the same hub facility, necessitating seamless coordination with the central hub operator. Similar to the decentralized scenario, there are various pathways for information flow, and the configuration varies based on whether the hub operator or the ATO communicates directly with law enforcement or through an intermediary.

Moreover, a notable characteristic of the centralized scenario is the potential outsourcing of enhanced pre-trip inspections to specialized subcontractors in the field (CC9). This stems from the opportunity for such actors to centralize enhanced pre-trip inspections required for all ATOs connected to the hub. Consequently, an additional interface was identified between the hub operator and the specialized subcontractor. CC9 expressed that regardless of whether the inspections are outsourced, the hub operator would offer these services on a per-use basis or through a monthly subscription model. However, the implementation of such a model hinges largely on the development of CVSA standards, which are currently under construction to determine whether autonomous trucks should undergo an enhanced pre-trip inspection every 24 hours as a prerequisite for operability without a safety driver.

In both scenarios, interview participants highlighted multiple information entities, as outlined in Table 4.6, pertaining to the enhanced pre-trip inspection. These data entities are exchanged among the involved stakeholders through the aforementioned digital interfaces. In the interface between the responsible inspector or third-party intermediary and LEA, two critical information entities are emphasized by CC9: the inspection status (pass or fail) and failure information (in instances where the truck fails to meet inspection criteria). CC9 clarified that if an autonomous truck fails inspection, both the status and failure information are internally communicated within the relevant divisions when inspections are managed in-house. Concurrently, the ATO continuously gathers information on inspection processes, serving as a statistical database accessible to authorities. Notable is that the authorities do not automatically receive failure information when a truck fails the inspection. Instead, notification is only issued once the issue is rectified or if specifically requested by authorities, either directly from the inspector or through the third-party intermediary. Furthermore, additional information entities mentioned by CC8 and CC9 were left unspecified concerning their respective interfaces, primarily due to the numerous uncertainties surrounding the enhanced pre-trip procedure.

When discussing the challenges associated with the enhanced pre-trip inspection, driver accountability (CC9), lack of established standards (CC7), industry immaturity (CC7), and scaling-up inspections (CC8) were mentioned for the decentralized scenario. Driver accountability, as noted by CC7, refers to the legal responsibility for the operation of the truck once it becomes fully autonomous. This responsibility connects to the DOT number and is typically associated with the human driver in conventional trucking, but it remains undecided whether it will belong to the AD technology provider or the ATO. Consequently, ambiguities persist regarding how this accountability will impact the enhanced pre-trip process. Furthermore, CC7 stated that *"the autonomous trucking ecosystem put pressure on establishing APIs and standards, to ensure proper integration and that collaborative partners conduct inspections in compliance with our requirements"*, highlighting the crucial part that industry harmonization plays. Additionally, CC8 pointed out limitations in scaling up inspections conducted at hubs, attributed to the manual process carried out by certified inspectors. To address this challenge, automating the inspection process to the fullest extent possible was identified as a potential solution. This would allow inspectors to increase the number of inspections conducted per day without compromising on quality.

On the other hand, participants highlighted pre-existing relationships (CC9), trust and verification (CC8), and uncertainty (CC8, CC9) as challenges within the centralized network. Regarding potential pre-existing relationships, CC9 elucidated that friction might arise among various actors in the ecosystem due to past experiences or biases. This could jeopardize the network's openness and potentially lead certain players to exclude others from their hub operations. Consequently, the stakeholder controlling the lion's share of hubs in the centralized network holds considerable influence over its development. Moreover, CC8 raised concerns about verification and trust when sharing hub premises with other ATOs, noting the competitive nature of these actors and a potential reluctance to share information with the hub operator for fear of it being disseminated. Lastly, both CC8 and CC9 underscored uncertainty as a major challenge facing the industry, given the ambiguity surrounding its future trajectory and who will ultimately assume the inspector role.

4.4.2 Slot reservation

Five interviews were conducted to explore the prospective slot reservation system, encompassing both decentralized and centralized network configurations. Participants included representatives from the case company, a university researcher, and a project manager in port operations. The findings from the interview are summarized and categorized in Table 4.7.

Table 4.7: Summarized findings on the slot reservation.

Slot reservation		
Category	Decentralized network	Centralized network
Key stakeholders	Hub operator Autonomous transport operator Logistics software provider AD technology provider Customer	Hub operator Autonomous transport operator Logistics software provider AD technology provider Customer
Information entities	Truck & trailer ID Cargo details Gate number Slot information ETA Transport updates ODD information	Truck & trailer ID Cargo details Gate number Slot information ETA Transport updates ODD information
Standards	Existing: N/A Emerging: Standard Scheduling Consortium (SSC)	Existing: N/A Emerging: Standard Scheduling Consortium (SSC)
Challenges	Lack of standards Industry immaturity Data sharing System inflexibility Resource constraints	Lack of standards Industry immaturity Data sharing System inflexibility Resource constraints Integration

The setup and quantity of digital interfaces in the slot reservation system, whether operating in a decentralized or centralized scenario, are greatly influenced by the future scheduling model implemented. During the interview, CC6 identified three potential scheduling models: contracted, static, and dynamic time slots. Contracted time slots involve reserving or allocating a predetermined period for arrival through a formal agreement or contract, where the expected arrival time is given for the final destination and not necessarily for the hubs (CC6). In a static time slot system, the time slots are predetermined and fixed beforehand (CC6). Activities are assigned specific time slots, which remain consistent over time, as suggested by CC7 for future use. This process was outlined by CC6, explaining that available time slots would be made accessible by the hub operator via a platform or separate interfaces, allowing visibility and booking of slots as needed. Conversely, a dynamic system offers flexible time slots that can adapt to changing conditions, priorities, or demands, allowing real-time adjustments based on relevant factors (CC6). In the envisioned hub-to-hub model, as described by CC6, customers or shippers would communicate their preferred shipment times, which could then be adjusted to accommodate the current bookings at the hubs. CC2 highlighted the necessity of such a system, particularly in situations where slot allocation may need to be reorganized in response to status updates concerning incoming trucks.

In the decentralized scenario, four digital interfaces were identified, with one of these interfaces facilitating internal communication. The stakeholders identified to be involved in the slot reservation system include the hub operator (CC7, UR5 & PM1), the ATO (CC2, CC6, UR5 & PM1), the logistics software provider (CC6, CC7, UR5 & PM1), the customer (CC2, CC6 & UR5) as well as the AD technology provider (CC2). It is worth noting that in this specific scenario, the ATO assumes the role of the hub operator, effectively unifying them as a single stakeholder.

Several interviewees emphasized that establishing an internal digital interface within the logistics software provider of the ATO's system is essential to facilitate seamless coordination between the TMS and the YMS (CC2, CC6 & PM1). This interface's purpose is to ensure that the scheduling of transportation and bookings aligns seamlessly with the availability of yard resources. Slot information was identified as the main information entity within this interface (CC2, CC6 & PM1).

In a static time slot system, establishing an external digital interface between the customer and the ATO's logistics software provider is crucial for accessing the available time slots (CC6). The interviewee further mentioned, *"the TMS and the related integrations towards stakeholder YMS and or TMS, are the main way that stakeholders get in contact with each other"*. Therefore, it is assumed that the customer connects to the ATO's TMS which further is connected to the YMS at hubs through the internal digital interface mentioned above. CC6 emphasized that in a dynamic system, a similar digital interface would be necessary. However, in this scenario, the customer would book a preferred transportation time for their order, prompting a response from the ATO's TMS accordingly. Within this interface, the slot information was underscored as a key information entity (CC2, CC6 & PM1).

To ensure precise adjustments to slot reservations, CC2 stressed the significance of establishing a digital interface between the ATO and the AD technology provider. This interface enables the ATO to receive real-time updates on truck progress (CC2, CC7, UR5 & PM1), ETA (CC2, CC6, UR5 & PM1), and ODD (CC6). As a result, there is a requirement for a digital interface between the ATO and its logistics software provider, enabling the transmission of information for slot reservation adjustments (CC2, CC6, CC7, UR5 & PM1). CC7 emphasized that this interface would facilitate *"matching available slots within the hub with incoming trucks and their ETA"*. Additionally, CC2, UR5, and PM1 noted that such an interface would allow for the management and adjustment of truck speed and arrival time to synchronize with the planning system of slot availability.

In addition to these interfaces, interview participants emphasized the critical need for a connection between the slot reservation system and the gate management system (CC2, CC6, CC7, UR5 & PM1). This linkage is essential to ensure that information concerning truck & trailer ID (PM1), cargo details (CC7, UR5), slot information (CC2, CC6,CC7, UR5 & PM1), and gate number (PM1), aligns with booking information and slot allocation. Further details regarding this integration will be explored in the subsequent "Gate management" section.

When discussing the centralized network, six digital interfaces were recognized. Interviewees pointed out that although the same stakeholders would participate in the system, in this instance, the ATO and the hub operator are separate entities. This means that these two stakeholders will operate distinct logistics software systems, possibly from different providers (CC2, CC6). This underscores the necessity for a digital interface between each stakeholder and their respective logistics software provider. Additionally, an internal digital interface is necessary between the hub operator's YMS and TMS systems (CC6).

In this context, the customer will engage with the ATO's TMS system through a digital interface (CC6). The data exchange within this interface may vary slightly, as highlighted by CC6, based on whether a contractual, static, or dynamic slot reservation system is utilized, mirroring the decentralized scenario. Since the ATO is not overseeing the hub, establishing a digital interface between these players becomes imperative. CC6 stresses the importance of integrating the ATO's TMS with the hub operator's YMS, whether through a direct connection or via the hub operator's TMS. However, it's essential to recognize that these configurations may vary, particularly if both parties utilize different logistics software providers (CC6). Information entities such as truck and trailer ID (PM1), cargo details (PM1), gate number (PM1), slot information (CC2, CC6, CC7 & UR5), and lane reservation (CC7), could be exchanged between these two stakeholders.

Similar to the decentralized network, a digital interface is necessary between the multiple ATOs and their respective AD technology providers (CC2). This interface enables the ATOs to gather and forward real-time updates on truck progress (CC2, CC7, UR5 & PM1) and ETA (CC2, CC6, UR5 & PM1) to the hub operator. Consequently, adjustments to the slot reservation system and the trucks' speed can be made accordingly (CC2, CC7, UR5 & PM1).

When asked about standards for slot reservation, all five interviewees unanimously confirmed the absence of industry-wide standards for this particular use case. CC2 provided further insight, noting that within the US trucking industry, integration among different stakeholders predominantly relies on outdated systems rooted in EDI integration, rather than modern APIs. This aggravates information sharing and underscores the necessity of maintaining integration compatibility not only with contemporary systems but also with decades-old operating systems existing within the same digital infrastructure. Moreover, CC2 and CC6 emphasized the emergence of the Standard Scheduling Consortium as a notable development. They explained that this consortium, involving major industry players such as Uber Freight, DHL, and Blue Yonder, aims to streamline system integration and enhance the efficiency of appointment scheduling processes. However, the potential of the SSC to establish itself as the new industry standard for scheduling autonomous road freight remains uncertain.

When examining challenges related to slot reservation, several key obstacles were identified for the decentralized scenario. These include lack of standards (CC2, CC6), industry immaturity (CC2), data sharing (UR5), system inflexibility (CC7, PM1), and resource constraints (CC6). The lack of standards and industry immaturity primarily stem from the current absence of established regulations for autonomous trucking in the US, coupled with a lack of dominant technology designs (CC2, CC6). UR5 emphasized the challenge of data sharing and transmitting information from the vehicle to the slot reservation software, underscoring the critical need for seamless integration among these separate systems to ensure timely communication. In this context, the decentralized scenario holds an advantage, operating under a unified system architecture that facilitates integration among its components.

Furthermore, system inflexibility, as highlighted by CC7 and PM1, pertains to the inability to handle outlier situations within slot reservations. This includes limitations imposed by self-driving technology, such as the inability to reverse, which necessitates hub operators to accommodate unplanned stops within slot planning and potentially involve human intervention. CC7 suggested implementing a hybrid solution during the transitional phase to manage outliers with manual processes. In addition, CC6 emphasized resource challenges for system execution within the centralized network, particularly concerning implementation time and investment costs. The industry's early stage of development means that necessary capabilities for automating slot reservations are currently unavailable. Prospective future solutions were anticipated to involve new optimization tools and standardization of appointment scheduling, which have yet to be introduced to the market.

The same challenges mentioned for the decentralized scenario were applied to the centralized scenario by interviewees (CC2, CC6, CC7, UR5 & PM1), with an additional hurdle being the challenge of integration (CC2). The intricate integration among multiple ATOs and a central hub facility is expected to necessitate continuous iteration and adjustment of APIs. CC2 further explained that this, coupled with the lack of standards, exacerbates the integration of network nodes, especially when different operators manage hubs.

4.4.3 Gate management

Like the slot reservation, five interview participants were queried regarding the digital interfaces in each scenario for gate management. The insights gathered from these interviews are summarized and categorized in Table 4.8.

Table 4.8: Summarized findings on the gate in flow.

Gate management		
Category	Decentralized network	Centralized network
Key stakeholders	Hub operator Autonomous transport operator Logistics software provider Customer/shipper AD technology provider	Hub operator Autonomous transport operator Logistics software provider Customer/shipper AD technology provider
Information entities	Truck & trailer ID Vehicle plate number DOT number Bill of Lading (BoL) Booking number Gate arrival time Slot information Truck & trailer conditions Seal of integrity	Truck & trailer ID Vehicle plate number DOT number Bill of Lading (BoL) Booking number Gate arrival time Slot information Transport operator ID & authentication
Standards	Existing: N/A	Existing: N/A Emerging: SSC
Challenges	Lack of standards Industry immaturity System inflexibility Untimely truck arrival Data inconsistency Readability	Lack of standards Industry immaturity System inflexibility Untimely truck arrival Integration

In the context of gate management within the decentralized scenario, interviews with CC2, CC6, CC7, UR5, and PM1 identified five crucial digital interfaces, with a few of these interfaces facilitating internal communication. The five roles identified to be involved in the gate management include the hub operator (CC6, UR5, PM1), the ATO (CC2, CC6, CC7, UR5, PM1), the logistics software provider (CC6, CC7), the customer (CC2, CC6, CC7) and the AD technology provider (CC2).

The initial digital interface connects the ATO with the logistics software provider, while a secondary internal digital link bridges the ATO's YMS and TMS, both managed by the logistics software provider (CC2, CC6). CC2 further explained that upon a truck's arrival at the hub gate, it undergoes examination communicated through an IoT platform equipped with technologies such as RFID, cameras, and scanners. Additionally, the interviewee emphasized the necessity of a third internal digital interface between the ATO's IoT platform and the YMS system. These two internal digital interfaces operate in real time to ensure precise alignment between truck arrivals at the gate and scheduled arrangements (CC2, CC6). The identified information entities exchanged in this process include truck and trailer IDs (CC2, CC6, CC7, UR5, PM1), vehicle plate number (CC6, UR5), DOT number (CC6), BoL (CC6), booking number (PM1), slot information (CC2, CC6, PM1), gate arrival time (CC6), truck & trailer conditions (CC7, UR5) and seal of integrity (CC7). CC6 and CC7 underscores the significance of digitalizing documents for this process.

The fourth digital interface is situated between the customer and the ATO's TMS, as underscored by (CC2, CC6, CC7). This interface is described in the slot reservation system section above. It serves as the platform for booking, which is then utilized to synchronize with the arrival of trucks at the gate (CC2, CC6, CC7, UR5 & PM1). The interviewee underscores the interconnected nature of these two processes. CC2 emphasizes the significance of the fifth digital interface, which connects the ATO with the AD technology provider, serving as a gateway to enable autonomous transport solutions. It remains ambiguous whether communication with the gate through V2I is conducted by the AD technology provider or the ATO (CC2, UR5). However, it is crucial for seamless integration between these two parties to ensure that the tractor can deliver this information in a timely manner.

Looking at the centralized scenario, seven types of digital interfaces were identified for the gate in flow (CC2, CC6, CC7, UR5 & PM1). Broadly speaking, five of these interfaces mirror those in the decentralized scenario. However, a notable difference lies in the increased number of stakeholders and their roles. In this scenario complexity increases as multiple ATOs utilize the hub, necessitating digital interfaces between these stakeholders and the hub operator (CC2, CC6 & UR5). In this interface, CC7 highlighted that transport operator ID and authentication as an additional required information entity. UR5 further pointed out, *"The main difference is that you have several companies coming in, but the functionality is the same with the scanning and everything"*.

In this scenario, both the ATO and the hub operator rely on separate logistics software systems (CC2, CC6). This indicates the need for a dedicated digital interface between each stakeholder and their respective logistics software provider. Furthermore, an additional interface will be necessary between the ATOs and the hub operator's TMS, in a similar manner to that described in the slot reservation system (CC2, CC6 & UR5). The two internal digital interfaces outlined in the decentralized scenario facilitate connections between the hub operator's IoT platform and YMS, as well as between the YMS and TMS (CC2, CC6). They will continue to facilitate the transfer of identical information entities across these platforms. Similarly, the digital interface between the customer and the ATO's TMS will remain unaffected (CC6). Furthermore, the digital interface between the ATO and the AD technology provider will also remain consistent (CC2). However, CC2 and UR5 noted that in this scenario, multiple ATOs and hub operators would engage in communication through V2I, necessitating a harmonized system among these stakeholders.

When questioned about gate management standards, all five interviewees confirmed the lack of established standards for both network scenarios. Regarding the centralized network, CC7 noted, *"Presently, standards are absent, but there is potential for extensive cross-industry collaboration such as with the airport industry"*. Additionally, CC2 and CC7 emphasized the emergence of SSC as a promising contender for a standardized framework, as outlined in the slot reservation section.

Delving into challenges associated with gate management in the decentralized scenario, interview participants identified multiple barriers. These encompass lack of standards (CC6, CC7), industry immaturity (CC6), system inflexibility (CC6, CC7 & PM1), untimely truck arrival (CC2, UR5, PM1), data inconsistency (CC6) and readability (CC2, CC6). Similar to slot reservation, the lack of standards and industry immaturity in autonomous trucking were emphasized (CC6, CC7). Moreover, CC6, CC7, and PM1 emphasized system inflexibility as the inability to handle outlier situations primarily due to limitations of AD technology, alluding to related thoughts for the slot reservation. This was perceived as impeding the optimization of hub operations' efficiency.

Untimely truck arrival emerged as another concern, imposing potential bottlenecks to the hub throughput beyond the control of the hub operator (CC2, UR5 & PM1). Additionally, CC6 defined data inconsistency as discrepancies between planning and execution data, complicating the implementation of efficient gate management systems in practice. This further ties in with the readability concerns, also mentioned by CC2, as high-quality data was considered a prerequisite for enabling accurate interpretation.

In the centralized scenario, the gate management faces the same four primary challenges mentioned earlier, along with an additional hurdle of integration (CC7). This issue encompasses establishing standardized communication protocols and data exchange practices for ensuring interoperability between disparate systems and thus, facilitating effective gate management across interconnected hubs managed by different operators. To address this challenge, CC7 emphasized the necessity of establishing standardized practices within the industry, stating that *"Standards are our language, and without them, we are unable to unanimously drive development forward"*. This underscored the importance of creating harmonized integration standards utilizing common standardized APIs. Such measures would facilitate connectivity with various transportation networks, enhancing interoperability and efficiency.

5

Discussion

5.1 Stakeholder analysis and role allocation in operational hubs for autonomous trucks

Aiming towards identifying the stakeholders involved and their respective roles in future autonomous trucking hubs, a reoccurring theme in the interviews was the potential development of the truck manufacturers. Specifically, truck manufacturers and their associated subsidiaries are poised to expand beyond their current roles to become providers of autonomous trucks. As the industry is anticipated to transition from its current state, where truck manufacturers are central, to a new era characterized by the increasing significance of the dynamic interplay between these manufacturers and software platform providers (Fritschy & Spinler, 2019), the entire road transportation industry will need to adapt. As explained by Monios and Bergqvist (2020), this entails moving away from traditional ownership-based models focusing mainly on conventional truck sales to increasingly adopting non-ownership models where the value is less rooted in truck technology.

Similarly, the interviews revealed expectations that truck manufacturers would start providing autonomous trucks through service-based models, evolving beyond their traditional roles as mere asset sellers. Supporting this perspective, Fritschy and Spinler (2019) suggest that truck OEMs will adapt their strategy to maintain vehicle ownership in-house and offer capacity as a service, thereby transforming into mobility service providers. Additionally, the interviews underscored the critical role of AD technology providers in developing software that enables driving automation and approving ODDs and routes between hubs. Liu et al. (2020) describe the intricate integration of technologies essential for autonomous driving, underscoring the essential involvement of AD technology providers due to their specialized knowledge. Furthermore, Pudasaini and Shahandashti (2021) note that the advanced technology in ATs necessitates more frequent inspection and maintenance than what is required for manually driven trucks. The interviews also highlighted a notable connection with the literature, suggesting that AD technology providers, due to their existing infrastructure and experience with pilot testing hubs, could play a pivotal role in the near-term operations of future autonomous trucking hubs.

Analysis of the autonomous transport operator role suggests that AT providers are the most prominent candidates, as indicated by the interviewees. Positioned favorably at the intersection between AD technology providers and transport buyers, AT providers offering autonomous trucks may, as previously mentioned, include truck OEMs collaborating with AD technology providers, specialized subsidiaries, or integrator companies. Interviewees generally agreed that AT providers are well-positioned to operate autonomous transportation, due to their closeness to the novel technology and financial stability. This allows them to maintain and operate large fleets of ATs and provide related services without deviating too much outside their core business. Additionally, a notable shift highlighted in the interviews was the projected decline of individual truck owners in the evolving transportation logistics system. Parallels may be drawn to the predictions of Fritschy and Spinler (2019), who foresee an industry consolidation leading to fewer, but more resource-plentiful actors capable of maintaining larger fleets of ATs.

The roles of hub owner and hub operator are underrepresented in existing scholarly literature. Consequently, the subsequent discussion of these roles will rely exclusively on insights derived from the interview findings. According to the interviews, the AT provider and real-estate companies were most frequently mentioned as potential hub owners, followed by logistics providers and large shippers. Arguments favoring AT providers as hub owners include their proximity to the product and the current absence of uniform industry regulations and standards. This suggests that AT providers, by necessity, may be involved in establishing inspection and maintenance processes for ATs at hubs, thereby positioning them as potential hub owners. Nevertheless, real-estate companies and logistics providers possess distinct advantages by utilizing their existing infrastructures as hub facilities. Particularly in areas with high traffic density, the transition to a hub-to-hub model may be expedited through the conversion of existing properties to support autonomous trucks, rather than constructing new facilities from the ground up. In remote locations, however, AT providers might find strategic benefits in owning hubs, particularly if these are optimally situated in relation to their customer base. While no single stakeholder is clearly favored to assume the role of hub owner, it appears that the successful candidate would benefit significantly from both existing infrastructure and a thorough understanding of the technologies that enable autonomous trucking.

A key question in the management of hub operations is whether it will be conducted by operators separate from the owners or if an owner-operator model will dominate. Insights from interviews indicate a division in opinion regarding the optimal configuration for hub management. Some interviewees advocate for an owner-operator model, where the same actor owns and operates the hub. For instance, if AT providers own hubs, they are likely to manage operations internally to optimize efficiency within a controlled network. This approach is favored for its streamlined decision-making and operational coherence, suggesting a unified strategy where the owner-operator is fully responsible for both the strategic oversight and day-to-day operations. The owner-operator might also be more invested in the maintenance and success of the hub since both capital investment and operational success are tied to the same stakeholder. In regions where smaller networks of hubs emerge within larger geographical macro-regions, this would allow a dominant player to oversee all hub operations, ensuring consistency across various locations. However, it is notable that even within the owner-operator framework, specific operational tasks such as gate management or inspections might still be subcontracted to specialized providers to harness niche expertise, though the overall control remains with the owner-operator.

Conversely, other interviewees believe that the hub owner and operator should be distinct stakeholders, entailing separate real estate ownership from operational management. This layout would involve the hub owner subcontracting the operational tasks to one or several players. For instance, if a real estate company owns a hub, it might still outsource the operational management to subcontractors specializing in specific functions like gate management and logistics planning. This separation can provide flexibility and the ability to leverage particular expertise from different subcontractors, but may also increase integration complexity. There are current examples of AD technology providers stepping into the role of owner-operators, suggesting a potential trend where these players collaborate with AT providers to manage hub operations. Whether there will be an integration or separation of the hub owner and operator roles remains uncertain, however, this decision will likely depend on factors such as the need for specialized knowledge, financial incentives, and the strategic benefits of gaining enhanced control.

Moving on, the next role that will be analyzed is that of the network operator. In the context of network business models, Palo and Tähntinen (2011) state that individual firms lack the capability to manage all activities and resources required for delivering a technology-based service, underscoring the necessity for industry collaboration. This view aligns with Fritschy and Spinler (2019), who argue that cooperation and partnership establishment are indispensable for enabling autonomous truck technologies, as firms adapt to changing dependency structures within the value network. In light of this development, a novel role of the network operator is anticipated to orchestrate interactions among diverse stakeholders in the future transportation ecosystem. This role might be assumed by existing actors or entirely new players, suggesting a flexible entry point into the industry (Monios & Bergqvist, 2020; Lind & Melander, 2023). Monios and Bergqvist (2020) discuss how new entrants might gain market share by renting rather than purchasing physical assets from existing suppliers. This strategy mirrors the business models of asset-light companies like Uber or Airbnb, which have successfully created new markets without owning the primary assets involved in their services. Interviews also reflected this perspective, suggesting the potential rise of a new platform provider as the network operator that could help smaller transport operators consolidate their capacities through an aggregation platform.

As the industry contemplates the advent of a network operator, significant uncertainty surrounds the identity of this stakeholder and its evolution over time. Authors such as Monios and Bergqvist (2020), and Lind and Melander (2023) speculate that truck manufacturers, in this report likened to AT providers, might initially adopt the network operator role due to their extensive technological expertise and established industry relationships. This could manifest either solely by AT providers or through collaborations with other actors. Interviews reveal no consensus on a definitive stakeholder for the network operator role, however, large shippers and AT providers frequently emerge as candidates. The suitability of AT providers is attributed to their contemporary market influence and central role in integrating essential actors within road transportation. Furthermore, as the industry advances, the evolving landscape will necessitate that the network operator acquire new IT competencies, particularly in managing the logistic flows. Monios and Bergqvist (2020) emphasize that significant investments and advanced software capabilities will be crucial for effectively overseeing the network transportation system. Coupled with advancements in connectivity and automation technology, there are burgeoning opportunities for IT specialists from various domains to leverage their competitive edge and venture into autonomous trucking.

Lastly, logistics software providers are defined as facilitators within operational hubs. Their primary role is to help manage the flow of goods and information efficiently. According to interviewees, this capability is crucial as the hub can become a bottleneck without effective traceability and optimization of these flows. The interplay between technological advancement and logistical operations underscores the need for robust software systems that can handle complex data and streamline processes to prevent congestion and inefficiencies. In a smart network, as described by Monios and Bergqvist (2020), IT and logistics software are central to value generation, orchestrating and overseeing logistical flows across the network. Following this development, the logistics software provider's role extends beyond mere facilitation and becomes crucial in integrating various stakeholders and managing interfaces. These providers must offer highly adaptable systems that can interface with diverse stakeholders, acting as integration platforms that enable more standardized network connections between different supplier's software systems. The interviews further highlighted the logistics software provider's vital role in ensuring integrations between different TMSs as well as between TMSs and YMSs, emphasizing the need for high-quality data that enable real-time tracking and control of goods transportation. Employing off-the-shelf solutions is an effective approach for acquiring these types of software, however, with more complex integration needed this puts pressure on the software providers to supply the market with more standardized APIs.

As the industry evolves, the initial role of AT providers as network operators is expected to shift to another actor possessing more sophisticated IT capabilities. This change will necessitate that network operators forge collaborative partnerships and heavily invest in IT capabilities to handle the increasing demands of autonomous truck hubs. The logistics software provider might even take on the network operator role themselves, however, this is deemed less likely in the near term. There is a particular emphasis in the interviews on collaborations between AT providers and logistics software providers to jointly develop advanced solutions that surpass current capabilities. Furthermore, there is a potential for forming consortia between major hub operators and software providers to co-develop these systems, highlighting the strategic shift towards a more integrated and cooperative industry configuration. As pointed out by Lind and Melander (2023), technological advancements are set to transform the network, making it more open and conducive to new entrants with specialized expertise. This openness will likely invite new actors into the market, influencing the development trajectory and introducing novel interactions within the logistics ecosystem. The dominant players in this evolving market are expected to be those with superior software design and technology, significant financial resources, as well as extensive data and informational assets (Monios & Bergqvist, 2020).

While the future points towards increased data sharing between network operators and ATOs, this is anticipated to be a long-term development. Initially, the network might exhibit a more decentralized configuration to streamline operations and manage complexities. However, as software providers gain market influence, they may assume more direct roles, potentially procuring or renting assets from OEMs to strengthen their control over the logistical aspects of hub operations. Nevertheless, it is evident that the role of the logistics software providers will be that of spiders in the web, facilitating not only the flow of information but also the integration of various technological and operational components. Their ability to adapt and develop in conjunction with other stakeholders will be crucial in shaping the future logistics landscape, making them indispensable in the drive toward a more connected and efficient transportation ecosystem.

5.2 Evolution of hub-to-hub transportation scenarios

To outline in which direction hub-to-hub transportation will likely evolve in the future, diverse perspectives were analyzed in the interviews. Some envisioned a fragmented industry characterized by highly vertically integrated companies owning and operating their own systems end-to-end, similar to the structure of national intermodal railway companies. Conversely, others envisioned a model where roles and responsibilities are divided among multiple stakeholders, resembling the setup seen in the aviation industry. Moreover, the concept of a hybrid approach, blending elements of both structures, was highlighted. Several interviewees emphasized that the evolution of hub-to-hub transportation is likely to unfold sequentially, beginning with a highly fragmented market and progressing towards a more consolidated one.

Currently, the absence of federal regulations, alongside companies building hub infrastructures tailored to their unique operations and the challenges of technological integration, suggests an initially decentralized development within the industry. Interviewees highlighted how the divergent regulatory frameworks across states significantly influence the nationwide expansion of the industry. This has led companies to develop infrastructure customized for their specific operations. Furthermore, this cultivates a hesitancy to participate in facility sharing due to the competitive advantage gained from their established setup. This scenario resembles a highly vertically integrated intermodal rail industry, that can be seen in numerous countries where tracks, terminals, and services are owned and operated by the same actor (Laurino, 2019).

Furthermore, the lack of technological integration along with an inherent reluctance to share vital information for collaborative efforts, outdated technologies, and resistance to adopting new software, pose significant obstacles to integration and collaboration. Jacobsson et al. (2017) further underscore the deficiencies in information exchange among stakeholders within intermodal freight transportation, highlighting a potential lack of integration across stakeholders in the transportation industry. This could be compared to the challenges with information exchange due to lacking integration brought up during the interviews. Achieving seamless collaboration among stakeholders, as emphasized by Monios and Bergqvist (2020), requires the integration of their systems. Interviewees observed that parameters advocating for industry decentralization would compel players to become owner-operators of their own end-to-end network, although this dynamic is anticipated to evolve as the industry progresses. As previously stated, Lind and Melander (2023) postulate a sequential progression, where truck manufacturers initially assume a network operator role owing to their expertise and legacy relationships.

On the other hand, Monios and Bergqivst (2019) emphasize that centralizing future truck hubs and permitting multiple suppliers to utilize the same facilities is beneficial for the stakeholders involved. Interviewees noted that this approach reduces costs and risks by distributing roles and responsibilities among stakeholders, mirroring practices observed in the aviation and intermodal railway industries in the

United States. Gran et al. (2008) underlined the collaborative roles of airports and airlines in serving customers, pointing to the potential benefits of exclusive and non-exclusive agreements similar to those in the aviation industry (Sabel, 2004). Such agreements could enable smaller transport operators to share hub facilities cost-effectively while allowing larger operators to forge strong relationships with hub owners. Additionally, a centralized and collaborative configuration finds resonance with the intermodal railway industry described by Monios and Bergqvist (2019), where separate companies manage tracks, terminals, and services. Moreover, interviewees envisioned a future where collaboration between ATOs, responsible for goods transportation, and hub owner-operators, in charge of infrastructure and operations oversight, could mitigate risks and reduce costs. This structure would allow several ATOs to offer middle-mile services connected to the same hub facilities, enabling greater efficiency and cooperation (Monios & Bergqvist, 2019).

Expected regulatory changes along with the costs and risks of owning a hub network are driving the industry towards a shift from decentralized to centralized networks. This is coupled with the prospects for future standardization of policies and processes for operating autonomous trucks, aiding the industry players with issues connected to these shortcomings. Interviewees emphasized that the anticipation of emerging regulations will play a crucial role in harmonizing regulatory frameworks nationwide. Moreover, the pivotal role of forthcoming regulations in harmonizing nationwide regulatory frameworks was stressed. With Texas currently leading the nation in commercial freight operations and setting best practices, most sunbelt states will likely emulate its development. A uniform and consistent regulatory landscape would facilitate the establishment of common practices, although it is recognized that such progress will require time to implement. As the industry evolves, interviewees expect standards to be developed to facilitate collaboration among stakeholders, addressing current gaps and enhancing operational efficiency in the freight transportation system. This evolution towards standardized practices further promotes the evolution from a decentralized towards a centralized network, fostering greater efficiency and collaboration among the stakeholders in the industry.

A mix of these scenarios is expected to coexist in the future. Similarities can be drawn to the varying ownership structure and degree of vertical integration seen in the intermodal railway industry (Monios & Bergqvist, 2019). Interviewees emphasized that the level of collaboration is likely to vary based on the hub's location, with facilities in popular areas, such as near city centers, being more inclined to be shared. This parallels the success of airports situated close to urban centers as described by Gran et al. (2008). Conversely, hubs located in rural areas are anticipated to lean towards high vertical integration, primarily due to the unique circumstances necessitating a hub's placement in such locations.

Considering the prevailing industry landscape and regulatory frameworks, the evolution of hub-to-hub transportation is expected to unfold sequentially. Initially, it is likely to be implemented through a decentralized network, gradually transitioning to a centralized network model. Nonetheless, exceptions may arise, especially in rural areas, where highly vertically integrated hubs might develop due to unique circumstances that justify their establishment in these locations. To elaborate, the decentralized network scenario consists of several smaller and decentralized networks, where each ATO manages its hub-to-hub infrastructure internally. Presumably, the ATO functions as an owner-operator of the hub, though alternative arrangements may exist — such as those involving a real estate company owning the premises while the ATO oversees operations. While certain in-hub operations could be outsourced to partnering subcontractors, the ATO retains control of the local network and its stakeholders, thus assuming the network operator role for that specific area. This arrangement simplifies the operational complexity, as the hub operator is not required to integrate transport activities from multiple operators, Moreover, it enables ATOs to leverage their established relationships to enhance the network reliability.

In the decentralized scenario, the ecosystem comprises six primary stakeholders: the ATO, the AD technology provider, logistics software provider(s), customers, LEA, and third-party intermediaries. In this arrangement, the ATO not only operates the hub but also forms strategic partnerships with key actors such as the AD technology providers, who may perform specific tasks within the hub on behalf of the ATO. Furthermore, the ATO assumes responsibility for autonomous transport operations and overall ecosystem integration, coordinating traffic and customer interactions. Logistics software essential for the hub's operation will be outsourced to established market players or possibly new entrants. These logistics software providers will collaborate with the ATOs to tailor logistics systems suited to each hub network. Notably, each ATO's network might be configured differently depending on the logistics systems integrated, which favors integration with existing partners already accustomed to the systems. The roles of law enforcement and third-party intermediaries remain consistent across different scenarios. They are responsible for providing necessary legal frameworks and conducting audits and inspections to ensure compliance with standards.

In contrast, the centralized network scenario constitutes one or a few centralized networks dominated by a few key players. In this model, hub facilities are collectively utilized by various ATOs, who either own or rent slot capacity from the central hub operator analogous to how airlines operate at airports. Ownership and operation of these hubs will reside with major players that possess the necessary financial resources to establish such an expansive system. Although this scenario introduces greater complexity, similar arrangements in adjacent industries, as previously mentioned, demonstrate significant advantages. These benefits include more seamless integration among stakeholders in the logistics value chain and access to a broader transportation network.

In the centralized network scenario, the ecosystem comprises seven key stakeholders: major logistics providers (or other significant players), multiple ATOs, a potential new network operator, logistics software providers, customers, LEAs, and third-party intermediaries. Supposedly, the hubs will be owned by major logistics providers or other players equipped with the necessary infrastructure and capital to pioneer this field. Hub operations may be managed directly by the owners or subcontracted to other actors specializing in such operations, including large shippers or newly emerging specialists. The role of the network operator could be assumed by the hub owner or a completely new platform provider, resembling asset-light companies like Uber or Convoy. Multiple ATOs will manage transportation and coordinate with their customers within this shared network, necessitating coexistence and cooperation, particularly at the hubs. As in the decentralized scenario, logistics software providers play a critical role, albeit with increased demands for integration among various stakeholders. Moreover, the AD technology provider will assume a more technology-centered role and be less involved in the hub operations than in the decentralized scenario.

5.3 Digital interfaces and key elements in future operational hubs for autonomous trucks

This study identifies several digital interfaces that are deemed crucial for effectively managing hub operations, including the key elements associated with each. The following section will delve into the necessity of standardized digital interfaces in three identified high-value use cases and subsequently, outline the prospective stakeholder and information entities involved within these interfaces.

5.3.1 Necessity of standardized digital interfaces in identified high-value use cases

During the process of identifying high-value use cases, interviewees pinpointed three pivotal hub activities directly contributing to enhancing overall productivity. These include *enhanced pre-trip inspection*, *slot reservation*, and *gate management*. Interviewees emphasized that enabling data exchange in these respective activities would significantly contribute to achieving their respective objectives. This perspective is reinforced by Gadde et al. (2003), underscoring the significance of facilitating interfaces to streamline operations that transcend ownership boundaries among the involved parties.

In all three scenarios, the absence of industry-wide standards has emerged as a pivotal barrier to enhancing productivity within each specific use case. This deficiency in standardization can be traced back to the industry's immaturity and the absence of a dominant technology design, resulting in interoperability challenges across operations. Jacobsson et al. (2020) emphasize the critical role of interoperable information systems in freight transportation, stressing the importance of seamlessly integrating both intra- and inter-organizational business processes. Given that these scenarios involve both intra- and inter-organizational processes, establishing industry-wide standards becomes imperative for optimizing productivity within each context. Jacobsson et al. (2017) further illuminate deficiencies in information exchange among stakeholders during their examination of intermodal freight transportation, which involves similar actors as the autonomous trucking industry. This further underscores the overarching challenge of the lack of standards and subsequent deficiency in interoperability among stakeholders across the freight transportation industry. Although interviewees acknowledge the current absence of standards within each use case, emerging standards such as the CVSA and the SSC have been highlighted; however, implementing these may necessitate updated operating systems among stakeholders.

The US trucking industry's reliance on outdated systems rooted in EDI integration, rather than modern APIs, as noted by interviewees, contributes to the lack of interoperability. Consequently, achieving compatibility of integration becomes a challenge not only with contemporary systems but also with decades-old operating systems existing within the same digital infrastructure. This not only poses obstacles in obtaining standardized digital interfaces but also impedes the challenge of receiving appropriate and high-quality data. Munch and Munch (2020) underscore the ability of APIs to enhance interoperability by facilitating seamless sharing and automatic exchange of real-time data and information. In all three high-value use cases, the necessity of exchanging real-time data in both intra- and inter-organizational processes was emphasized to ensure timely communication amongst the involved stakeholders. Thus, highlighting the difficulty in efficiently exchanging data due to divergent operating systems among stakeholders and, consequently, accentuating the challenge of enhancing productivity and establishing industry-wide standards for these high-value use cases.

The importance of enhanced pre-trip inspection is underscored by the interviewees, identifying it as a pivotal high-value use case. This process primarily aims at ensuring safety, traceability, and reliability. Although still in development, it is and will remain a legal requirement enforced by law enforcement agencies for automated truck operations. Consequently, as the number of inspections conducted at hubs is scaled up, standardizing digital interfaces among stakeholders becomes imperative. Such standardization is crucial for maintaining road safety, ensuring full compliance with regulatory mandates, and facilitating the continuous operation of automated trucks. Moreover, the current duration of 60-90 minutes for conducting an enhanced pre-trip inspection on an automated truck, compared to 15 minutes for a conventional truck, poses a bottleneck in hub operations. This prolonged duration also imposes a physical constraint on the number of trucks that can be accommodated at the hub. Moreover, if the inspection is mandated every 24 hours by the CVSA, it will further challenge the overall productivity of the hub operations. Therefore, standardizing digital interfaces becomes crucial to reduce the inspection process cycle time and consequently improve the flow of vehicles and overall hub throughput.

Interviewees emphasized the need to standardize digital interfaces within the slot reservation system, with the overarching aim of streamlining operations, boosting efficiency, and fostering improved market dynamics. Additionally, gate management has emerged as a pivotal process requiring standardization through digital interfaces. Interviewees identified it as a high-value use case, essential for optimizing efficiency, traceability, and security in managing the flow of autonomous trucks accessing the hub's facilities. Recognizing the crucial role of gate management in validating bookings and cargo details, interviewees emphasized the profound connection to the slot reservation and the imperative for seamless data transfer between them. To ensure this connection, an IoT platform within the gate management system that integrates technologies such as RFID, cameras, and scanners is necessary. Additionally, to support the operation of IoT devices and cloud operating systems, Meng et al. (2017) underscored API interfaces as fundamental, serving as the backbone of communication between systems. Therefore, it is imperative to implement and standardize APIs to facilitate the flow of data among these processes. This ensures an efficient slot reservation and gate management system to mitigate hub queues, thereby maximizing vehicle uptime – an aspect of paramount importance for ATOs.

The criticality of accessing real-time data to efficiently manage and regulate vehicle speed, thus preventing disruptions that could impact system operations, was emphasized in both scenarios. Arena & Pau (2019) further reinforced this notion by highlighting how data exchange between vehicles and infrastructure empowers the adjustment of speed limits. When coupled with real-time communication, this functionality optimizes traffic flow by dynamically adjusting speeds to ensure precise arrival time estimates. Standardizing these processes is instrumental in mitigating hub queues. However, to ensure that digital interfaces and APIs effectively influence decision-making accuracy and efficacy, it is imperative that data be of high quality and timely (Stefansson & Russel, 2008; Meng et al., 2017). The deficiencies in data quality were evident in both cases, thereby complicating the implementation of efficient slot reservation and gate management systems, underscoring the need to enhance quality standards.

As these two processes involve numerous stakeholders, it is evident that robust digital capabilities are indispensable. Within the slot reservation system interviewees stressed the importance of synchronizing efforts with all stakeholders engaged in the process to enhance customer satisfaction. This viewpoint is reinforced in the findings of Stefansson and Russell (2008), who emphasized the significance of interfaces in the transportation industry to ensure optimal service levels and satisfactory performance to customers. Similarly, the current reliance on physical document presentation by drivers within the gate management system highlights the necessity for digitalization, especially considering that drivers will not be physically present during this process. Moreover, interviewees stressed the importance of standardizing digital interfaces across interconnected hubs managed by different actors. This necessitates the adoption of standardized communication protocols and data exchange mechanisms to ensure seamless interoperability among diverse systems. Further underscoring the importance of seamless data exchange among stakeholders to ensure customer satisfaction, verify bookings and cargo details, and interconnect hubs managed by different entities. As highlighted by Penubarthi (2018), APIs play a crucial role in facilitating the exchange of transactional data, thereby enhancing B2B integration. This emphasizes the need for seamless APIs to streamline information flow and enable the integration of various players, particularly in a centralized scenario.

5.3.2 Prospective stakeholders and information entities for future digital interfaces

This section outlines the prospective key stakeholders and information entities that must be involved in digital interfaces for each high-value use case, aiming to shed new light on this subject. To support this discussion, two diagrams have been developed for each anticipated scenario, drawing inspiration from the CLM model (Stefansson, 2006; Stefansson & Russel, 2008). These are shown in Figures 5.1 and 5.2. The diagrams serve as visual aids to illustrate the key stakeholders likely to be involved in hub-to-hub transportation, along with the critical digital interfaces necessary for effective integration among them. The digital interfaces are numerically labeled from 1 to 10 in each scenario, highlighting the points where information is exchanged externally between two distinct stakeholders. While internal information flows within a single integration stakeholder are crucial, these are not depicted in the diagrams but will rather be detailed in the text to maintain clarity and focus on external exchanges.

In the diagrams, stakeholders are represented as circles when referring to individual actors and ovals when indicating multiple roles encompassed within a single stakeholder. The system components essential for the operability of hubs are illustrated using dark rounded squares to signify a high-level breakdown of the necessary logistics software system. Connections between stakeholders in the diagrams are depicted with either solid or dashed lines. Solid lines denote frequent data exchanges, highlighting routine communication paths, while dashed lines suggest intermittent data exchanges that occur less regularly. Red Xs mark the external digital interfaces, pinpointing where data exchange occurs between different stakeholders and identifying active interactions and those that are not yet in place. Regarding potential internal interfaces, these are mentioned only briefly in the text, as their location is considered less significant to illustrate. Abbreviations have been used to denote some stakeholders; AD technology provider is referred to as "AD tech", subcontractors as "subcont.", customers as "Cust.", third-party intermediaries as "3rd party", and law enforcement authorities as "LEA".

5.3.2.1 Decentralized network scenario

Figure 5.1 illustrates a network diagram for a decentralized network scenario in autonomous trucking. In this scenario, six key stakeholders play integral roles: the local network operator, the AD technology provider, the customer, logistics software provider(s), third-party intermediaries, and LEA. This structure provides a visual representation of the connectivity and data sharing within the decentralized network, highlighting the central role of the local network operator in the exchange and coordination among stakeholders. The high-value use cases within this network involve various configurations of these stakeholders, with some interfaces being more coupled than others. The digital interfaces pertinent to each high-value use case, along with the specific stakeholders involved, are detailed in Table 5.1. This summary provides a clear overview of the interactions and data flows essential to the operation of the decentralized network.

When investigating the digital interfaces for the enhanced pre-trip inspection, results indicate that five key stakeholders will likely be involved in this future process, as summarized in Table 5.1. Additionally, six digital interfaces have been identified, among which five are external interfaces involving different stakeholders (1, 2, 4, 5, & 6). The sixth interface, as previously detailed, is an internal interface within the role of the local network operator. This operator coordinates activities typically associated with the ATO and hub operator in an integrated manner. Although this internal interface focuses solely on the transmission of information within the local network operator and is not shown in Figure 5.1, its significance lies in its function in minimizing oversight risks and enhancing the efficiency of tasks related to the enhanced pre-trip inspection, particularly those preceding the truck's arrival at the inspection site. While not explicitly mentioned in the interviews, the data exchanged via the internal interface likely includes information on hub conditions and equipment utilization. This assumption stems from the nature of the data, which is relevant for managing in-hub operations effectively.

Furthermore, the digital interface connecting the local network operator with the

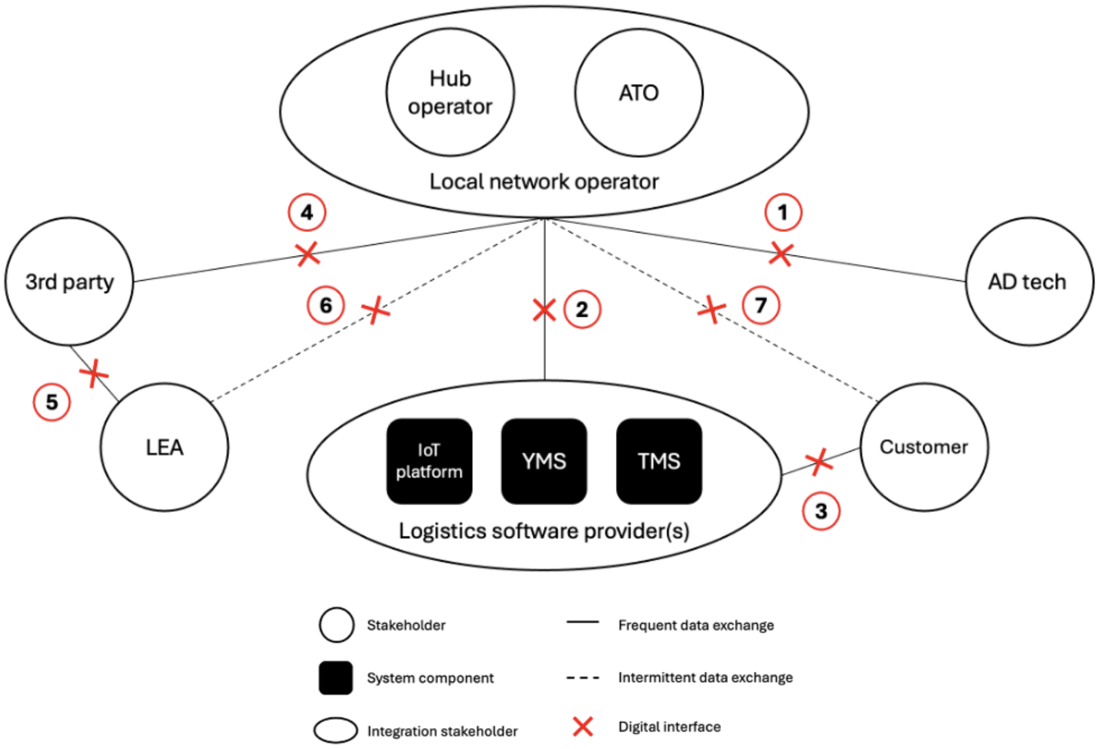

Figure 5.1: Decentralized network diagram.

logistics software provider (2) is critical because the logistics system is outsourced within the decentralized scenario, requiring relevant information for the enhanced pre-trip inspection to be retrieved through this system. Through this interface, data such as the arrival and departure times of trucks, slot information, and truck and trailer information are exchanged between the logistics system and the local network operator. Notably, this information is then cascaded in the internal interface by the local network operator to ensure timely and accurate truck inspections at the designated locations.

The digital interfaces that received particular emphasis during the interviews involve the local network operator, the third-party intermediary, and LEA (4, 5, & 6). Information will primarily be exchanged through the pathways involving the third-party intermediary (4 & 5) and less frequently involve LEAs(6) as they perform audits on a more ad-hoc basis. These interfaces facilitate the communication of inspection status (pass or fail) and detailed failure information among these stakeholders, which is crucial for confirming the vehicles' safety and operability. Such exchanges help identify issues that require corrective actions and confirm compliance when no errors are found. Concerning the interface between the local network operator and the AD technology provider (1), the specific information exchanged remains somewhat ambiguous. However, it is clear that this data, likely pertaining to self-driving technologies and potentially detailed failure diagnostics, is conveyed through the transport operator. This interface likely focuses on inspection areas requiring specialized technological expertise by the AD technology providers.

Table 5.1: Digital interfaces for high-value use cases within the decentralized network scenario.

Decentralized scenario summary			
Use case	Digital interfaces	Stakeholders involved	Information entities
Enhanced pre-trip inspection	1, 2, 4, 5 & 6	Local network operator AD technology provider Logistics software provider(s) Third-party intermediaries Law enforcement authorities	Arrival time Departure time Slot information Truck & trailer information Inspection status Failure information Hub conditions Equipment utilization
Slot reservation	1, 2, 3 & 7	Local network operator AD technology provider Logistics software provider(s) Customers	Truck & trailer ID Cargo details Gate number Slot information ETA Transport updates ODD information
Gate management	1, 2, 3 & 7	Local network operator AD technology provider Logistics software provider(s) Customers	Truck & trailer ID Vehicle plate number DOT number BoL Booking number Gate arrival time Slot information Seal of integrity

During the investigation of digital interfaces for the slot reservation system, findings revealed the probable involvement of four distinct stakeholders in this upcoming process, as outlined in Table 5.1. Furthermore, five digital interfaces have been identified, with four being external and involving various stakeholders (1, 2, 3, & 7). The fifth interface constitutes an internal connection within the logistics software provider, facilitating communication between the TMS and YMS. This internal link streamlines the exchange of information between slot reservation and gate management processes, ensuring smooth coordination between transportation scheduling and yard resource availability. Key information entities exchanged through this interface encompass truck and trailer IDs, cargo details, gate assignments, and slot information.

The first external interface pinpointed connects the local network operator and the AD technology provider (1). The identified information entities within this interface include transportation updates, ETAs, and ODDs. The second digital interface facilitates communication between the local network operator and the logistics software provider (2). In this interface, the information entities include ETAs and transportation updates, enabling the alignment of available slots with incoming trucks. Moreover, the combination of these interfaces (1 & 2) serves as synchronization points for adjustments in truck speed and arrival time, ensuring coherence with the slot availability planning system.

The third digital interface establishes the connection between the customer and the logistics software provider (3). This interface retains its significance regardless of whether a dynamic or static slot system is in place, though the communication standards will adapt according to the selected booking system. Within this interface, slot information stands out as the primary information entity. Additionally, it is worth noting that regular transportation updates are likely to flow through this interface to uphold customer satisfaction. As for the fourth external digital interface, it links the customer directly with the local network operator (7). While it may not see frequent utilization, its presence remains vital for operational completeness, especially for communicating outlier situations.

In the exploration of digital interfaces for the gate management system, the investigation uncovered the likely participation of four distinct stakeholders in the forthcoming process, as detailed in 5.1. Moreover, six digital interfaces have been identified, with four being external (1, 2, 3, & 7). The remaining two internal interfaces facilitate communication between the logistic software provider's system components. The internal interface linking the IoT platform and YMS ensures precise synchronization between truck arrivals at the gate and scheduled arrangements within the YMS system. Critical information entities exchanged through this interface include truck and trailer IDs, vehicle plate numbers, DOT numbers, BoL details, booking numbers, slot information, gate arrival times, truck and trailer conditions, and seal of integrity. This data is then seamlessly transmitted to the internal interface connecting the YMS and TMS, further ensuring the exchange of these information entities between slot reservation and gate management processes.

The initial external interface links the local network operator and the AD technology provider (1). This interface, in conjunction with the digital interface between the AD technology provider and the local network operator (2), establishes the connection between the truck and the logistics software provider. Although it remains unclear whether the AD technology provider facilitates communication with the gate through V2I, the integration of these interfaces is crucial for ensuring the truck's timely delivery of real-time information. The specific information entities exchanged in this process have not yet been clarified. The third digital interface links the customer with the logistics software provider (3), serving as the booking platform. This connection plays a pivotal role in synchronizing truck arrivals at the gates with slot reservations, highlighting the interconnected relationship between these processes. As a result, the primary information exchanged within this interface revolves around slot information. Lastly, the fourth digital interface directly connects the customer with the local network operator (7). Similar to the slot reservation system, this interface serves to communicate outlier situations and remains essential for ensuring operational integrity.

5.3.2.2 Centralized network scenario

When analyzing the centralized network scenario, there are some noticeable differences from the decentralized scenario. In Figure 5.2, the centralized network scenario is depicted through a network diagram involving nine key stakeholders: the network operator, the central hub operator, subcontractors, autonomous transport operators (ATOs), AD technology providers, logistics software providers, customers, third-party intermediaries, and LEA. This diagram underscores two potential configurations within the centralized network scenario. These configurations arise from discussions about the possible emergence of a new platform provider, similar to Uber for robotaxis, which could assume the role of the network operator, distinct from the central hub operator.

This delineation increases complexity by proposing two distinct configurations: one in which the central hub operator also functions as the network operator and another where these roles are separated. The choice of configuration influences the structure and flow of information exchange within the network. In Figure 5.2, this variability is illustrated by depicting the potential new network operator in a dashed outline, along with its associated digital interfaces. Depending on the adopted model, the pathways through which information entities are exchanged will differ, reflecting the dynamic and adaptable nature of the centralized network scenario.

Focusing on the information exchange, digital interfaces are numbered in a manner similar to those in the decentralized network scenario. A notable distinction, indicated by "1,...,n" in Figure 5.2, is the necessity for multiple transport operators to perform inspections at the same hub facility. As depicted, each ATO will collaborate internally with an AD technology provider and a logistic software provider supplying the TMS system, which may be identical to or distinct from the central hub's logistics software provider(s). However, the communication interfaces with other ecosystem players are directly managed by the ATOs and therefore, these interfaces are not accounted for in the subsequent analysis. Table 5.2 presents a breakdown of the digital interfaces associated with the high-value use cases, accompanied by the specific stakeholders involved. This overview aids in understanding the interactions and dependencies within the centralized network scenario.

In the analysis of the enhanced pre-trip inspection within the centralized network scenario, findings indicate the involvement of seven distinct stakeholders, as detailed in Table 5.2. Among these stakeholders, seven digital interfaces have been recognized, six of which are external interfaces involving various stakeholder interactions (1, 2, 3, 5, 6, & 7). Notably, the interface (2) between the logistics software provider(s) and the central hub operator mirrors that of the decentralized network scenario. This interface facilitates the exchange of information such as truck arrival and departure times, slot information, as well as truck and trailer information. A significant difference in the centralized network scenario is the presence of multiple

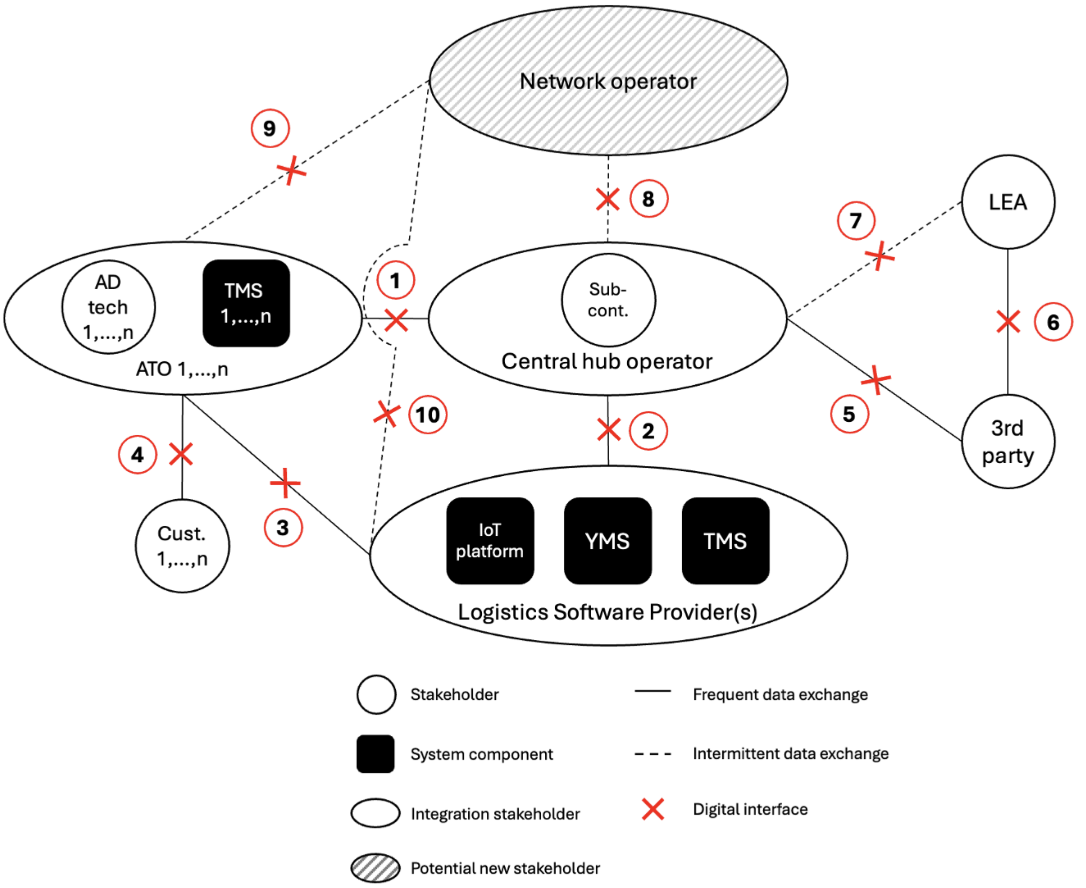

Figure 5.2: Centralized network diagram.

transport operators conducting inspections at the same hub facility, necessitating effective management of communications with other stakeholders. Additionally, this scenario introduces external interfaces (1 & 3) that connect the ATOs both with the central hub operator and the logistics software provider(s). While these interfaces were not explicitly discussed in the interviews, the information entities exchanged are anticipated to be similar to those of interface number 2.

Similar to the decentralized scenario, interfaces between the central hub operator, third-party intermediaries, and LEA were given particular consideration during the interviews. However, in the centralized scenario, a notable shift occurs. While information predominantly flows through pathways involving third-party intermediaries (5 & 6), the interface between LEA and the central hub operator (7) gains heightened significance, primarily due to the anticipated continuous transmission of audit information. Within the centralized scenario, a unique opportunity arises for the central hub operator to centralize enhanced pre-trip inspections required for all ATOs operating at the hub. This centralization can be achieved either independently or through collaboration with specialized subcontractors. Such centralization necessitates the establishment of an internal interface between the central hub operator and the subcontractor(s), ensuring the exchange of all information entities previously shared with the hub operator. Regardless of whether a subcontractor

Table 5.2: Digital interfaces for high-value use cases within the centralized network scenario.

Centralized network scenario summary			
Use case	Digital interfaces	Stakeholders involved	Information entities
Enhanced pre-trip inspection	1, 2, 5, 6, & 7	AD technology providers Autonomous transport operators Logistics software provider(s) Central hub operator Subcontractor(s) Third-party intermediaries Law enforcement authorities	Arrival time Departure time Slot information Truck & trailer information Inspection status Failure information Hub conditions Equipment utilization Audit information
Slot reservation	1, 2, 3, 4, 8, 9 & 10	Network operator AD technology providers Autonomous transport operators Logistics software provider(s) Central hub operator Customers	Truck & trailer ID Cargo details Gate number Slot information ETA Transport updates ODD information
Gate management	1, 2, 3, 4, 8, 9 & 10	Network operator AD technology providers Autonomous transport operators Logistics software provider(s) Central hub operator Subcontractor(s) Customers	Truck & trailer ID Vehicle plate number DOT number BoL Booking number Gate arrival time Slot information Seal of integrity Transport operator ID & authentication

undertakes this responsibility, it is expected that the central hub operator will provide this service, offering various premium models such as pay-per-use or monthly subscriptions.

When examining the digital interfaces for the slot reservation system in a centralized network scenario, findings revealed the probable involvement of six stakeholders, as outlined in 5.2. With two distinct configurations—one where the hub operator assumes the network operator role and another where these roles are held by separate stakeholders—the interface configurations will differ. The investigation identified a total of nine potential digital interfaces across these two setups (1, 2, 3, 4, 8, 9 & 10), with seven being external and two internal. In a similar manner to the decentralized scenario, an internal interface is required for the logistics software provider(s) connecting the YMS and TMS. Key information entities exchanged through this interface encompass truck and trailer IDs, cargo details, gate assignments, and slot information.

When the network operator role is taken on by the central hub operator, four external interfaces have been identified (1, 2, 3 & 4). The first interface connects each respective ATO with the central hub operator (1). The second interface links the central hub operator with the logistics software provider(s) (2), while the third interface connects the ATOs' TMS systems with the logistics software provider(s) (3). The specific configuration among these interfaces remains undetermined; the ATO might communicate directly with the logistics software provider through interface 3, or a combination of 1 and 2. Through these interfaces, the following information entities will be exchanged among the ATO, central hub operator, and logistics software provider: truck and trailer ID, cargo details, gate number, slot information, transportation details, ETAs, ODD notifications, and potential lane reservations. In cases involving a subcontractor, an internal digital interface is crucial to link this stakeholder with the central hub operator. In such instances, all the mentioned information entities must be communicated further to the subcontractor through this internal digital interface. Lastly, a digital interface (4) connecting the customer and the ATO is essential. The specific configuration of this interface may vary depending on the slot booking system in use. Nonetheless, the primary information entity to be exchanged within this interface is slot information, ensuring that the customer can book freight accordingly.

In the configuration when the central hub operator and the network operator are two separate stakeholders, three additional digital interfaces (8, 9 & 10) have been identified. In such cases, some coordination tasks related to slot reservation will be assumed by the network operator, reducing the reliance on interfaces (1) and (3). Communication between the ATO, central hub operator, and logistics software provider will primarily occur through interfaces 8, 9, and 10. Since this is a potential emerging new actor not yet present in the market, detailed information about the exchanged information entities cannot be specified at this stage.

When investigating digital interfaces for the gate management system, the analysis revealed the anticipated involvement of seven distinct stakeholders in the upcoming process, as outlined in Table 5.2. As with the slot reservation system, the two configurations regarding the role of the network operator will cause slight variations in their interface setups. A total of seven potential external digital interfaces were identified across the two configurations (1, 2, 3, 4, 8, 9 & 10), accompanied by three internal interfaces. Similar to the decentralized scenario, the logistics software provider(s) necessitates internal digital interfaces to link the IoT platform with the YMS, and subsequently, the YMS with the TMS. The key information entities to be communicated across these interfaces encompass truck and trailer ID, vehicle plate number, DOT number, booking number, slot information, gate arrival time, truck and trailer conditions, seal of integrity, and transport operator ID and authentication.

If the central hub operator assumes the network operator role, four external interfaces (1, 2, 3 & 4) were pinpointed. The first interface establishes a connection between the respective ATO and the central hub operator (1). The second interface links the central hub operator with the logistics software provider(s) (2), while the third interface facilitates communication between the ATOs' TMS and the logistics software provider(s) (3). Like the slot reservation system, the specific configuration among these interfaces remains unknown, and the three stakeholders are likely to interact through a combination of these interfaces. Interface 1, 2, and 3 are anticipated to enable V2I communication with the gate, however, the exact pathway remains unclear. Crucial information entities to be exchanged among interfaces 1, 2, and 3 encompass truck and trailer IDs, vehicle plate numbers, DOT numbers, BoL, booking numbers, gate arrival times, slot information, and transportation operator IDs and authentication. In the case of a subcontractor, an internal digital interface will be established between the central hub operator and the subcontractor, through which the aforementioned information entities will be transmitted further. Due to the close connection between the slot reservation and gate management system digital interface (4) serves as a booking platform between the customer and ATO. The key information entity exchanged in this interface is the slot information, which is subsequently synchronized upon the truck's arrival at the gate.

In the setup where the central hub operator and the network operator are independent stakeholders, three additional digital interfaces (8, 9 & 10) have been identified. However, it is anticipated that the network operator's involvement in the gate management system will be limited, primarily focusing on linking the previously discussed slot reservation system. Consequently, the information entities and digital interfaces are expected to be largely similar in both configurations for gate management.

6

Conclusion

The primary goal of this study is to identify critical digital interfaces essential for hub operations within the hub-to-hub model, while also outlining the key stakeholders expected to engage in the evolving transportation ecosystem enabling autonomous trucking. The identified stakeholders were analyzed to envision the evolution of future scenarios of hub-to-hub transportation. These scenarios subsequently enabled the development of three high-value use cases pinpointing necessary digital interfaces enhancing overall operational performance, productivity, or success.

The literature review constituted four parts: Autonomous road freight transportation, Business network perspective, Supply chain interfaces, and Use cases from adjacent industries. In the first section key concepts crucial for grasping autonomous road freight transportation, including various levels of driving automation and the subsystem components integral to this technology, are described to equip the reader with an overview of the topic. Consecutively, business network perspectives and supply chain interfaces provide valuable insight into recent literature on the investigated areas, such as anticipated stakeholder configurations and digital interfaces, which were later contrasted with the results. Lastly, use cases from adjacent industries emphasized various ecosystem layouts, to which parallels were drawn to portray future scenarios in autonomous road transportation.

Subsequently, the results were presented, detailing the key stakeholders and roles associated with the hubs, followed by the anticipated future scenarios for autonomous trucking. Distinguishments were made between the current and future industry landscapes, where the results indicated the emergence of new roles previously nonexistent in conventional trucking. Furthermore, the most prominent high-value use cases were outlined, complete with their respective digital interfaces and defining characteristics.

Findings from the results were incorporated with the literature review and further elaborated upon in the discussion section. Based on the discussion, certain stakeholders emerged as particularly relevant for key roles. Specifically for the autonomous transport operator role, AT providers were identified as particularly well-suited due to their robust capabilities and technology proximity. This alignment is expected to be strengthened by increasing collaborations with AD technology providers, who are likely to become more integrated with AT providers in their function as ATOs. Regarding the roles of hub owner and hub operator, the analysis revealed various configurations, including both integrated owner-operator roles and distinct, separate roles. While there was no consensus on the ideal stakeholder to assume these roles, candidates with existing infrastructure and a thorough understanding of autonomous trucking technologies will experience advantages.

Moreover, the discussion thoroughly analyzed the emerging network operator role, anticipated to significantly impact the autonomous trucking industry. This role could be filled by current players or new entrants not yet present in the market. Initially, the network operator role might be adopted by AT providers, but it is expected to transition to stakeholders with advanced IT capabilities over time. New entrants employing business models similar to asset-light companies like Uber or Airbnb could dramatically reshape the industry, potentially without owning any physical assets themselves. Following this, the role of logistics software providers is examined. As the significance of IT capabilities is expected to increase as the industry transitions toward a smart network, logistics software providers are essential not just for facilitating logistics flows but for integrating key stakeholders and managing digital interfaces.

Drawing from the stakeholder and role allocation discussion, two future scenarios were predicted: the decentralized and centralized networks. In the decentralized network, the industry is decentralized with vertically integrated companies managing their systems end-to-end. Conversely, the centralized network is centralized and distributes responsibilities among stakeholders, fostering greater cooperation. It is anticipated that these scenarios will unfold sequentially, with a decentralized network gradually transitioning to a centralized model. However, exceptions may arise, with decentralized hubs emerging in rural locales, while urban areas typically exhibit a prevalence of centralized networks. Based on these forecasted future scenarios, three high-value use cases were identified: enhanced pre-trip inspection, slot reservation, and gate management. All three entail multiple stakeholders requiring high-quality, real-time data exchange – a challenge due to outdated logistics systems and the absence of industry-wide standards. These bottlenecks underscore the imperative to standardize digital interfaces to enhance operational productivity.

Regarding the enhanced pre-trip inspection, the AD technology provider, logistics software provider(s), third-party intermediaries, and law enforcement authorities are present in both scenarios. In the decentralized network, the local network operator is a key additional stakeholder, whereas the centralized network scenario includes the central hub operator, multiple autonomous transport providers, and subcontractors. The information entities shared in both scenarios are largely similar, encompassing arrival and departure times, slot information, truck and trailer information, inspection status, failure data, hub conditions, and equipment utilization. The primary distinction in the centralized network scenario is the inclusion of audit information.

In the slot reservation system, the AD technology provider, logistics software provider(s), and customer were consistent stakeholders across both scenarios. In the decentralized network, the local network operator was recognized as a supplementary stakeholder, while in the centralized network, the network operator, central hub operator, and autonomous transport provider emerged instead. Across both scenarios, the information entities exchanged remained the same, encompassing truck and trailer

IDs, cargo details, gate numbers, slot information, ETAs, transport updates, and ODD information.

Across scenarios in the gate management system, the AD technology provider, logistics software provider(s), and customer remained consistent stakeholders. In the decentralized network, the local network operator was identified as an additional stakeholder, whereas in the centralized network, roles expanded to include the network operator, central hub operator, autonomous transport provider, and subcontractor. Common information entities across scenarios included truck and trailer IDs, slot information, vehicle plate numbers, DOT numbers, BoLs, booking numbers, gate arrival times, truck and trailer conditions, and seal integrity. Notably, the centralized network scenario introduced transport operator ID and authentication as additional information entities.

By mapping out potential future scenarios and identifying high-value use cases, this thesis lays the groundwork for strategic advancements in the transportation industry, ensuring readiness for technological integration and enhanced operational synergy. As stated by Fritschy and Spinler (2019), "*autonomous technologies will gradually change the rules of the game in the industry [...] by creating new and potentially disruptive ways of doing business in the future. Thus, autonomous trucks will enable new business models which require building new capabilities and understand the opportunities to survive in the era of autonomous trucks*". In essence, this indicates that digital interfaces hold the potential to bring together stakeholders and drive the advancement of the hub-to-hub model and autonomous trucking industry as a whole.

6.1 Future research

This thesis has contributed to the literature by detailing which digital interfaces are critical for streamlining hub operations within the hub-to-hub model, outlining the anticipated ecosystem of stakeholders, information entities, and challenges associated with three prominent high-value use cases. Future research could extend these insights by adopting a Supply Chain Management (SCM) perspective that concentrates on the goods dimension of autonomous road freight. Given that customers, as owners of the goods and trailers, significantly influence the industry's trajectory, their impact on the pace of development is substantial. To enhance the generalizability of these findings, future studies should explore a broader array of case companies and incorporate the perspectives of stakeholders deemed critical for establishing operational hubs in autonomous trucking.

Furthermore, addressing the challenges tied to these high-value use cases could benefit from further investigation such as deep-diving into similar scenarios in other adjacent industries. Additionally, the technology underpinning autonomous driving, not extensively covered in this thesis, presents an interesting area for further exploration. A deeper examination of this technology could yield valuable insights into the practicality and efficiency of the hub-to-hub model, offering a clearer understanding of its feasibility.

Finally, this study has excluded the financial considerations of hub-to-hub transportation, while in reality, these factors are deemed crucial for its implementation. Financial barriers, including the business models' profitability and competition from conventional trucking companies, could impede the widespread adoption of autonomous trucking. In light of the conclusions of this thesis, exploring the financial implications associated with the hub-to-hub model represents another interesting field for future research.

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A

Appendix 1

The Appendix of this document serves as a repository for supplementary materials that support and enrich the main text. Included within are the interview guides used during the two rounds of interviews conducted with the case company. These documents provide transparency into the methodology employed and offer valuable insights into the structured approach taken during the data collection phase. Readers are encouraged to refer to these guides to better understand the depth and context of the interactions that have shaped the conclusions of this study.

A.1 First round interview guide

Please provide a brief background about yourself and your role at the company.

1. In a future scenario, where there are multiple autonomous freight truck operators within the hub-to-hub model, which stakeholders would you consider necessary to involve in such a network operating the hubs?
2. What different roles do you see these stakeholders taking on in the hubs?
3. Which stakeholder(s) do you believe will be operating the autonomous truck hubs?
4. Which stakeholder(s) will have ownership of the hubs?
5. Which stakeholder(s) will have ownership of physical assets such as real-estate facilities or truck fleets?
6. What do you think will be the role of the transport operator?
7. Do you see the emergence of a network operator?
8. Who will take on the role of the network operator?
9. What will be the role of the IT provider or logistic software provider in the future hubs?
10. Do you see any new emerging or major players on the market that we have not yet seen?
11. According to you, what are the high-value use cases for effective hub operations?

12. What is the main goal of each use case?
13. Which stakeholders should be involved in each use case?
14. What major challenges for each use case do you envision? What potential solutions do you suggest dealing with them?

A.2 Second round interview guide

Decentralized network scenario:

1. In the decentralized network scenario, what key stakeholders are involved in the enhanced pre-trip inspection?
2. What are the information entities exchanged in the enhanced pre-trip inspection?
3. What are the existing and emerging standards in the enhanced pre-trip inspection?
4. What are the challenges and potential solutions in the enhanced pre-trip inspection?
5. What key stakeholders are involved in the slot reservation?
6. What are the information entities exchanged in the enhanced slot reservation?
7. What are the existing and emerging standards in the slot reservation?
8. What are the challenges and potential solutions in the slot reservation?
9. What key stakeholders are involved in the gate management?
10. What are the information entities exchanged in the gate management?
11. What are the existing and emerging standards in gate management?
12. What are the challenges and potential solutions in gate management?

Centralized network scenario:

1. In the centralized network scenario, what key stakeholders are involved in the enhanced pre-trip inspection?
2. What are the information entities exchanged in the enhanced pre-trip inspection?
3. What are the existing and emerging standards in the enhanced pre-trip inspection?
4. What are the challenges and potential solutions in the enhanced pre-trip inspection?
5. What key stakeholders are involved in the slot reservation?
6. What are the information entities exchanged in the enhanced slot reservation?

7. What are the existing and emerging standards in the slot reservation?
8. What are the challenges and potential solutions in the slot reservation?
9. What key stakeholders are involved in the gate management?
10. What are the information entities exchanged in the gate management?
11. What are the existing and emerging standards in gate management?
12. What are the challenges and potential solutions in the gate management?

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