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Analysis of Technical and Operational Requirements of Alternative Drive Systems by Transport Companies: The Case of the Overhead Contact Line Truck

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Abstract: A change to zero-emission drive systems in road freight transport is required to achieve climate protection targets. Therefore, alternative drive systems for road freight transport are being tested in field trials in Germany. One such technology is the eHighway system. The eHighway system combines an overhead contact line hybrid truck (OH truck) and an overhead contact line infrastructure. The objective of this study was to evaluate technical and operational success factors and barriers influencing the adoption of the eHighway system by freight transport companies. We evaluated expert interviews, written surveys, and vehicle data. We found that transport companies had no major restrictions concerning the technical equipment of the OH trucks. Furthermore, we found no operational restrictions in the use of OH trucks while the OH trucks can be integrated into different transport operations.

Keywords: electric road systems; alternative drive system; freight transport; sustainability; overhead contact line truck

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1. Introduction

Greenhouse gas (GHG) emissions from transportation have stagnated at a high level in Germany over the past 30 years. This corresponds to a share of around 20% of the total GHG emissions. So far, efficiency gains in climate-friendly alternatives have been offset by steady growth in freight transport due to increasing demand for transport and logistics services [1]. To achieve climate neutrality in the transport sector by 2045 [2], various measures must be implemented. In road freight transport, measures are especially needed, as this sector is not climate-friendly because of its high share of conventional trucks, and it has the largest share of total transport volume [1]. Regarding heavy-duty commercial vehicles, the Climate Action Program 2030 states the following: Heavy-duty trucks with alternative drive systems must be attractive via government subsidies, concepts for various charging options are to be developed, and a CO_2-effective surcharge on the truck toll for conventional drives is to be introduced as an incentive to switch to alternative drives [3] (pp. 61–68).

At present, however, climate targets and corresponding measures are conflicting with the ability of transport companies to reasonably and cost-effectively switch to alternative drive systems. For transport companies, conventional diesel trucks are a familiar means of transport that have been sufficiently analyzed in terms of their strengths and weaknesses. However, transport companies lack practical experience and information about alternative drive systems, as they bring new technical characteristics, challenges, strengths, and weaknesses. Therefore, a major barrier to adopting alternative drive systems is the limited knowledge about their technical and operational aspects [4].

Alternatives to conventional trucks have continuously been introduced into the market as prototypes or series production vehicles. Currently available alternative drive systems on the market in small series or as prototypes include liquefied natural gas vehicles, fuel cell electric vehicles, vehicles with stationary electric charging options (purely electric with plug-in) or dynamic charging options, and the so-called Electric Road Systems (ERSs) [5]. ERSs can be a solution for road freight transport. The special feature of an ERS is the possibility of keeping the battery installed in the vehicle as small as possible. Analyzing the life cycle of ERS shows that they have the potential to significantly reduce the environmental impact of road freight transport by using renewable energies [6].

One of the most advanced dynamic charging options is the overhead contact line hybrid truck (OH truck) in combination with an overhead contact line infrastructure, which is called "eHighway system" (see Figure 1). When operating the OH truck under the overhead contact line, the OH truck receives energy via the pantograph mounted on top of the truck. On sections without an overhead contact line infrastructure, the OH truck operates fully electrically using the energy of an onboard battery. As soon as the energy stored in the battery is depleted, a conventional combustion engine takes over [7].

Figure 1. eHighway system in Germany (IVV, 2021).

In Germany, the eHighway system is currently being tested through three field tests [7]. One essential part of the field tests is to disseminate the eHighway technology and ensure the economic viability and sustainability of transport companies when integrating the eHighway system. In this study, we evaluated to what extent the OH truck meets the existing requirements of transport companies to operate economically and environmentally friendly heavy-duty truck fleets at the same time. We ask: *Does the OH truck meet the technical and operational requirements of transport companies?*

To answer this research question, we accompanied the ongoing eHighway field trial by conducting regular expert interviews, a written survey, and an analysis of selected OH truck data. Our analyses of the technical requirements focused on aspects such as the desired vehicle types, minimum powertrain requirements, loading capacity, driving speed, and range. We examined the operational requirements including integrability in transport chains, fulfillment of operational requirements, additional infrastructural facilities, or possible restrictions in the transport of different goods.

To present our findings, this research paper follows the following structure: Section 2 examines the current state of research on the adaptation of alternative drive systems by transport companies, highlighting that the OH truck remains unexplored due to its novelty. In particular, the technical and operational aspects of integrating OH trucks have not been addressed. Section 3 outlines the roles that technical and operational factors play in the integration of alternative drive systems and their consideration in previous studies. Section 4 presents the method used to assess the technical and operational integrability of OH trucks. The results are then presented in Section 5. Section 6 discusses the results and places them in the context of existing research. In Section 7, we conclude that transport companies can integrate the OH truck as a component of the eHighway system from both a technical and operational perspective; thus, our study closes the research gap regarding the evaluation of the integrability of the OH truck by transport companies. These findings lay the groundwork for further studies on the eHighway system and its adoption by transport companies. Additionally, companies that have not yet had the chance to test the eHighway technology will find this information valuable for an easier adoption of the system.

2. Transport Companies' Adoption of Alternative Drive Systems

To establish new, alternative drive systems on the market, it is important to identify the various user requirements. Previous studies focused on identifying the influencing factors by employing various qualitative and, in some cases, quantitative survey methods. An early study published on this topic is Sierzchula's [8] analysis of the factors influencing the adoption of electric vehicles. Using qualitative interviews, Sierzchula [8] found that the strongest drivers of the adoption of electric vehicles are the opportunity to test new technologies, reduce environmental effects, governmental grants, and improvement of the organization's public image. Seitz et al. [9] extended these findings using expert interviews and a written survey, and they found that an important reason for switching to alternative drive systems is corporate social responsibility. In addition, Seitz et al. [9] went deeper into the willingness to switch to alternative drive systems and found that companies will show a higher willingness to switch to the alternative drive system as long as the new technology improves current operational processes and the performance of transportation task is not compromised. Kluschke et al. [10] chose a similar survey design: using a web-based survey of 70 participants from the German freight forwarding and logistics industry, they found that the most important requirements of the companies were total cost of ownership and reliability of the alternative drive technology.

Prior studies also identified enablers and barriers to the adoption of alternative drive systems. Mohammed et al.'s [4] results showed that the enablers include efficiency, environmental, economic, and strategic gains, and the barriers include limited knowledge, organizational policies, and operational and economic factors. One of the most recent studies by Bae et al. [11] focused explicitly on heavy freight transport using qualitative interviews in California, USA, to investigate the factors influencing the adoption of alternative drive systems. The results align with findings of previous studies; however, they found that previously undefined aspects such as functional suitability and availability of vehicles were added as new requirements.

Using a standardized online survey of 250 logistic companies, a recent German study found that the central necessities for the use of alternative drive systems are the operational reliability and suitability of the vehicles for the tour requirements (incl. cargo load requirements) and a comprehensive energy supply infrastructure [12].

As studies by Sierzchula [8] and Göckeler et al. [12] stated, the possibility of testing alternative drive systems is decisive for companies. The definition of the influencing factors is only the first step towards the identification of the adoption of alternative drive systems by companies. The next step is now the transfer of technology into real operations to prove the degree of fulfillment of these factors. This was made possible with the start of the real-world operation of the eHighway technology on German highways. Through the scientific accompaniment of transport companies during real-world operations, the influencing factors can be successively verified. In this study, we chose to examine the fulfillment of the technical requirements of transport companies for OH trucks and the integrability of OH trucks into operational processes. We used different criteria for this purpose, which we briefly explain in Section 3.

3. Technical and Operational Requirements of Transport Companies for Alternative Drive Systems

In this section, we delve into the significance of factors identified in the literature concerning the technical and operational feasibility of integrating alternative drive systems within transport companies. Section 3.1 outlines the technical requirements as viewed by these companies, while Section 3.2 addresses the operational necessities.

3.1. Technical Requirements of Transport Companies

Functional suitability is a key factor for adopting alternative drive systems [11]. To evaluate the functionality of an alternative drive system, we define the following criteria as particularly relevant: truck configuration, truck tare weight, operating speed, and range.

To evaluate the integrability of an alternative drive system, transport companies need to familiarize themselves with **truck characteristics and configuration**. First, the specific vehicle class and vehicle type must be taken into account as both criteria have a significant influence on the intended use of the vehicle. Vehicles for the carriage of goods can be divided into three classes [13]. Class N1 includes light commercial vehicles up to a total gross vehicle weight of 3.5 t; class N2 considers medium commercial vehicles with a gross vehicle weight between 3.5 t and 12 t; and class N3 comprises heavy commercial vehicles with a gross vehicle weight of more than 12 t [13]. A distinction for the vehicle type is made considering §34 Strassenverkehrs-Zulassungs-Ordnung (StVZO, Germany) between single trains, truck–trailer combinations, and semitrailer combinations.

In addition to the vehicle class and type, the performance of the powertrain is of particular importance for companies [10,11]. Here, distinctions of driving power for heavy-duty transport range from approx. 205 kW to approx. 566 kW [14].

Another important criterion is the toll classification [10]. Electrically powered trucks are currently exempt from tolls in Germany [15]. Since the toll has a high impact on the additional costs or cost savings associated with the operation of the OH truck, this is particularly beneficial for companies.

Assistance systems support the driver before and during the journey and offer benefits to the safety and fuel consumption of trucks [16]. It is, therefore, particularly important for transport companies that trucks with alternative drive systems are equipped with driver assistance systems, such as the turning assistant, lane departure warning system, and emergency brake assistant [10].

Total truck length is a criterion that has not yet been mentioned in the literature as a factor influencing the adaptation but is, nevertheless, relevant for German transport companies. German regulations stipulate that a semitrailer truck may not exceed a length of 16.5 m (§32 StVZO, Germany). This length, therefore, cannot be exceeded by semitrailer trucks with alternative drive systems, or special permits need to be obtained.

We summarize the named criteria for evaluating the integrability of the vehicle type to the following hypothesis: "*The OH truck configuration meets the requirements of transport companies*".

Based on current regulations, only trucks with a **total weight of the semitrailer combination** of up to 40 t (44 t in combined transport) are permitted on German roads (§34 StVZO, Germany). For many types of transport with trucks, the available load space volume is currently fully utilized. In other transports, however, the maximum payload in tons is reached before the cargo space is exhausted [17]. Kluschke et al. [10] indicate that loading capacity is an important user requirement. A reduction in loading capacity for companies will lead to changes in transport planning, loss of revenue, and increased time expenditure. Therefore, it is important to investigate to what extent changes in loading capacity occur for alternative drive systems. Based upon these requirements and the prior literature, we tested the hypothesis: "*The higher weight of the tractor unit does not limit the load capacity*".

None of the existing studies addressed the issue of possible changes in **driving speed** for alternative drive systems. However, a limitation of the driving speed can be possible for alternative drive systems. Maintaining a maximum driving speed of 80 km/h is critical for the fulfillment of the transport task, as a reduction in maximum driving speed affects route planning and delivery time. (German legislation defines a maximum speed limit of 80 km/h for trucks on highways.) If the OH trucks must reduce their driving speed when connecting to the overhead contact line, this would affect the time for the transport task. Therefore, we tested the hypothesis: "*The driving speed on highways does not change compared to a conventional truck*".

Several studies have shown that, especially for the operation of commercial electric vehicles, the **range** is an important factor for the integration of an alternative drive system by transport companies [9]. According to survey results from Kluschke et al. [10], the desired minimum range of a truck is 800 km. The data on daily mileage ranged between 400 to 800 km. Therefore, it is necessary to verify to what extent the OH truck fulfills the range requirements. Therefore, we developed the following hypothesis: "*The OH truck meets the range requirements of transport companies*".

3.2. Operational Requirements

In addition to technical requirements, the ability to integrate alternative drive systems into logistical processes is essential for successful long-term use [4,9,11]. For the evaluation of the operational integrability of an alternative drive system, we defined the following criteria as particularly relevant: transport chain structure, integration into transport processes, additional facilities at the carrier or customer side, and transport of different goods.

A transport chain is a sequence of technical and organizational processes in which goods are transported from a source to a destination [18]. An important requirement for switching to alternative drive systems is that they can be integrated into existing **transport chain structures** [9,19]. A distinction is made in transport chains between single-stage and multi-stage chains. In single-stage chains, there is no change in the means of transport when the goods are transported; this is also referred to as direct transport. Multi-stage transport chains involve a change of means of transport in the course of transport, with the goods being reloaded or temporarily stored at a transshipment point [20]. A part of a transport chain can be handled by road transport using trucks. This transport can be differentiated into pick-up or delivery transports or collective or distribution transports. In pick-up and delivery transport, the goods are brought from a delivery point to a receiving point or a transshipment point or vice versa; an example is shuttle transport. In collective or distribution transport, goods are either picked up from several delivery points and brought to one receiving point or brought from one delivery point to several receiving points [20].

To evaluate the integrability of the alternative drive system, we analyzed in which part of the transport chain the alternative drive system is used and for which type of transport. We derived changes in the transportation task that have a positive or negative impact on performance. To test this, we formulated the following hypothesis: "*The OH truck can be integrated into different transport chain structures*".

The willingness of a company to switch to an alternative drive system depends upon the ability to integrate it into **operational processes** [9]. If the adoption of an alternative drive system can be integrated without additional effort and with additional benefits, then the overall adoption creates positive effects. The most important operational requirements include minimizing transport times, the flexibility of truck deployment, meeting customer deadlines, ensuring smooth handling processes, and achieving customer satisfaction. Furthermore, smooth operations at transshipment points and the company's depots are necessary for the operation. To test these requirements, we formulated the following hypothesis: "*The OH truck meets the transport task requirements*".

A company's willingness to switch to an alternative drive system is influenced by the required investment [10]. If **additional facilities** are required, companies incur additional costs as well as the need to keep space free at the depot or at the customer's side. In terms of OH trucks, these facilities include, in particular, a stationary charging infrastructure to supplement battery charging under the overhead line. Therefore, to analyze whether additional infrastructure is necessary for the use of the OH truck, we formulated the following hypothesis: "*No additional facilities are required at the transport companies or customer's yard to operate the current type of OH truck*".

A wide **variety of goods** are transported by road. The freight groups with the largest shares transported by trucks include consumer goods (approx. 14%), ores and stones (approx. 28%), and chemical and mineral products (approx. 16%) [21]. For each group of goods, different transport characteristics have to be taken into account. The grouping of quantity and shipping units into transport units plays an important role. In addition, goods that are declared as air freight or hazardous goods place special demands on transport. For companies, it is, therefore, important that alternative drive systems meet transport requirements arising from the structure of goods. We formulated the following hypothesis: "*No significant restrictions can be identified concerning the transport of different types of goods with the OH truck type currently in use*".

4. Methodology

To assess how well OH trucks meet the technical and operational needs of transport companies, we conducted an in-depth study by monitoring the deployment of OH trucks across five distinct transport companies (referred to as use cases) for two years. This section details the case study, including the selection of use cases, as well as the methodologies employed for surveying and evaluating their performance during actual operations.

4.1. Case Study—eHighway Test Track in Hesse Germany

The field test considered for this study is located in the Federal State of Hesse and is one of three field tests in Germany. A five-kilometer section in the North and South directions between Frankfurt am Main and Darmstadt is equipped with an overhead line infrastructure and was to be extended in the Southern direction to a total length of 12 km by the end of 2022. In total, the eHighway system and its components have been tested for the last four years in Germany [7].

All OH trucks currently operated in the field test are tractor units of the Scania R450 A4x2NB R17N series (Scania, Södertälje, Sweden) with the national emission class EURO VI. They are equipped with a parallel hybrid drive system. Essentially, the technology installed in the trucks consists of a 450 hp combustion engine, a 130 kW electric machine, an 18.5 kWh battery (gross capacity), and the pantograph for contact with the overhead contact line for power transmission [22–24]. The OH trucks are also equipped with all the standard assistance systems, e.g., the distance warning system or the emergency brake assistant. Special eHighway system features designed to make it easier for drivers to operate the OH truck include a catenary keep assist (abbreviated to CKA) and a pantograph camera. The weight of the tractor unit without a trailer is approx. 9.2 t. According to the current German registration regulation, the OH truck may weigh a total of 42 tons (§ 36 6(a) StVZO, Germany). Assuming an unladen weight of the trailer of around 7 t, this allows a payload of approx. 25 t.

In total, five OH trucks are operated regularly by five different transport companies on the test track. The daily use of the OH trucks by the five participating companies can be translated into five use cases (Table 1).

In the first use case, the OH truck is used by a medium-sized transport company for a regional shuttle transport of emulsion paint and other construction materials. The second OH truck is used at a large company in the region for the distribution transport of refrigerated goods. The third truck is used in combined transport for the transportation of containers in hinterland transport in the Rhine-Main region (Hesse, Germany). The fourth OH truck transports construction material for a larger company. The fifth truck is used by a large company in day and night shifts for transporting liquid sludge and air freight to Frankfurt Airport. The defined use cases serve as the basis for differentiated investigations to examine the extent to which different company structures influence the integrability of the OH truck into their fleet.

Table 1. Overview of use cases.

	Use Case 1	Use Case 2	Use Case 3	Use Case 4	Use Case 5
Company structure					
Company size	Medium-sized company	Large company	Large company	Large company	Large company
Transport sector	National forwarding and construction site logistics	Temperature-controlled distribution of food	Container hinterland logistics network in Europe	National transport of construction materials	Regional transports
Transport scope					
Operation area	Local and regional transport	Local and regional transport	Local and regional transport	Local and regional transport	Local and regional transport
Vehicle type + trailer type	Truck tractor + box trailer	Truck tractor + box trailer and cooling system	Truck tractor + container chassis	Truck tractor + box trailer	Truck tractor + box trailer/chemical liquids trailer
Transported goods (incl. special requirements)	Emulsion paint and other construction materials	Consumer goods, esp. refrigerated food	Different kinds of goods in containers, e.g., raw timber	Construction materials, e.g., wall profiles	Liquid sludge, different goods for air freight
Transport structure	Shuttle transport	Distribution transport	Combined transport	Distribution transport	Shuttle transport

4.2. *Applied Qualitative and Quantitative Methods*

For our study, we used an explorative process with a mixture of qualitative and quantitative analyses to analyze the real-world operation of five OH trucks. We chose qualitative analysis because prior studies indicate that it is suitable for understanding a complicated phenomenon and allows for in-depth analysis [25]. The qualitative data collected from five operating OH trucks is limited and does not allow for a large-scale statistical analysis. Therefore, we combined our qualitative analysis with a quantitative analysis based on operational data of the OH trucks.

As qualitative methods, we chose written surveys as well as expert interviews and applied them for testing the associated hypotheses. Between 2020 and 2022, we conducted 32 digital expert interviews with the management of the participating transport companies. In particular, the expert interviews focused on experience with the operation of the OH trucks, possible changes in logistics processes, vehicle configuration, equipment, experiences with usage of the overhead contact line system, and press and public relations. We documented interview results using memory protocols and evaluated them according to predefined topics related to our hypotheses. For the identification of the technical requirements, we conducted a written survey with all interested transport companies before the handover of the OH trucks to allow for a comparison of companies' uninfluenced truck requirements with OH truck configurations.

For the quantitative section, we analyzed data collected through data loggers within the OH trucks as well as additional tour-based weight data manually collected by the drivers combined with a vehicle diary we have kept since the start of operations.

While the OH truck is operating, every 0.1 s, a set of data including more than one hundred different parameters is collected through a datalogger installed within the OH trucks. To simplify the evaluation, we first reduced the vehicle data sets to the necessary parameters including timestamp, km traveled, GPS longitude, GPS latitude, pantograph status, and vehicle speed. Afterward, we analyzed the daily distance traveled and the frequency of trips over the test track. For this analysis, we used a combination of a daily vehicle operation diary and the vehicle data set. We determined the regular operation days of the OH trucks based on the vehicle diary. Afterward, we reduced the vehicle data set based on the regular operation days to make reliable statements about the daily distance traveled and the average frequency of trips on a regular operating day. We used the data for all OH trucks between the start of OH truck operation and June 2022 and calculated an average value for the daily distance traveled as well as the daily trip frequency for each use case.

For the analysis of the OH truck operating speed, we analyzed a reduced data set by filtering through the GPS parameters to the time when the truck was operated under the overhead contact line and simultaneously connected to the overhead contact line via the pantograph. We plotted the data points into a histogram and clustered them into groups for analysis.

The second analyzed data set includes the collection of the weight data of the OH trucks. A separate collection of the weight data of the OH trucks was necessary since a recording of the weight data via the installed data logger was not yet possible for the period under consideration. Therefore, we prepared a recording sheet for the OH truck drivers to collect tour-based weight data. For the analysis of this study, we focused on one OH truck. After data transfer and cleaning, we graphically visualized and analyzed the data.

5. Results

To foreshadow our conclusions, our results show that transport companies can effectively and efficiently integrate the OH truck as a component of the eHighway system from both technical and operational perspectives. In the following sections, we provide evidence to support the system's ability to meet all requirements regarding truck configuration, truck tare weight, operating speed, driving range, transport chain structure, transport task, additional facilities at the carriers or customer side, and transport of different goods.

5.1. Findings from the Technical Assessment of OH Truck Configurations

"**The OH truck configuration meets the requirements of transport companies**".

The OH trucks currently in use are tractor–trailer combinations and are classified as class N3 (see Figure 2). The transport companies who participated in our survey used class N3 trucks, with a large number also using tractor–trailer combinations. The power of the combustion engine (330 kW/450 hp) and the power of the electric machine (130 kW) comprise the driving power of the OH truck. As these can be used simultaneously due to the parallel hybrid, this produces a possible total power of approx. 580 kW. Based on the feedback from the written survey, the transport companies require a minimum of 330 kW. Comparing the two values, we prove that the transport companies' requirement of all use cases for the drive power of the OH trucks is met.

Figure 2. Visualization of OH trucks with extended and lowered pantographs.

We also found that the OH truck is compatible with a variety of trailer types, e.g., trailers with a refrigeration function, trailer chassis for 20 ft or 40 ft containers, or trailers transporting liquids. For this reason, we did not identify any restrictions with regard to the combination with different trailers for any of the use cases.

Moreover, all necessary assistant systems were installed inside the OH truck and had been expanded to include additional assistance systems, such as the "Catenary Keep Assist" and a pantograph camera for the operation under the overhead contact line.

The OH truck has a greater length compared to a conventional truck. The excess of the total length of the tractor–trailer combination arises due to the additional installation space of the pantograph system behind the driver's cab, creating an extension of approximately 0.35 m. For the approval of the OH trucks in the field test, it was possible to obtain an exemption from the approval authority so that the legal requirement of 16.5 m may be exceeded by 1 m. Due to this adaptation of the legal requirement, all transport companies can use the OH truck without restrictions.

"**The higher weight of the tractor unit does not limit the load capacity**".

We found that the tractor unit has a higher unladen weight compared to a conventional truck. The installed pantograph components, the battery, and the electrical machine create a higher unladen weight. The pantograph system consists of a pantograph frame and the pantograph mounted on top. In total, the pantograph system weighs approx. 350 kg but requires further additional superstructures behind the driver's cab. The additionally installed battery weighs approx. 200 kg. These three components must be added to the weight of a basic tractor unit. Reducing the size of the fuel tank from 1000 to 300 L makes weight-saving possible. Moreover, it was possible to obtain an exemption from the German approval authority, so that the legal requirement of 40 t (§34 StVZO) may be exceeded by approximately 1.8 t.

Despite the heavier weight of the tractor unit, no loss of payload was observed because of the higher tare weight of the tractor unit for any of the use cases. The analysis of the weight data for the first use case shows that a large proportion of the tours were made with a load between 20 t and 25 t for 35 months (Figure 3). The roughly equal number of trips with a load between 0 t and up to 5 t is due to the shuttle transport in which the OH truck transports goods daily from the manufacturer to a distribution warehouse. A load of 25 t is comparable to loads of conventional vehicles with a gross vehicle weight of 40 t.

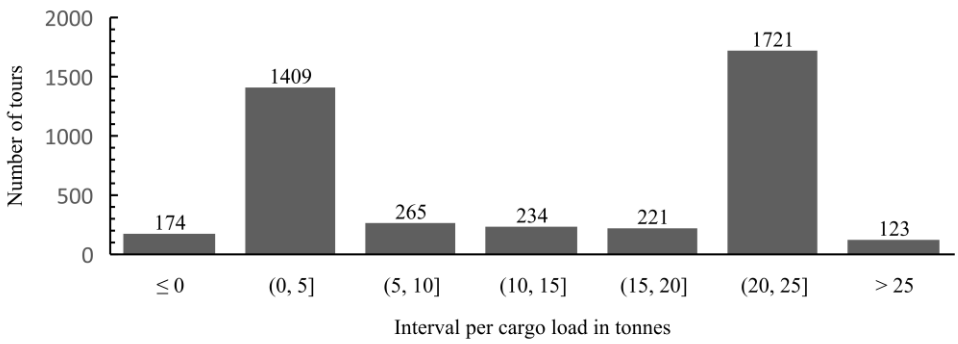

Figure 3. Load per tour for use case 1 (data period: June 2019–May 2022).

"**The driving speed on highways does not change compared to a conventional truck".**

The OH trucks in all use cases generally operate under the overhead contact line at the maximum permissible vehicle speed (the system is designed for 90 km/h). This means the OH trucks do not impose any scheduling restrictions on transport companies.

"**The OH truck meets the range requirements of transport companies**".

The results of our expert interviews show that the transport companies of all use cases did not face any range restrictions. The additionally installed combustion engine can cover routes that cannot be driven with the use of the pantograph or the battery. The transporters hope, however, that future OH truck configurations will have a higher battery capacity and a more efficient electric machine so that the electric range and the associated CO_2 savings can be increased.

5.2. Findings from the Integration of OH Trucks into Transport Processes

"**The OH truck can be integrated into different transport chain structures**".

The analysis of the transport chain structure of the five use cases shows that three of the five OH trucks are part of a longer transport chain of goods and are used in precarriage or on-carriage, which means that after arrival at a transshipment point, the goods pass through further stages to the end customer. The other two OH trucks are used in direct transport and, thus, cover an entire transport chain. Looking at the structure of the transport trips of use case 1 and use case 5, it becomes clear that they are mainly used as shuttles between two locations close to the test track. The OH truck for use case 1 travels an average of 376 km per day with an average of 4.7 trips over the test track (Figure 4). The OH truck for use case 2 travels an average of 250 km and makes an average of 7.4 trips per day along the test track.

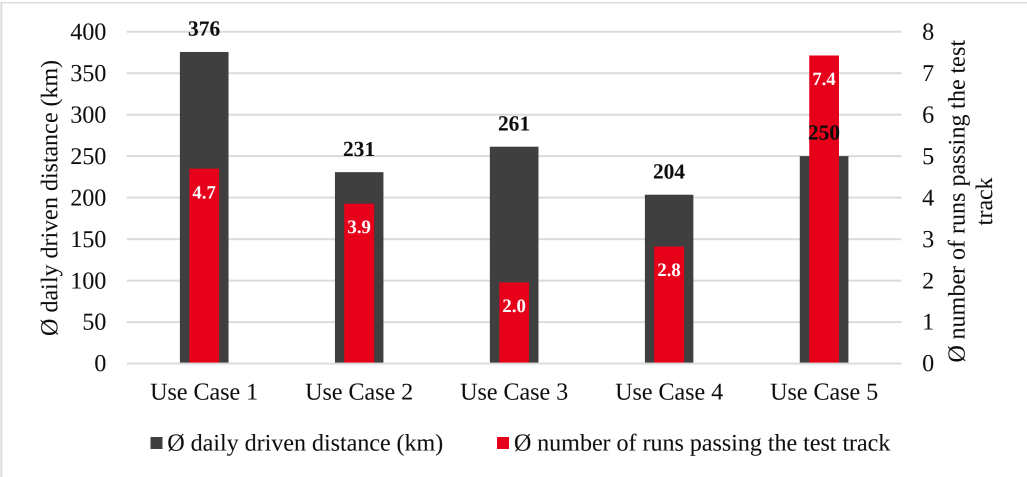

Figure 4. Average daily driven distance and average number of runs passing the test track.

In comparison, the OH trucks in use cases 2, 3, and 4 operate in a more extensive region, increasing the average trip length and causing them to pass the test track less frequently. The OH truck in use case 2 travels an average of approximately 231 km per day and functions as a distribution trip. Here, the OH truck delivers refrigerated goods to supermarkets in the Rhine-Main region. We investigated how even distribution trips enable a high trip frequency of almost four trips per day via the test route. The OH truck in use case 4 operates similarly to a shuttle with an average daily traveled distance of 204 km. The relatively short daily distance shows that this use case has a lower order volume compared to the other cases but is still able to pass the test track on average 2.8 times per day.

Particularly noteworthy is the structure of the transport trips of the OH truck in use case 3, which is used for delivery or pick-up trips in combined transport. In comparison, this use case sees the lowest frequency of trips under the system because of the transport chain structure.

"**The OH truck meets the transport task requirements**".

We conclude that the OH truck type currently in use meets the operational requirements of the transport companies. The results show that all the transport companies of all use cases were able to integrate the OH truck into their regular operations. None of the transporters reported delivery delays or problems with the customer (client of the transports) due to OH truck failures. We found that transport companies working with very time-sensitive customers, as in use case 2, did not notice any negative impact from OH truck use in the fleet. Therefore, we conclude that the requirements of maintaining the transport time, flexibility of vehicle deployment, meeting customer deadlines, ensuring smooth handling processes, and achieving customer satisfaction can be met.

In two of the five use cases, the trucks deliver from or to a transshipment point. For another use case, one of the OH trucks delivers goods to a transshipment point where the mode is changed to rail or inland waterway transport. None of the transport companies reported any restrictions or problems with cargo handling. It can, therefore, be assumed that no restrictions are to be expected here in the future.

"**No additional facilities are required at the transport companies or customer's yard to operate the current type of OH truck**".

The current OH truck configuration, which does not include a plug-in system, does not require additional equipment for the OH truck at transshipment points or the transport companies' depots. When charging the 24 V battery system, however, a conventional household connection can be required, which the vehicles will not necessarily need in the long term, according to the vehicle manufacturer.

"**No significant restrictions can be identified concerning the transport of different types of goods with the OH truck type currently in use**".

The analysis of the use cases showed that very different goods with different trailer configurations can be transported with the OH truck. It is possible to connect semitrailers with refrigeration to the OH truck and also flexible chassis with which different container lengths, such as 20 ft or 40 ft containers, can be transported. Another particularly interesting feature is the possibility of attaching a trailer that can transport liquids. However, analyses also revealed limitations concerning the transport of goods that are declared hazardous goods or bulk goods that must be transported with a dump truck. Nevertheless, further development of the vehicles does not completely rule this out for future OH truck configurations.

6. Discussion

We argue that OH trucks can be integrated into different transport companies with a wide range in their size, scale, and type of freight. The adaptation of new technologies by transport companies depends on various factors, as demonstrated by several studies from different countries [4,8–11,19]. These studies have focused on identifying the different influencing factors and categorizing them in terms of their relevance. Only a few studies, however, provide insights into the degree of fulfillment of the requirements for alternative drive systems. This paper builds upon this foundation and extends the analyses to examine the degree of fulfillment of the adaptation requirements for an alternative drive system—the eHighway System—at selected transport companies with very different company profiles.

For transport companies to switch from conventional trucks to the eHighway system, the OH truck must demonstrate comparable technical characteristics. Kluschke et al. [10] identified key technical requirements for alternative drive systems as meeting propulsion power, toll rating, driver assistance systems, loading capacities, and minimum range. Seitz et al. [9] summarize the technical requirements under the term "functional suitability" and emphasize that this is one of the most recurring factors for the adaptation of an alternative drive system. We used these identified requirements as a basis for evaluating the technical requirements of transport companies for the OH truck. Using a variety of survey methods, we were able to demonstrate that the OH truck meets both the companies' requirements for the type of vehicle to be used and the desired vehicle characteristics. In addition, we were able to demonstrate an absence of limitations in loading capacity and that the driving speed was comparable to a conventional diesel truck. The current OH truck lacks range limitations because of the combination of a diesel engine and an electric engine. The fulfillment of the technical requirements is an important first step with regard to the dissemination of OH trucks. Our findings form the basis for research into further requirements as well as important insights for companies that have not yet decided to switch to alternative drive systems.

The results of this study show that, apart from a few restrictions, the OH truck fulfills the transport task similarly to a conventional truck. At any time, according to the transport companies, customer requirements could be met. The very relevant barrier named by Bae et al. [11] regarding additional costs in setting up an infrastructure at the transport company's or the customer's depot did not occur. In addition to meeting the technical requirements, Seitz et al.'s [9] findings indicate that it is important for transport companies to ensure that alternative propulsion technologies do not negatively impact the fulfillment of the transportation task. The primary goal of transportation is to move a commodity from a source to a destination [18]. When analyzing the fulfillment of the transport task, influencing factors such as the structure of the transport chain, the type of goods transported, the transport time, the flexibility of vehicle deployment, customer requirements, and satisfaction must be taken into account.

Operation as a shuttle turned out to be particularly advantageous, based primarily on the spatial limitation of the overhead line system. We acknowledge the decisive role of the limited test facility in the field trial, which must be harmonized with route planning in the future. In addition, distribution runs within the Rhine-Main region can also be carried out with the OH truck without any problems.

7. Conclusions and Outlook

To achieve climate targets, transport companies must select suitable alternatives for conventional diesel trucks. Multiple factors influence the transport companies' selection of an alternative drive system. Only a few transport companies have been able to gain experience with the integration of alternative drive systems in their fleet, as the availability is still very low. The eHighway system is one alternative drive system that is currently being tested on three German test tracks. With this paper, we contribute to filling the knowledge gap of transport companies by analyzing the technical and operational experiences of transport companies with the eHighway system for the first time. We conclude as follows:

- **No major restrictions** regarding the technical equipment of the OH trucks exist.
- Despite the higher total weight of the tractor unit, **no loss of payload** was observed.
- **Approval of the OH trucks was possible** despite the higher weight of the tractor unit and the greater length of the OH trucks due to the additionally installed pantograph components.
- The **driving speed of an OH truck is comparable** to that of a conventional truck. Therefore, the use of the OH truck will not produce an increase in tour duration due to reduced driving speeds.
- OH trucks **can be integrated** into different transport structures. Shuttle transport proved to be particularly advantageous for the utilization of the overhead line infrastructure.
- **Important operational requirements**, such as on-time delivery, transport time, or customer satisfaction, **could be guaranteed** at all times when using the current OH truck type.
- **No additional facilities** were required at the depot or the customer's site for the current OH truck type.
- **All goods could be transported.** However, OH trucks with a tipper trailer, or for hazardous goods, have yet to be officially approved.

Our study only included technical and operational requirements of transport companies in the analyses. Other requirements, such as the evaluation of the total cost of ownership, the availability and reliability of the OH trucks and the overhead contact line infrastructure, the acceptance of truck drivers, or the detailed analysis or modeling of changes in route planning, play an important role in the overall evaluation of the system from the perspective of transport companies.

Furthermore, the findings are limited as they only refer to the first generation of OH trucks. In parallel with the ongoing field test, the technology of the OH trucks has been further developed. This includes increasing the engine size of the electric machine and battery size and equipping the trucks with a plug-in charging option. With these new truck configurations, the issue of stationary charging infrastructure at the transport companies' depot must be re-evaluated. Here, it is important to analyze for which operating scenarios the infrastructure is essential and where it may not be necessary, since sufficient energy can be absorbed when driving and using the overhead contact line infrastructure to operate fully electrically. Future evaluations will integrate further requirements as well as new OH truck configurations by extending the data collection throughout the ongoing field trial.

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