Current technical findings on the eHighway system from field tests and accompanying research in Germany

Working paper compiled by the German cross-project Working Group on eHighway Technology (AG Technikbewertung)

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Introduction

Apart from urban trolley buses, the dynamic energy supply of commercial vehicles on public roads via overhead contact lines or conductor rails is still a relatively new technology with only about 10 years of research and development experience. However, if renewable energies are used, it can make a significant contribution to reducing emissions from heavy road freight transport and thus to achieving climate protection targets. Following shorter pilot routes in Sweden and California, intensive testing of the overhead contact line infrastructure and of about 15 trucks with pantographs is currently taking place on two federal motorways and one federal highway as part of the field test in Germany. In addition, in other European countries, intensive feasibility studies are being carried out on so-called ERS - Electric Road Systems - with overhead contact lines or other power transmission technologies.

The objectives of this short report are:

- the description of the overall system, its essential subsystems and the most important motives for the intensive research and development,
- the compact presentation of current findings from practical technology testing on the field test routes, including the operational environment at the logistics companies and freight forwarders, as well as
- an outlook on the next steps and the research questions that are still open.

Due to the focus on the findings of the German field test, the variant for supplying energy to heavy commercial vehicles by means of overhead contact lines dominates this report. On the one hand, there are good reasons for this, as the technological maturity based on over 130 years of development and application experience with overhead contact lines in rail and road applications is particularly high. On the other hand, intensive efforts are also being made in some cases with other transmission technologies in other European and non-European countries, for which, however, reference is made to the relevant studies and projects.

This working paper is an interim report that concisely summarises the current state of knowledge of the field test in Germany and aims to stimulate exchange among experts and interested members of the public.

The working paper was produced as a joint work of the Technical Working Group (AK Technik), which sees itself as an exchange platform for the field test and development projects. Thanks are due to all researchers and participants in the field tests who contributed to the acquisition, discussion and assembly of the findings.

Part I System overview eHighway

1 What challenges are addressed by the eHighway system?

Author: J. Jöhrens

According to the German Climate Protection Act amended in June 2021, emissions from the entire German transport sector are to be almost halved from 146 Mt in 2021 to 85 Mt CO_2 annually by 2030 [Agora Energiewende 2022]. For road freight transport, which currently accounts for about one third of emissions, this means enormous challenges. Even with extremely ambitious measures to shift parts of freight transport to rail[1] , around two thirds of freight transport volume will probably still have to be carried on the road in 2030 and will need solutions for efficient decarbonisation.

Current energy system studies (e.g. [Prognos et al. 2021]), unanimously found that direct use of electricity is the most cost-effective and, in terms of CO_2 savings, the most effective solution for all applications where this is technically possible. This is due to the electricity system being planned to be almost completely renewables-based in the long term, while almost half of electricity production in Germany is based on renewables already today. In road freight transport, electrification is currently happening primarily through battery trucks. At least for delivery traffic and for smaller trucks, the number of vehicles on offer here is already increasing continuously. For long-distance transport, however, there are considerable technical, organisational and resource challenges for pure battery-electric trucks:

- The batteries (for a tractor with a range of 500 km, a battery capacity of about 650 kWh with 4-5 t weight is required) represent a considerable cost factor and limit the payload. Similarly, there is little experience on lifetimes in this application profile, as major fleet trials with e-trucks have only recently started.
- For the intermediate charging of such batteries with power demands in the range of 1 MW, additional areas along the motorways and very high grid connection capacities are necessary [Plötz et al. 2020]. Public or private charging infrastructures are also required beyond the motorways [Beckers/Bieschke 2021].
- The raw material requirements for the required high battery capacities pose risks in terms of availability, world market prices and sustainable supply chains with regard to environmental and social aspects.

These challenges can be mitigated by using systems for dynamic energy supply while driving. [Plötz et al. 2021] provides a detailed overview of the opportunities and risks of both systems. A comparison of the user costs at the level of individual mission profiles also shows that, especially for long-distance transports, significant cost savings can be achieved in some cases through power supply via overhead contact line compared to the use of purely stationary charged battery trucks [Jöhrens et al. 2022]. Overhead contact line systems can show their advantages especially on highly trafficked routes. Previous studies see a reasonable long-term application potential for an overhead contact line network of 3,000 to 4,000 km total length on motorways in Germany [Hacker et al. 2020].

[1] In (KCW 2019), an increase in the rail-bound share from the current 19% to 35% of transport performance was considered realistic for the year 2035 and backed up with measures.

While energy transmission via ground conductor rails or inductive coupling by means of coils embedded in the road body is also possible in principle, transmission via overhead contact line currently has the highest technical maturity[2] and is therefore the focus of German research in terms of rapid implementability.

In principle, all drive systems with electric motors can use a power supply via overhead contact lines, i.e. also hybrid or fuel cell drives in addition to battery vehicles. The resulting synergy potentials are discussed in section 10.

2 What subsystems does the eHighway system consist of?

Author: M. Lehmann

The eHighway system, like other high-performance transport and rail systems, consists of a number of subsystems and a surrounding system environment. Figure 1 shows the overall system, the subsystems and their most important components. The focus of this electrification solution is an external energy supply of the vehicles by means of overhead contact lines as well as the equipment of the trucks with an electric drive as well as a current collector (pantograph), which enables the vehicles to draw energy from the contact wires of the overhead contact line (OCL) while driving. A detailed system description can be found in [Boltze et. al. 2021].

For the pantograph and especially the overhead contact line, proven and tested components from the railway system were used and adapted to the road application. As a result, the system has a high level of technological maturity and is already being tested by haulage companies in the field test discussed later. In addition to railway applications, extensive experience with overhead contact lines in road applications were also made in over 300 trolleybus operations worldwide as well as with several electric heavy haulage systems in open-cast mines.

By retrofitting and integrating the overhead contact line system (OCS) into existing road infrastructures, the system allows for the comprehensive use of renewable energies to truck traffic. Moreover, recharging batteries takes place flexibly during the journey and not only with operational restrictions during driving breaks, loading and unloading processes or other vehicle stops. The batteries necessary for sections that cannot be electrified and for the pre- and post-carriageway to the motorways can be designed smaller according to demand and applications. The overall eHighway system also includes the system periphery with, on the one hand, technical integration into traffic management and energy supply and billing systems. On the other hand, on the regulatory side, the national and European planning, financing and approval regimes must also be adapted and further developed, see e.g. [Hartwig et. al. 2020a] and [Hartwig 2020b].

[2] This is partly due to the fact that the overhead contact line and pantograph technology can be based on many years of experience in the railway sector, cf. section 2 and [Widegren et al. 2022].

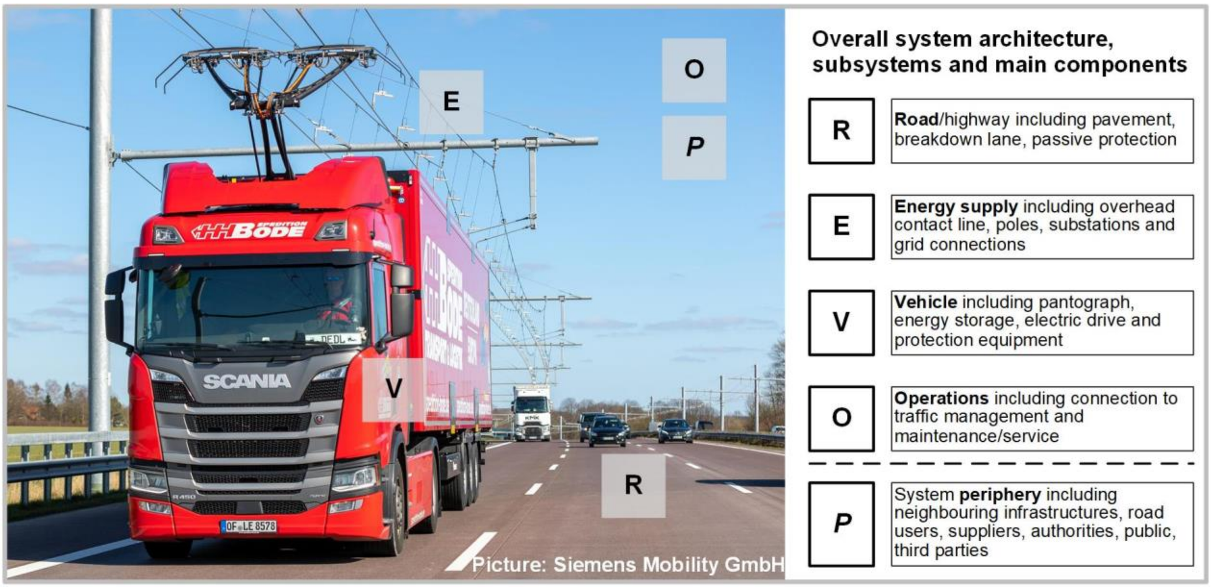

Figure 1: **Overall system architecture and subsystems of the overhead contact line truck system (Image source: Siemens Mobility GmbH with additions by the author)**

3 How is the power supply of the eHighway system structured?

Authors: M. Werner, M. Staub

The basic principle of the power supply of the eHighway system is shown schematically with the components of power transmission in the distribution/transmission grid, power distribution through substations, and power supply and return current via the overhead contact line in Figure 2 ([Werner 2020] according to [Biesenack et al. 2006]). The power supply system of the eHighway is based on many years of experience in the railway and local transport sector and is therefore basically known and tested. In contrast to railway applications, however, the return current cannot be fed back via the track (rail), which is why both the power supply and the return current are realised via a two-pole DC overhead contact line (see Figure 2).

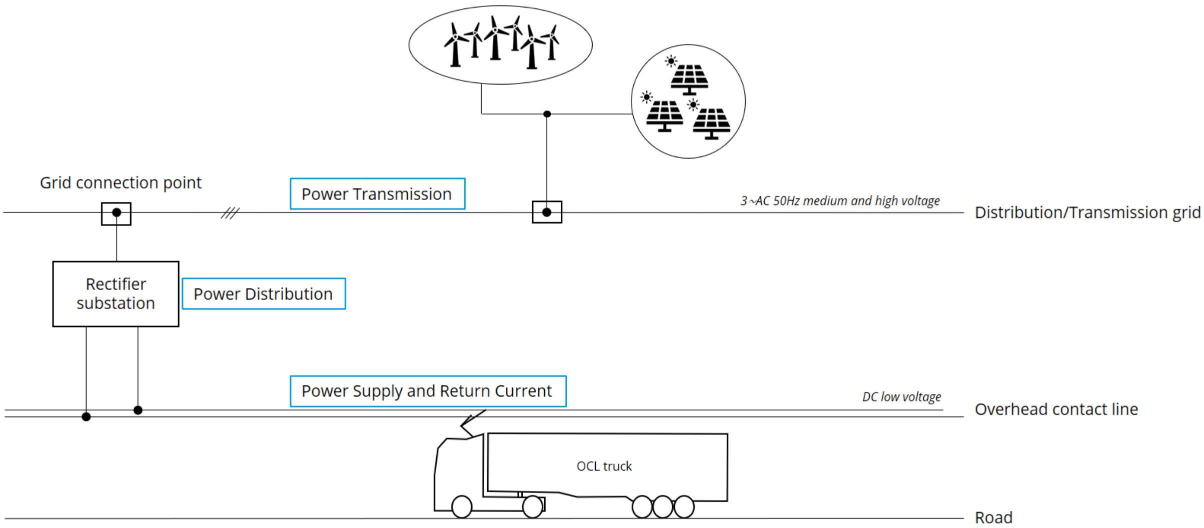

Figure 2 **Schematic representation of the power supply of the eHighway ([Werner 2020] according to [Biesenack et al. 2006])**

The traction and charging power for supplying the vehicles is drawn from a power supply grid at medium or high voltage level. For this purpose, rectifier substations (RSS) distributed at defined grid connection points (GCP) along the route are connected to the superordinate grid level[3] , which at the same time represents the system boundary to the eHighway. The RSS are designed in containerised construction or as prefabricated concrete houses, which enables compact construction and simple integration into the surroundings. The RSS have the task of reducing the three-phase AC voltage from the higher-level distribution/transmission grid to the (low) voltage level of the overhead contact line system using a transformer and rectifying it using a rectifier (usually a diode rectifier). If braking energy caused by vehicles is to be fed back into the distribution/transmission grid through recuperation, the RSS can be equipped with a bidirectional rectifier or inverter. The substations are connected to the feed-in points on the overhead contact line via feeder- and return cables. Several RSS that feed into the overhead contact line together form a feeder section. The specific number, spacing and power class of the substations are project-specific and largely depend on the route topography and the number of vehicles to be supplied. Possible synergies with stationary charging systems (so-called megachargers for trucks or charging columns for cars) at car parks and service stations should already be taken into account in the dimensioning and system design of the grid connections (see section 10).

The power supply to the vehicles as well as the return current to the substation is carried out in the current system design by a two-pole DC overhead contact line with two parallel catenaries, each consisting of a high-strength copper contact wire with magnesium alloy and a messenger wire (see Figure 1). The contact wire is suspended from the messenger wire at short intervals via droppers.

The power supply of the eHighway system is characterised by a high overall efficiency, also in comparison to other alternative drive technologies in road freight transport [Lehmann et al. 2014].

4 How is the drive train of the overhead contact line trucks designed in the field test?

Authors: F. Schöpp, M. Worbs, A. Bulenda, T. Burgert, Ö. Öztürk, R. Linke

All overhead contact line trucks used in the field test are prototypes so far. Specifically, these are overhead contact line *hybrid* trucks (OH trucks). The OH trucks are based on vehicles from the Scania R450 A4x2NB R17N series.Depending on the configuration, the trucks are equipped with a parallel or power-split hybrid drive, which contains a conventional combustion engine, one or two electric machines (E-machines), a current collector (pantograph) and an electrochemical energy storage (battery). As soon as a stretch has an overhead contact line system, the OH truck uses the pantograph to draw electric energy from the overhead contact line for propulsion and battery charging. If an OH truck drives on sections of track without an overhead contact line system, the previously charged electric energy from the battery is used. As soon as the energy available in the battery is used up, the combustion engine takes over

[3] If this connection is not possible due to the unavailability of a public power supply network or for other project-specific reasons, there is also the option of connecting the substations to a system's own medium-voltage level.

[Boltze et al. 2020; Schöpp et al. 2021a]. The operation of an OH truck is basically an interplay of the components of overhead contact line system, pantograph, battery, electric machine and combustion engine [Schöpp et al. 2022] (cf. Figure 3).

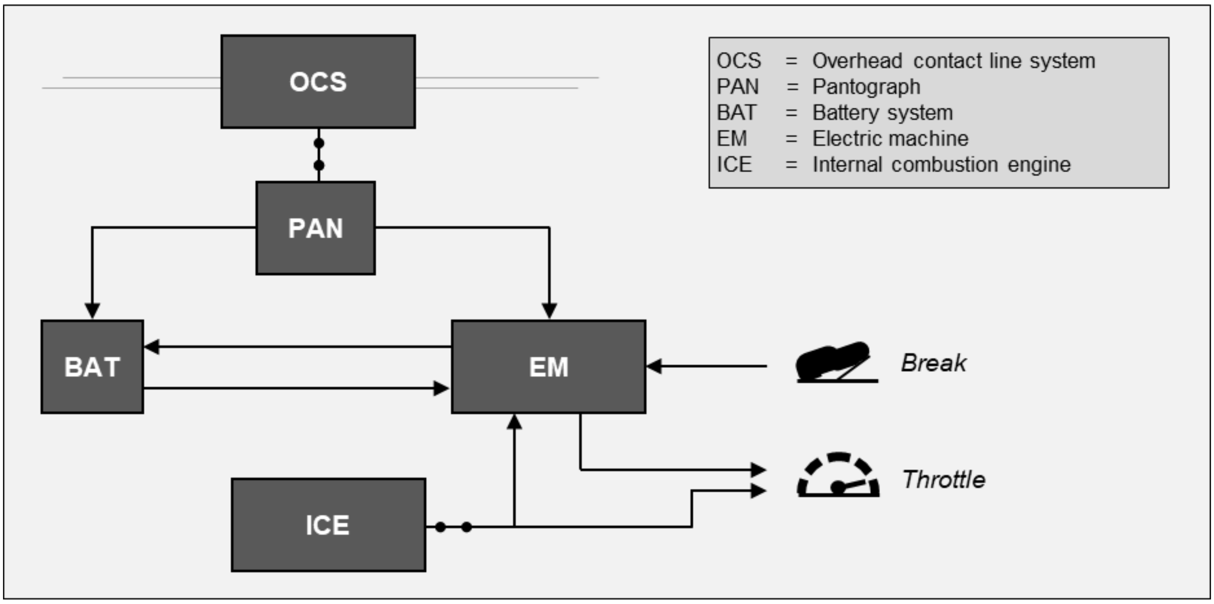

Figure 3: Simplified, schematic representation of the drive train of an OH truck [after Schöpp et al. 2022].

At present, OH trucks with different technical configurations are being tested in the field. Their characteristics are compared in Table 1. In the **field test project ELISA** (Electrified, innovative road freight transport on motorways), five OH trucks of *configuration 1* are in operation. Five transport companies with different operational profiles act as associated partners and use the OH truck provided to them in their daily business [Boltze et al. 2020]. The first two OH trucks have been operated by Spedition Hans Adam Schanz GmbH & Co. KG and Ludwig Meyer GmbH & Co. KG since May and September 2019. Three more OH trucks started their operation in July 2020 by Contargo GmbH & Co. KG (in cooperation with Rhenus Trucking), Knauf Gips KG and Merck KGaA. The stretch, which is electrified with an overhead contact line system, has a length of approximately 5 km in both directions and is currently being extended by 7 more kilometres in the direction of Darmstadt.

In the field test project FESH (Field test eHighway Schleswig-Holstein), OH trucks in all three configurations are in use. They are used exclusively by Spedition Bode GmbH und Co. KG in (combined) shuttle transport within a radius of 30 km around the headquarter in Reinfeld near Lübeck. The first vehicle in *configuration 1* has been in use since December 2019. In 2021, one vehicle of *configuration 2* followed in June and two vehicles of *configuration 3* in September. The handover of the last vehicle of *configuration 3* took place at the beginning of March 2022. The electrified stretch with an overhead contact line system is approximately 5 km in both directions of travel.

Table 1: Key figures and technical data on the OH truck configurations currently being operated in the field test

Key figures for the...	***Configuration 1***		***Configuration 2***		***Configuration 3***	
Combustion engine power	450 hp (331 kW)					
EURO class	EURO VI					
E-machine power	1 x 130 kW		2 x 130 kW			
Gearbox type	Automatic, 12 gears		DHT[1], clutchless, 6 gears			
Battery capacity	18.5 kWh (gross)				4 x 18.5 kWh (gross)	
Unladen weight of the tractor unit	9,2 t				10,5 t	
GVW of the articulated vehicle (special approval) [3]	41,786 t (CT[2] 44 t)					
Tractor unit length	16,85 m				17,50 m (wheelbase extended by 0.4 m)	
Composition of the vehicle fleet on the field test routes	ELISA	5	ELISA	0	ELISA	0
	FESH	1	FESH	1	FESH	3
	eWayBW	0	eWayBW	5	eWayBW	0

1) DHT dedicated hybrid transmission
2) CT combined transport
3) GVW gross vehicle weight

In the field test project eWayBW (pilot project on hybrid trolleybuses on the B 462), only *configuration 2* OH trucks are in use. These are operated by the haulage companies Huettemann and Fahrner. All OH trucks are used in shuttle operation and commute between two paper mills and the respective logistics centre in Kuppenheim. Started with two tractor units in September 2021, five OH trucks are also expected to be used on the shuttle route from 2022. In each direction of travel, two opposite sections with overhead contact line system will be available. Electrification section 1 is 2.6 km long in each direction (with a 600 m extension option not yet realized) and electrification section 2 is 750 m long in each direction.

Primarily as a result of the field test status and the limited availability of overhead contact line systems, the OH truck configurations currently in use are still dependent on combustion engines to cover even longer distances. In the future, however, other drive technologies appear to be possible and reasonable instead of an internal combustion engine. Depending on the network of overhead contact line systems and stationary truck charging infrastructure that will be available in the future, it is increasingly becoming probable that purely electric variants will also meet the requirements and that more complex powertrains can be completely dispensed (see for example section 10).

Part II Research and first results in the field test

5 What does the interdisciplinary evaluation concept look like in the field test?

Authors: R. Linke, M. Werner, T. Burgert, F. Schöpp, M. Worbs, U. Burghard, E. Kaßens-Noor

A comparison of the evaluation concepts of the three test routes in Germany reveals common contents on the one hand and significant differences on the other. These result from the structural boundary conditions of the test routes and different focal points of the accompanying scientific research. Figure 4 shows an overview of the interdisciplinary evaluation concept of the field test, which is explained subsequently. Figure 5 provides an overview of the location of the eHighway test tracks in Germany.

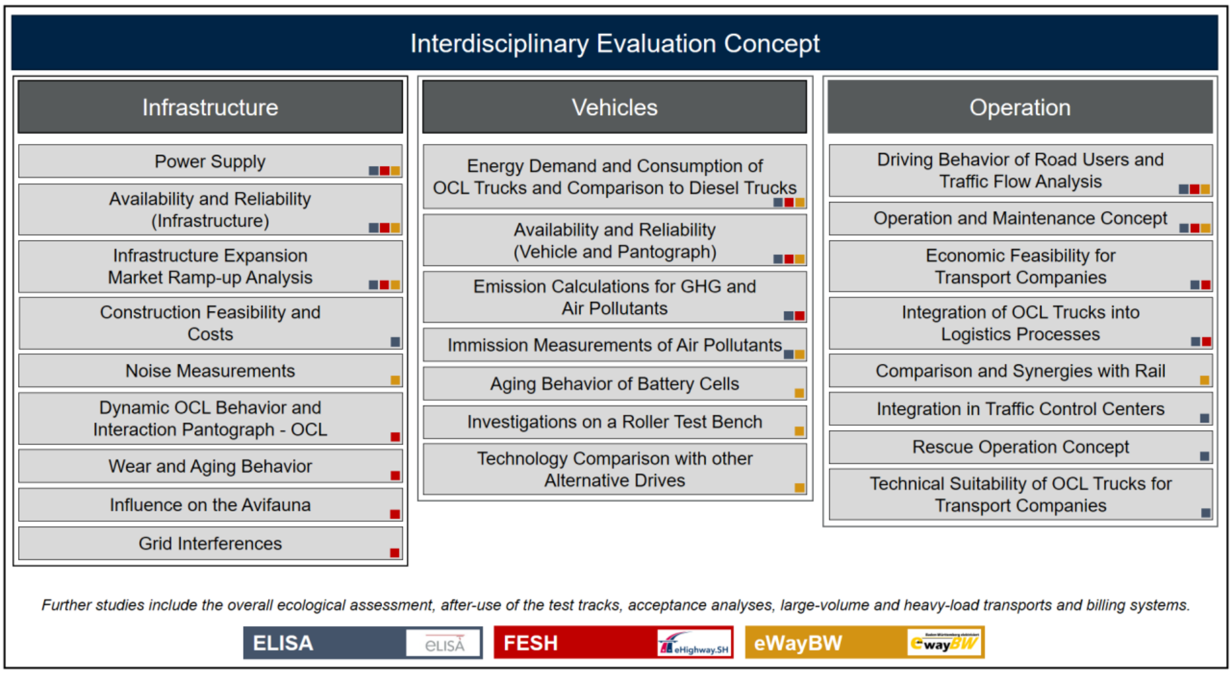

Figure 4: Interdisciplinary evaluation concept of the field test

Figure 5: Location of the eHighway field test routes in Germany [Schöpp et al. 2021c].

ELISA - Electrified, innovative road freight transport on motorways

The ELISA test track is characterised by its central location in the Rhine-Main region, an important traffic hub in Germany. Thus, the test section is located on an 8-lane motorway with an average daily traffic volume of approx. 140,000 motor vehicles (as of 2019) and a heavy traffic share of approx. 10 % in a densely populated area near the Frankfurt interchange and Frankfurt Airport. These characteristics allow for transferability of the research results to other motorway sections, a challenging operating environment with public visibility, and the potential of frequent use of the OH trucks on the test track.

The accompanying research of the ELISA project comprises the preparation, implementation and evaluation of a realistic trial operation of OH trucks on the pilot test track. Valuable findings on planning, traffic, road construction and road operation aspects are provided. The special focus of the evaluation is on analyses of the fuel and electricity consumption of OH trucks, the verification of the functionality and reliability of the vehicle and infrastructure systems in real operation, the ability of the vehicles to be integrated into existing logistics processes, and the assessment of the economic efficiency of OH trucks for transport companies. In addition, the eHighway system will be evaluated according to road design and road operation criteria in the traffic system and in interaction with existing traffic management strategies, and the effects of electrified heavy goods traffic on road safety, traffic flow and road users will be investigated under different load, weather and traffic conditions.

FESH – Field test eHighway Schleswig-Holstein

On the FESH field test , the practical suitability and potential of the electrification of heavy road freight transport with overhead contact lines is being investigated under real operation conditions on the A1 federal motorway. The accompanying scientific research focuses on a holistic system evaluation under technical, economic, ecological, traffic-related and psychological aspects. Extensive experience and knowledge will be generated on the integration and migration of the technology into the road space, the energy supply, the traffic management and the logistics of the transport companies. The 2 x 5 km eHighway test track is located between Reinfeld and Lübeck on the A1 motorway and is used by the Bode haulage company involved in the project in daily shuttle operations in several rotations with different OH truck types, which should enable the creation of a valid data basis for the evaluations.

The accompanying research is characterised in particular by an in-depth evaluation of the technical suitability of the overhead contact line infrastructure and its interfaces to the vehicles as well as the energy supply network, taking into account all relevant influencing parameters. The investigations include, among other things, the dynamic behaviour of the overhead contact line, the wear and ageing behaviour of relevant components, energy demand and consumption analyses of the OH trucks as well as the availability and reliability of vehicles and infrastructure. In addition, a separate research substation with inverter and intermediate storage is operated for the analysis of the topics of grid interferences and grid stability. Further research focuses on economic efficiency (from a haulage company's point of view), social acceptance and the ecological effects of the eHighway system with regard to, for example, air pollution control, use of resources, land requirements and impact on avifauna. Overall, valuable experience is being gathered in the operation of an eHighway system, empirical data is being generated to evaluate the practicality and functionality of the eHighway, opportunities for improvement are being identified and, based on this, recommendations for a rollout of the technology are being derived.

eWayBW - Field test to test electric drives for heavy commercial vehicles on federal trunk roads in Baden-Württemberg

The ewayBW pilot route runs between the towns of Kuppenheim and Gernsbach-Obertsrot in the Murgtal in Baden-Württemberg on the B 462 and has a total length of about 18 kilometres. On the pilot line, up to 500,000 tonnes of paper are transported annually in fully continuous 24-hour operation seven days a week from three paper manufacturers in Obertsrot to two logistics centres in Kuppenheim. This results in up to 64 circulations per day.

In the accompanying research of the eWayBW test route, it will be examined from a techno-economic point of view how suitable the federal road and motorway network in Baden-Württemberg is for electrification, how high the additional electricity requirements are due to OH trucks in various market ramp-up scenarios and which transports in the Murg Valley can be better handled by rail and which can be better handled by overhead contact line trucks. Furthermore, the effects of the use of overhead contact line trucks on noise pollution and air pollutants will be determined by measurements on the track and on a roller test stand and modelling. In addition, the effects of the use of overhead contact line trucks on road planning, road operation and user behaviour will be investigated by comparing traffic behaviour before and after the installation of the overhead contact line. The installation of a charging infrastructure similar to the overhead contact line enables the realistic operation of overhead contact line trucks on the chassis dynamometer and thus, in addition to the measurements on the road, allows further investigations of different driving profiles and electrification scenarios.

In this respect, the techno-economic work in eWayBW takes special account of the special conditions of such a test route in the Murgtal in the Black Forest, such as confined space, narrow curve radii, bridges and tunnels as well as noise protection requirements. This means that additional valuable knowledge can be gained compared to the other two pilot routes in Hesse and Schleswig-Holstein. Another unique selling point of the project is that in the phase now starting, in addition to testing the OH trucks, there will be a technology comparison with all alternative forms of drive for heavy commercial vehicles currently under consideration. For this purpose, real data on the vehicles, e.g. on energy consumption or refuelling or loading times, will be collected during the operating phase in order to analyse the overhead contact line trucks with regard to their economic and ecological data, to compare them with other types of trucks and to examine them with regard to the fulfilment of logistics tasks.

Other topics of the accompanying research in eWayBW include comprehensive research into the social acceptance of the technology, both locally on site and in regional and national perception. In addition, there is close networking with actors in neighbouring countries with regard to their activities in the field of eHighway.

6 In which states can the drive train operate and how do the states differ?

Authors: F. Schöpp, A. Bulenda, M. Worbs, Ö. Öztürk, R. Linke

The drives of the OH trucks in the field test operate in different so-called *operating modes*. OH trucks can basically operate in a hybrid mode, in which the combustion engine plays a major role in the traction of the vehicle, or in a purely electric mode, in which the electric machine solely provides the propulsion. Depending on the availability of an overhead contact line system, there are further combinations, which are shown in Figure 6.[4]

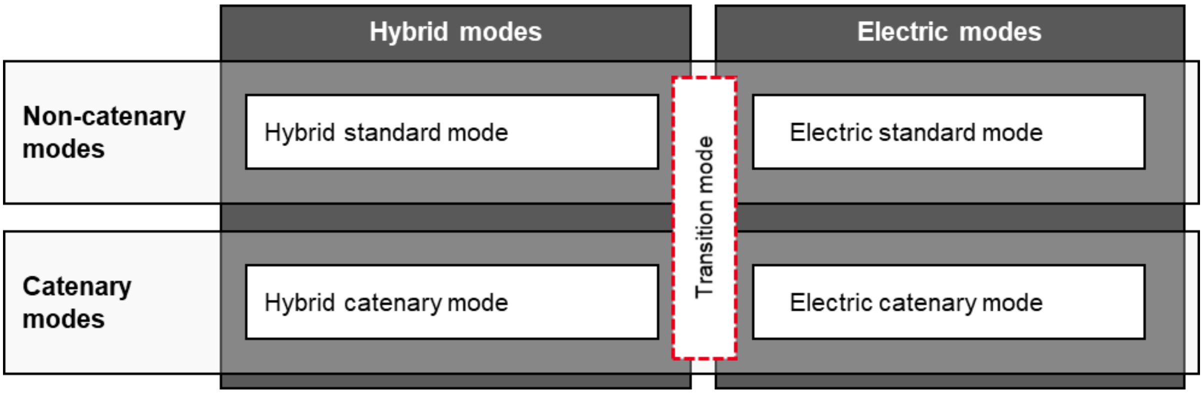

Figure 6: **Interaction of the operating modes of an OH truck [after Schöpp et al. 2021b].**

Outside of an overhead contact line system, the hybrid and electric standard modes are possible. The drive control unit decides on the optimum operating program and the operating mode to be selected according to the requirement profile of a section of the journey. In the **hybrid standard mode,** the combustion engine is always active. The interaction between the combustion engine and the electric machine ensures traction, with the combustion engine taking over the major portion. The pantograph is not used in this operating mode. The battery can be charged by power surpluses and recuperation. The main energy sources are diesel fuel as the primary energy source and electric energy from the battery as the secondary energy source. In the **electric standard mode,** the combustion engine is not active. Only the electric machine is responsible for traction. The pantograph is not used in this operating mode. The battery can be charged by recuperation. The sole energy source for this operating mode is electric energy from the battery as the primary energy source.

When an OH truck approaches an overhead contact line system, the OH truck drivers decide independently on the use of the overhead contact line system by pressing a button (so far). If the pantograph is raised and the connection to the overhead contact line system is established, either the electric catenary mode is possible, or, in some situations, the hybrid catenary mode, in which the combustion engine supports the traction or takes over operation-relevant functions. Again, the drive control unit decides whether the combustion engine is activated or switched off according to the requirement profile of the stretch. If the OH truck operates in the **electric catenary mode**, the combustion engine is not active. Only the electric machine is responsible for traction. In this operating mode, the pantograph is connected to the overhead contact line system and transmits electric energy. On the one hand, this energy is used for traction, on the other hand, the battery can be charged at the same time. Recuperation can

[4]Minor differences in the operating mode definitions on the individual field test projects are possible.

contribute to charge the battery, too. In some cases, it is additionally possible for the combustion engine to support traction or to run for operationally relevant reasons, for example for heating or air conditioning. In this case, the OH truck operates in the **hybrid catenary mode**. A low diesel fuel consumption can be observed. Moreover, **transitions** between the change of two operating modes take place to a small extent. [Schöpp et al. 2021a]

Remote from the overhead contact line system, the OH truck drivers also have the option of influencing the operating mode and thus, for example, charging the battery by means of the combustion engine or forcing the vehicle to drive purely electrically depending on the battery state of charge [Boltze et al. 2020; Schöpp et al. 2021a].

Figure 7 shows the different operating modes and the change between the traction from the combustion engine and the electric machine based on an exemplary journey of an OH truck in configuration 1 in the shuttle operation on FESH. The vehicle speed in km/h, the mechanical power of the combustion engine (P_{ICE}) and the electric machine (P_{EM}) in kW, the current diesel consumption in l/h, and the battery state of charge (SOC) in % of the gross capacity are shown over time.

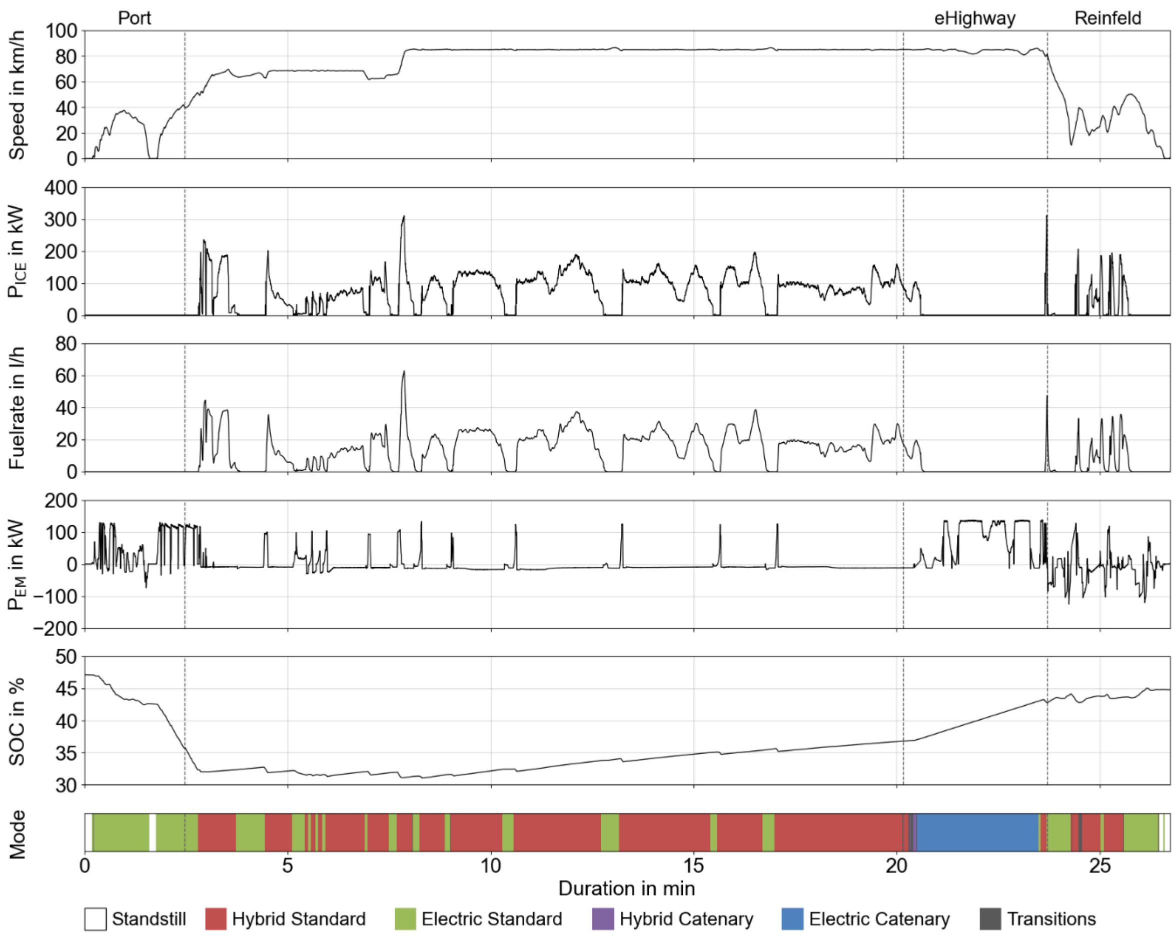

Figure 7: Curves of speed, mech. power of combustion engine and EM as well as SOC for an exemplary journey on the FESH test track

In the urban areas at the beginning and end of the journey – here the port area and the freight forwarding area in Reinfeld – it can be seen that the OH truck largely travels purely electrically and without local emissions. On sections of the route without an overhead contact line system, the combustion engine can be operated in the optimal efficiency range and the battery can be charged with energy, which is exceeding propulsion need. This increases the battery state of charge (SOC). In overhead contact line operation, the OH truck drives purely electrically and charges the battery in parallel.

An evaluation in the field test project FESH showed an average share of the electric operating modes of 29 % and the hybrid operating modes of 64 % in relation to the distance travelled for this vehicle in 2020. At this point it must be considered that due to the short test track distance, only approximately 20 % of the total distance was covered under the overhead contact line. With the newer vehicle configurations (see section 4), a further increase in the share of electric operation can be expected due to higher battery capacities and higher OCL charging power.

7 How can the eHighway system be integrated into logistics processes?

Authors: R. Linke, M. Bramme, T. Burgert, F. Schöpp, C. Doll, C. Brauer

The OH trucks currently in use on the three German test routes fulfil different transport purposes, which can be differentiated according to the operating profile. The 15 OH trucks currently in operation can be assigned to the following categories: Shuttle transport, distribution transport and combined transport (see Table 2).

Table 2: Structure of transport travel and frequency of travel under the overhead contact line system

Transport structure	Shuttle transport	Distribution transport	Combined transport
Vehicles per project			
ELISA	2	2	1
FESH	1	-	4
eWayBW	5	-	-
Frequency of trips under the overhead contact line system per OH truck (maximum per day)*.			
ELISA	11	4	1
FESH	14	-	12
eWayBW	11	-	-
**) subject to fluctuations depending on transport volume*			

The ELISA project focuses specifically on the use of the OH trucks by different transport companies with different vehicle configuration requirements and different logistical processes. Two of the OH trucks are used in the Rhine-Main region as a shuttle between Darmstadt and Frankfurt am Main. They pass the ELISA test track with a high frequency. One of the OH trucks in shuttle traffic also operates in two shifts. Another vehicle is used in temperature-controlled logistics and delivers to regional supermarkets as distribution traffic. The fourth vehicle transports building materials and delivers to various customers in the region from a central location. The operation of the fifth OH truck is particularly characterised by its use in combined transport (CT). The OH truck mainly serves inland ports in the region with containers.

In the FESH project, all available OH trucks are used by a single haulage company. The vehicles commute on a total of three different routes and use the overhead contact line on the outward and return journey in each case. Two routes represent the pre-carriage and onward carriage to unaccompanied CT by rail or ferry to Scandinavia. Here, the OH trucks used drive from the freight forwarder's depot to the CT terminal in the port of Lübeck or to the port terminal in Travemünde. On these routes, foodstuffs are mainly transported in refrigerated box trailers, but sometimes canvas trailers or containers are also used. A trailer exchange takes place at the terminals. The delivered semi-trailer is made available for onward transport by ship or rail and a semi-trailer in the onward leg is transported back to the depot. The third route is served by an OH truck with a canvas trailer. Here, shuttle transports take place between a production site of one of the forwarder's customers in Bad Oldesloe and a warehouse in Lübeck-Moisling.

In eWayBW, the OH trucks are also used as shuttles in regular logistics operations at two haulage companies along the B462 near Rastatt. A special feature here is that they shuttle

24/7 on the pilot route between logistics centres and paper mills on a federal highway. The logistics processes are designed to achieve the highest possible degree of utilisation of the articulated vehicles. Accordingly, after reaching the parking position at the three companies in Obertsrot or at the two logistics centres in Kuppenheim, the articulated trucks are uncoupled from the semi-trailers in order to be able to immediately pick up a fully loaded semi-trailer. As a result of this turnover, the vehicles are in constant use and downtimes are largely avoided. This means that an OH truck makes 10-11 trips per day, 365 days a year. In order to integrate the HGVs into various logistics concepts, prospective assessments of the environmental impacts of HGVs and O-BEVs were carried out on the one hand in the existing shuttle operation between the paper mills and the storage locations, i.e. the currently served test route, and on the other hand in use for the supply to the combined transport terminals in Karlsruhe and Wörth (Rhineland-Palatinate) as well as for long-distance transport (see [Zembrot et al. 2021]).

The analysis of the transport journeys of the OH trucks in the field test shows that due to the current location and length of the test routes, the use in regional shuttle transports is the first choice. In addition, the OH trucks were also successfully used in distribution transport as well as in the pre-carriage and onward carriage of CT as shuttles around the test routes. It can be assumed that with the expansion of the overhead contact line infrastructure (see section 10) and the associated possibility of being able to use the OH trucks more flexibly, CT elsewhere and long-distance transport will also benefit greatly.

In addition to the analysis of the structure of the transport chain, the perception on the part of the transport companies plays a decisive role in the integration of OH trucks into logistic processes. Overall, the transport companies have so far reported mainly positive experiences from real operations. Interviews with several experts have shown that particularly important operational requirements such as transport time or customer satisfaction could be guaranteed at all times when using the current OH truck configurations. The reduction of downtimes of the current OH truck prototypes as well as the possibility to increase the electric range of the OH trucks by extending or upgrading the overhead contact line system are also important prerequisites for the acquisition of further OH trucks by transport companies.

The previous investigations in the field tests have further shown that the technical configuration of the OH trucks has an influence on their application possibilities. Overall, the OH-truck configurations 1 to 3 (s. Table 1 in section 4) fulfil the essential technical requirements of the transport companies participating in the field tests. These essential requirements include the drive power, the axle configuration, no restrictions with regard to the payload, the provision of necessary assistance systems and compatibility with different trailer types.

On the current field test routes, different types of semi-trailers are used in combination with the OH truck tractor. These include box trailers (some with refrigeration function), container chassis (20ft or 40ft) and tank trailers. So far, tipper trailers are not compatible with the OH truck prototypes, although further development of the trucks will not rule out this combination in the future.

The OH trucks used in real operations transport a variety of goods with different characteristics. These goods include emulsion paint, thin sludge, paper and profiles for dry construction as well as temperature-sensitive goods such as food. Despite the different requirements of the goods for transport, it was found that there are no restrictions for the goods transported in the project. However, the current OH trucks are not approved for the transport of hazardous goods. The background here is the prototype status that has existed up to now, which should then, however, also enable the transport of hazardous goods with the transition to series production of OH trucks.

The evaluation of the driving speeds of the OH trucks over the monthly periods has shown that the OH trucks pass the overhead contact line for the most part at the maximum permissible driving speed (80 km/h). Furthermore, there are no range restrictions due to the hybrid drive train. Due to the different configurations of the OH trucks, additional facilities such as charging stations may be necessary. The OH trucks currently used in the ELISA project do not require any additional facilities at the depot or at the customer's premises. The OH trucks of configuration 3 used in FESH are also equipped with a plug-in function of medium power (22 kW), which additionally enables stationary charging via a charging station at the depot.

In the FESH and eWayBW projects, the complementary installation of stationary charging infrastructure for charging via the pantograph is being examined, which could provide initial insights with regard to the synergy potentials discussed in section 10.

8 What is the availability of the overhead contact line infrastructure?

Authors: M. Werner, J. Wilke

As part of the accompanying research of the field test, important measures of the **availability of the overhead contact line system** (OCS) are being investigated and determined. In this context, availability describes the ability of the overhead contact line system to be in a state in which it can fulfil the required function of continuous external energy supply to the overhead contact line vehicles within a defined observation framework with specified boundary conditions during a certain period of time. The basis for the availability considerations are system diaries from the field test sections, in which all events are documented that are associated with an operational interruption of the OCS. This essentially includes information on the time of the failure and the restart, the cause of the operational interruption, the repair measures as well as the affected plant sections and track areas. The aim of the investigations on the availability of the OCS is to determine important key figures on operation times and downtimes, causes of malfunctions as well as relevant availability measures. The evaluations presented here as examples are intended to provide initial findings on the availability of the OCS. For this purpose, the following **framework** is defined:

- Period from 01.01.2020 to 31.12.2020 with 24/7 operation of the overhead contact line system
- Field test sections considered FESH and ELISA
- Inclusion of all infrastructure-related operation interruptions

The analyses include, among other things, the comparison of the **theoretically possible operation times** of the OCS in 24/7 operation in FESH and ELISA with the **real operation times** in 2020 as well as the categorisation and investigation of the **causes of the operation interruptions**. Figure 8 shows, as an example for FESH, the proportion of operation times of the overhead contact line system (left) and the distribution of the duration of operation interruptions by the categories formed[5] (right). This shows that the overhead contact line was in operation for a large part (> 96 %) of the time. When looking at the operation interruptions and their causes, it can also be seen that the unavailability of the OCS at FESH was mainly caused by construction measures in the road area that were independent of the overhead contact line, such as road improvements, as well as due to the inspections planned on the OCS during the field test. In order to minimise the impact on truck traffic, it is advisable to schedule work that can be planned during off-peak hours as far as possible.

Plant operation in ELISA showed similar operation and interruption times during the period under review. In ELISA in particular, the interruption of operation was mainly caused by a requested precautionary shutdown due to an external road traffic accident.

According to the investigations, in both FESH and ELISA, the recorded operational interruptions are dominated by external effects on the OCS; faults in the OCS itself only account for a small proportion of the total downtime.

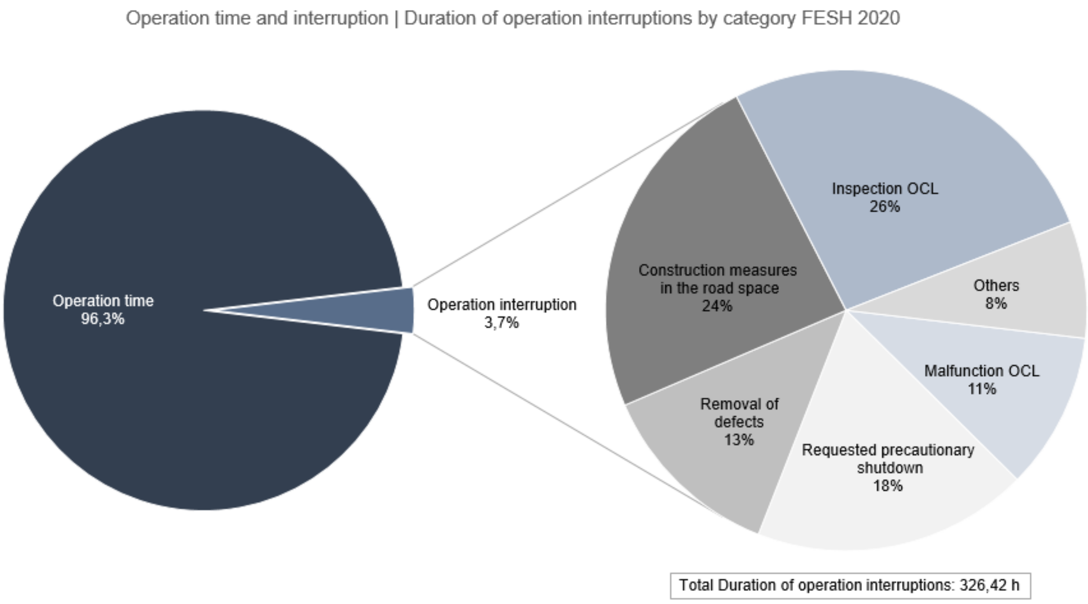

Figure 8: **Exemplary representation of the proportion of operation time (left) as well as the duration of operation interruption by category (right) for FESH in 2020**

The failure behaviour of the OCS can be characterised in analogy to railway overhead contact lines with the help of the **constant availability** A_{D} sufficiently precisely [Kießling et al. 2014]. The value of the constant availability varies depending on the defined framework. If, for example, only the operation interruptions due to a malfunction in the overhead contact line system itself are taken into account, FESH results in a constant availability of over 99.6 %. Overall, on the basis of the evaluations carried out so far and especially against the background of the current **phase of technology testing**, the statement can be made that the **overhead contact**

[5] The category malfunction OCS includes all events that are directly attributable to a failure in the functionality of the OCS itself. Others includes, for example, shutdowns of the OCS for research installations in the field test tracks or malfunctions in the operations centre. Operation interruptions resulting from so-called early defects of the technology (e.g. from the subsequent correction of avoidable construction defects after initial installation) are classified as removal of defects. Inspections comprise the cyclical inspection work on the overhead contact line system within the scope of the maintenance strategy of the field test tracks.

line systems in the field test sections FESH and ELISA fundamentally have **a high availability**, which is essential for the practical suitability of the **eHighway** overall system. In further detailed studies, annual and monthly evaluations are compared over the entire project duration and statistical key figures are determined and evaluated as measures of availability and reliability.

Part III Outlook for further development

9 What are the international prospects for cross-border electrified road freight transport?

Authors: M. Staub, M. Lehmann

There is great international interest in electrification solutions for heavy road transport. Five major Electric Road Systems (ERS) conferences were held to date[6] According to these and other publications, ERS related studies and – in some cases – public trials are currently being carried out or planned in Europe in the following countries, among others: Sweden, France, Italy, the UK, Belgium, the Netherlands, Austria, see [Gustavsson et. al. 2021], [Bateman et. al. 2018], [Suul et. al. 2018] and Figure 9. Outside Europe, there is great interest especially in China, India, Japan, Canada and the USA.

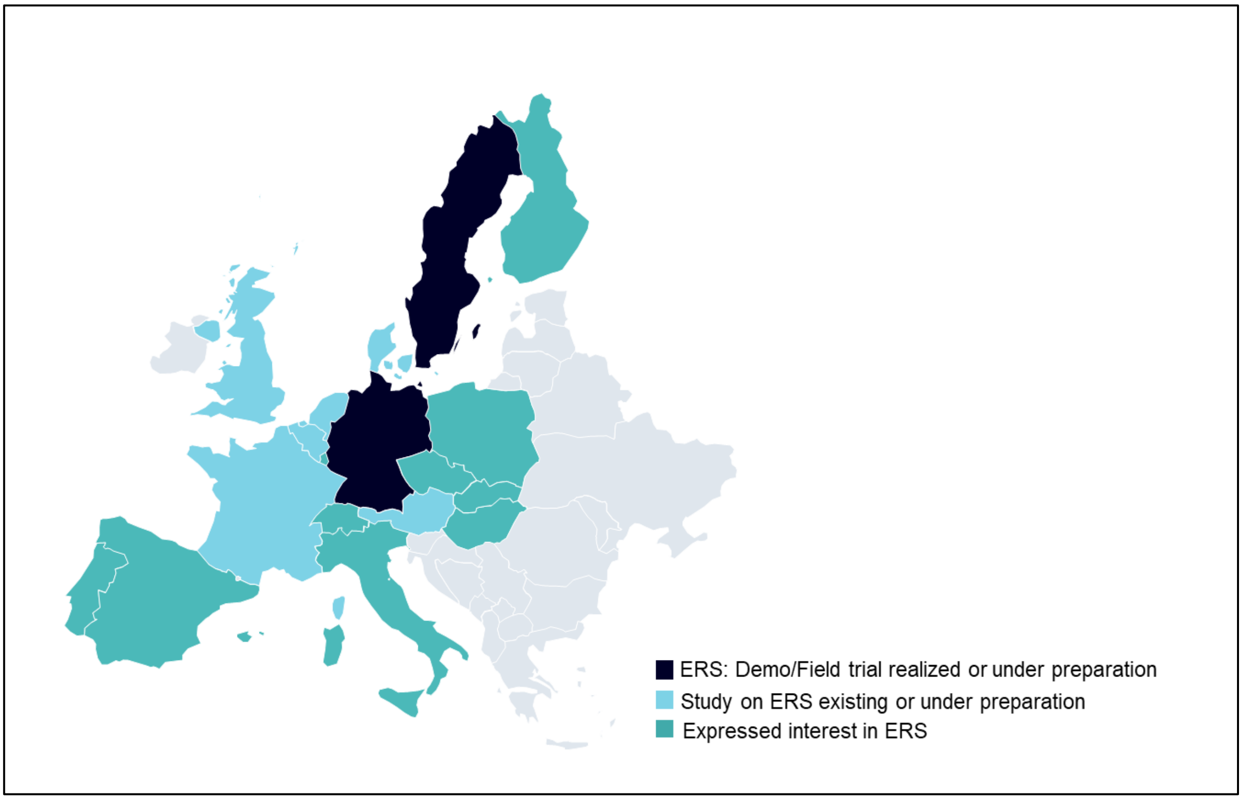

Figure 9 Overview of European interest in ERS solutions

Road freight transport in Europe very often takes place across borders or is very frequently carried out by foreign companies in other national markets. The already existing demands for technical, operational and organisational interoperability (i.e. the ability to cooperate seamlessly) are met by numerous activities of the EU (especially in the area of regulation) and the member states (especially in the area of technical specifications). This already known interplay of national and international actors in regulation and standardisation can also be used as reference in the international implementation of overhead contact line systems.

[6] www.electricroads.org

Figure 10 illustrates the distinction between regulation (i.e. in particular adaptation and further development of the system environment) and standardisation as the technically binding coordination of the interfaces between the subsystems. Due to the novelty of the technology, not all components of an ERS with overhead contact lines or other transmission solutions can yet be mapped in the existing regulatory or standardisation landscape, which leads in some cases to standardisation gaps and the resulting need for further standardisation. In order to address these, the interface between overhead contact line and vehicles, for example, which is crucial for technical interoperability, is already the subject of ongoing international standardisation work by CENELEC as the umbrella organisation of European electrotechnical standardisation. In parallel, various standardisation projects are pending to update existing standards in order to cover partial aspects of ERS through extensions and adaptations. An overview of the standardisation activities of various drive technologies for heavy electric commercial vehicles is provided in the current report of Working Group 6 of the National Platform for the Future of Mobility [NPM AG6 2021].

Various research projects such as AMELIE and AMELIE2 are dedicated to the necessary regulatory adjustments (e.g. for billing and financing), especially for ERS with overhead contact lines. In [Hartwig et. al. 2020a], different implementation and decision paths in the context of interoperability are outlined on the basis of a universal, European-compatible actor model. The identified steps of normative and regulatory localisation of individual aspects of the overall system are an important basis for interoperable and cross-border road freight transport.

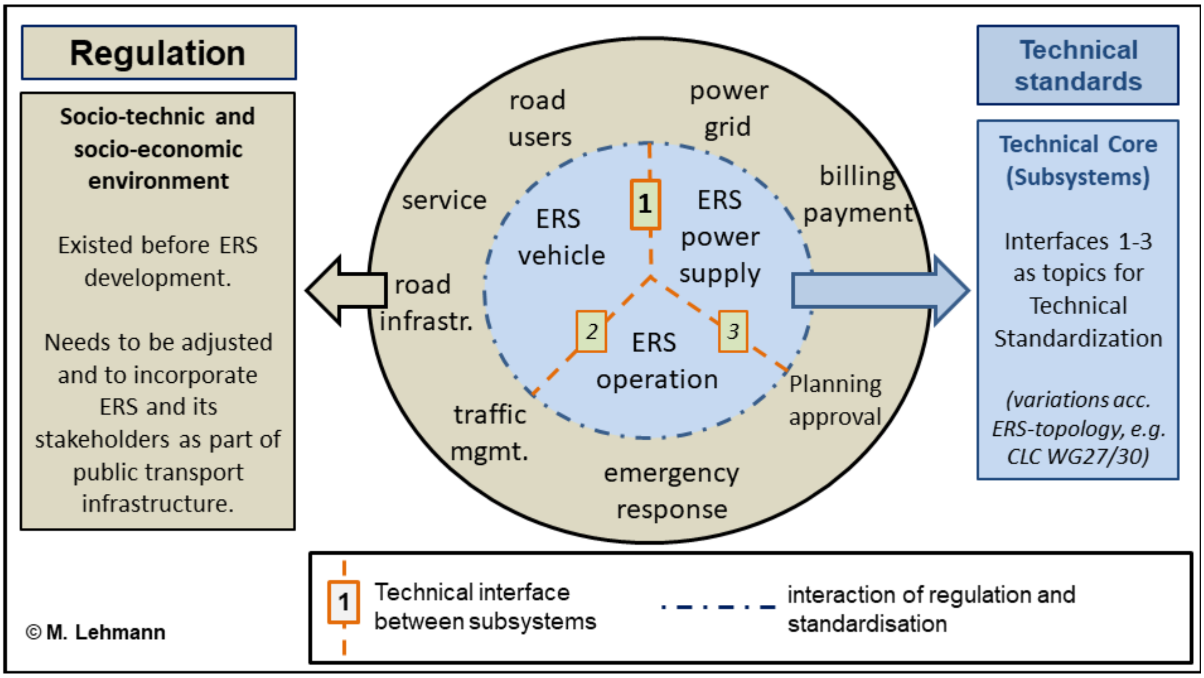

Figure 10: Relationship between regulation and standardisation in the (international) construction of overhead contact line systems

10 What are the synergy potentials with other ERS and alternative drive technologies?

Authors: J. Jöhrens, M. Lehmann

In general, all drive systems with electric motors can use the energy power supply via overhead contact lines, i.e. not only battery-powered vehicles but also vehicles with hybrid or fuel cell drives. It is thus possible to combine the efficiency advantages of direct electricity use on electrified highway sections with the further flexibility of on-board energy storage systems for not electrified sections. The use of battery trucks in long-distance transport, for example, requires very large batteries and high stationary charging capacities (see section 1). If battery trucks can draw power from the overhead contact line via a current collector, the on-board battery capacity can be significantly reduced depending on the application profile of the vehicle and the extent of the overhead contact line network, thus saving costs. The use of hydrogen in fuel cell trucks, in turn, is foreseeably associated with significantly higher energy costs compared to direct electricity use [UBA 2019]. If fuel cell vehicles on overhead contact lines can draw electricity directly from the line, this holds considerable potential for reducing operating costs.

The future costs of an energy system increasingly based on renewable electricity, including the necessary distribution grids, are expected to depend significantly on how efficiently electricity supply and demand can be synchronised in time. If both stationary and dynamic charging infrastructures are available and used, a high temporal availability of (possibly also regenerative) consumers can be expected, which can bring additional degrees of freedom for optimising the energy system. How the infrastructure costs of the distribution grids in particular depend on the share and spatial distribution of stationary and dynamic charging technologies is an important subject of future research.

In terms of deployment paths, an overhead contact line system can also complement stationary charging infrastructure and even hydrogen refuelling stations well: While the latter are relatively easy to introduce rather decentrally for the initially limited numbers of vehicles, an overhead contact line system brings the advantage of good scalability for routes with high traffic volumes.

Last but not least, synergies are also conceivable on the operational side. Dynamic charging via the pantograph could simplify operational processes, especially in a scenario with autonomously driving trucks, in which the previously obligatory driving time breaks as battery charging periods are eliminated or at least greatly reduced. Additionally, the possibility of stationary charging via the pantograph could create operational incentives to equip trucks with pantographs and thus use both infrastructures. An operational systematisation of the various stationary charging infrastructures for battery-electric trucks was undertaken in [Beckers/Bieschke 2021]. Initial studies on the capacity requirements for charging infrastructures with a focus on fast chargers (so-called mega-chargers) for different electrification rates / fleet sizes can be found in [Plötz et al. 2020] and [Plötz et. al. 2021].

Summarising the previous results from the overhead contact line ERS operation and system set-up as well as the developments in stationary charging of electric trucks with regard to possible synergies and further need for investigation, the following focal points emerge:

- Determination of the total energy demand for electric trucks with stationary and dynamic energy supply both along the motorways and at other stationary charging infrastructures.
- Determination of the required capacities for network connections along the federal highway network and corresponding design or expansion of the power supply network levels.
- Intensive monitoring of the testing of the various drive and supply technologies and their interaction in heavy goods traffic

These aspects will be taken up, among others, in the "Ad-hoc task force on dynamic and stationary charging using overhead contact line technology" led by the Federal Ministry of Digital Affairs and Transport (BMDV)[7]. Practical experience regarding the strengths and weaknesses as well as the development of synergies between the different drive technologies can be gained in the innovation cluster projects in Bavaria, Hesse and Baden-Württemberg as well as along the A2[8]. Both the work of the expert group and the innovation projects mentioned are measures and activities implementing the overall strategy "Electrification of Heavy Commercial Vehicles", which the then Federal Ministry of Transport and Digital Infrastructure (BMVI) presented at the end of 2020 [BMVI 2020].

[7] https://www.klimafreundliche-nutzfahrzeuge.de/gesamtkonzept/task-forces-studien/

[8] https://www.klimafreundliche-nutzfahrzeuge.de/bmvd-bringt-innovationscluster-fuer-klimafreundliche-lkw-antriebstechnologien-auf-den-weg/

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