Designing and Demonstrating a System for Efficient and Sustainable Road Freight based on Dynamic Power Supply

Patrik **Akerman**, Georg Hasso **Gruenjes**, Michael **Lehmann**
Siemens AG, Erlangen, Germany

Summary

To meet constraints faced by road freight in terms of significantly lowering or reducing CO2 emissions and improved air quality an Electric Road System (ERS), based on an Overhead Contact Line (OCL)-hybrid heavy-duty vehicle (HDV), has been designed, developed, tested and demonstrated. The ERS demonstrated has twice the energy efficiency of conventional diesel HDVs and enables the use of renewable energy. The technological development was made possible by combining expertise from rail electrification, electric drives and a newly developed active current collector for dynamically connecting to the OCL and receiving a continuous supply of electricity to power the vehicle's engine and to store energy on-board. The research project demonstrated that a hybrid truck can run in pure electric mode without any change in the operations for the driver and without concessions on truck performance. The ERS infrastructure was successfully integrated into a highway environment. The result was the first fully operable prototype on a test track with dedicated infrastructure. Since mid-2011 it has been undergoing testing and demonstration. During trials, the OCL-hybrid prototypes demonstrated full performance and suitability for everyday use – regardless of the environmental and load conditions. In addition to providing highly promising results in terms of technology, the tests also demonstrated benefits to the environment and economy. The ERS can be integrated with existing infrastructure, thus making it much easier and cheaper to implement and maintain. Lower energy consumption yields lower operating costs and the resulting savings can finance the infrastructure investment, especially on heavily trafficked routes, such as port-to-rail connections near metropolitan areas. These aspects will be further demonstrated on public roads, with operations commencing in the first half of 2016. This paper presents the latest available results and points the way to a heavy-duty road freight system with full electric power and full flexibility.

Keywords: dynamic charging, heavy-duty, HEV (hybrid electric vehicle), infrastructure, truck

1 Background

1.1 The challenge of road freight CO2 emissions

Transport remains the end-sector most dependent on fossil fuels, with oil accounting for more than 90% of its primary energy. According to Sims et al. [1] transport is a leading source of green-house gases (GHG), with passenger surface transport being the largest sub-component. However, a recent forecast by the OECD [2] points to a shift, with emissions from freight surface transport growing much faster than those of passenger surface transport, rising from currently 40% to a forecasted 58% share of surface transport emissions by 2050. Within freight transport, the majority of CO2 is emitted by road freight, and its share is forecasted to grow.

To counter the trend of growing road freight emissions a study of the German Council of Environmental Advisors, SRU [3] examined what positive environmental effects could be achieved through existing policy options, such as expansion of rail capacity, improved logistics and more efficient vehicles (e. g. aerodynamic optimization) as well as the use of bio-fuels as part of the propulsion fuel. The conclusion was that this set of measures will be insufficient to reach the GHG reduction goals.

Furthermore the International Food Policy Research Institute IFPRI [4] has concluded that bio-fuels are likely to have limited availability, especially when considering those that don't have any incremental land use change or other effects that negate their CO2-reduction potential. If so, it would then be more beneficial to apply this limited supply of sustainable bio-fuel to air or sea transport, that are even more challenging to electrify. According to Jaffe et al. [5] natural gas (in compressed or liquefied form) is another alternative, but its potential to reduce CO2 is very small even under optimal conditions. If solutions cannot be found to address methane leakage from production, transmission and distribution and the net effect could even be negative. Therefore additional solutions to significantly reducing the CO2 foot-print of the road freight sector are needed.

Given that several countries already have very low carbon footprint for electricity and that global electricity generation will need to decarbonize over the coming decades as part of climate mitigation measures as shown by the International Energy Agency IEA [6], it makes sense to explore solutions using electricity in road freight transport. Further immediate benefits of an electric solution are improved local air quality, fuel diversification and increased energy efficiency as well as reduced operating costs. This much is already known, explaining today's significant world-wide interest and support for the development of electric solutions for personal transport and urban freight. The central question this paper addresses is how the benefits of electricity can be applied to heavy road freight and to sharply reverse its current trend of growing total emissions.

1.2 Alternative ways to use renewable electricity for road freight

The most common approach to use renewable electricity for road freight is on-board battery storage. This makes sense for vehicles that are light, travel short distances, have regular stops or a lot of idle time that can be used for battery charging. The demands in road freight are much more challenging, with heavy loads, long distances and few regular stops. To illustrate this, typically one kilogram of battery is needed per tonne-kilometer with current technologies. This would imply for a 40 ton truck travelling 500 km, a 20 t battery would be needed. In addition to the weight constraint there is also the challenge of how such a battery could be charged quickly, without diminishing its useable life or disrupting the grid. Clearly, for heavy goods transport over longer distances, operation with only on-board electrical energy storage looks unlikely, even under highly optimistic future battery development forecasts.

Another way to use renewable electricity is electrolysis to create hydrogen for use in fuel cells. A similar approach is known as Power-to-Gas where the hydrogen created also undergoes methanation. According to Zoerner [7] both of these processes are associated with notable losses. Using estimates for electricity distribution (95%), and for electrolysis (70%), hydrogen distribution (91%), fuel cell (55%), on-board power electronics and electric machine (79%) as shown by the BMUB [8] the well-to-wheel efficiency of hydrogen fuel cell vehicles is around 27%. Studies by the Hessian Ministry for Environment, Nature, Agriculture and Consumer Protection [9] as well as by IVECO [10] show that for Power-to-Gas the same assumptions for electricity distribution and electrolysis apply, while methanation (80%) and distribution of Compressed Natural Gas (CNG) (98%) and CNG combustion (35%) mean that the well-to-wheel efficiency is around 19%.

If, however, electricity can be brought directly to the vehicle, losses would be limited to those of electricity distribution and the on-board power electronics and electric machine, yielding a well-to-wheel efficiency of 76%. Such differences in efficiency also translate into equally significant differences in costs. A natural step is therefore to investigate the various ways in which electricity can be brought directly to the vehicle on the road, powering its propulsion. This step is analogous to electrification of rail, which has been undertaken on those routes where a sufficient high utilization can be expected. The same kinds of applications, i.e. where traffic is going back and forth or on highways with very high number of vehicles, could benefit most from electric road technology.

1.3 Concepts for Electric Roads Systems (ERS)

There are several technologies enabling electricity to be transferred from the road to vehicles at standstill. In heavy freight applications energy consumption is very high, stops are few and irregular and on-board battery storage highly unlikely to be sufficient. Therefore battery-based solutions are inadequate. Electricity will need to be continuously provided to the vehicle while moving.

Solutions with dynamic and continuous charging have been described by Tongur [11] as ERS. So far there are three main kinds of solutions proposed: inductive in the roadway, conductive in the road surface and conductive from an overhead contact line (OCL).

Installing infrastructure for electrification in the roadway or surface poses substantial challenges. Most obviously the road needs to be dug up, which means a significant disruption to the traffic flow. Given that the places where one would want to install ERS are places with a lot of traffic, these locations are also highly undesirable to disrupt. Another challenge comes from ensuring that the installed infrastructure will function without active maintenance or repair just as long as the service intervals for the road surface itself. Anything less would mean added disruptions and costs.

A further important challenge concerns safety. This is most obvious for conductive systems in the road surface, which would change the grip of the road surface. For electrical safety reasons in-road solutions –both inductive and conductive- must consist of short segments, e. g. by the Viktoria Swedish ICT [12] 20 m or even shorter depending on the vehicle length of the shortest vehicles running on the electrified lanes. These segments can only be activated when a single suitable vehicle is on top of it and thus preventing the transmitting section from being accessed by third-parties. For all other situations the segment needs to be deactivated. This makes these concepts much more complex, which increases investment costs. It also reduces reliability and availability due to the required detection and switching devices. According to Viktoria Swedish ICT [12] [13] the segment length also dictates the speeds which vehicles can be powered (between around 50-60 km/h to around 90 km/h for segments of 20m), implying a trade-off between transferring power at higher and lower speeds for in-road ERS concepts.

To justify the costs it is important to have high energy efficiency and thus generate savings on operational costs. This requires that electricity can be transferred to a moving vehicle at a high level of efficiency. As shown by the BMUB [8] and the Viktoria Swedish ICT [13] the substation to wheel efficiency for conductive supply in the road has been shown to be around 79%. For inductive in the road with dynamic charging it is more difficult to establish overall efficiency which correspond to highway driving conditions (e.g. high speed, lateral misalignment, normal air-gap to road surface, etc). Viktoria Swedish ICT [12] looking specifically at inductive ERS did not report any results regarding efficiency while moving at highway speeds.

An OCL-ERS has advantages over in-road systems in terms of safety, reliability and efficiency, but can only be used by large vehicles. This limitation has little practical consequences, as alternatives for light duty vehicles already exist. However, these solutions will not be viable for heavy freight vehicles (see section 1.2), thus calling for an alternative solution specific to heavy freight transport. It could be noted that no inductive system suitable for powering light and heavy duty vehicles currently exists [14], thus making this purported advantage over OCL-ERS even more theoretical.

ERS solutions need transition from the laboratory to the real world through commercially viable use cases. For ERS this requires a situation where both the ERS infrastructure and the ERS vehicles have high utilization and cost savings. Different kinds of shuttle applications with large commercial vehicle therefore represent promising candidates for an early commercialisation [14] [15]. LDVs are seen as “highly unlikely” ERS adopters, especially outside of metropolitan areas, i.e. on highways [15]. For freight there are many situations where trucks are in intense shuttle-operation between two points. These use-cases stimulated the design and development of an OCL-ERS.

1.4 Overview of an electric road system using overhead contact line

The developed OCL-ERS utilizes a continuous power supply system. This electric transport system consists of an overhead contact line (catenary) infrastructure as well as trucks equipped with current collectors (pantographs) and hybrid drives, see Figure 1. It combines the advantages of proven technologies from rail and road systems and is an open, scalable and reliable system for electrified road transport. Designed as an overlay system it improves the existing road infrastructure. Furthermore it enhances the transport operation while providing unlimited flexibility due to the hybrid configuration of the vehicles.

Compared to e.g. diesel operated trucks, the ERS-adapted trucks increase their energy efficiency in truck operation significantly and have the opportunity to utilize renewable power instead of fossil fuels. Such operational savings can be used to finance the capital investment and thus offer a business case supporting the implementation and application of the technology. The German Environmental Protection Agency calculated that an OCL-ERS installed on the German Autobahn (highway) system would not only be cheaper than the other investigated zero emission options but also be cheaper than diesel [16]. The primary challenge they saw was the need for cross-border (e.g. pan-European) coordination.

To support that development, a concept like this has to prove feasibility in terms of:

- Applied technologies
- Economic benefits
- Achievement of ecologic targets

The subsequent sections present major results of the research project ENUBA (Elektromobilität bei schweren Nutzfahrzeugen zur Umweltentlastung von Ballungsräumen – electric mobility concepts for heavy-duty vehicles for the environmental relief of conurbations) which was co-funded by the Germany Federal Ministry for Environment (BMUB) and Siemens AG, to evaluate the technical, ecological and economical feasibility. Based on these results the paper furthermore provides an overview on the focused transport applications and opportunities.

2 Technical Solution and Functionality

Similarly to typical electrical traffic systems the OCL-ERS comprises of four sub-systems: the electrical vehicle/truck, the traction power supply and distribution, the roadway and an operation control center, see Figure 1. The following sections describe these sub-systems in further detail.

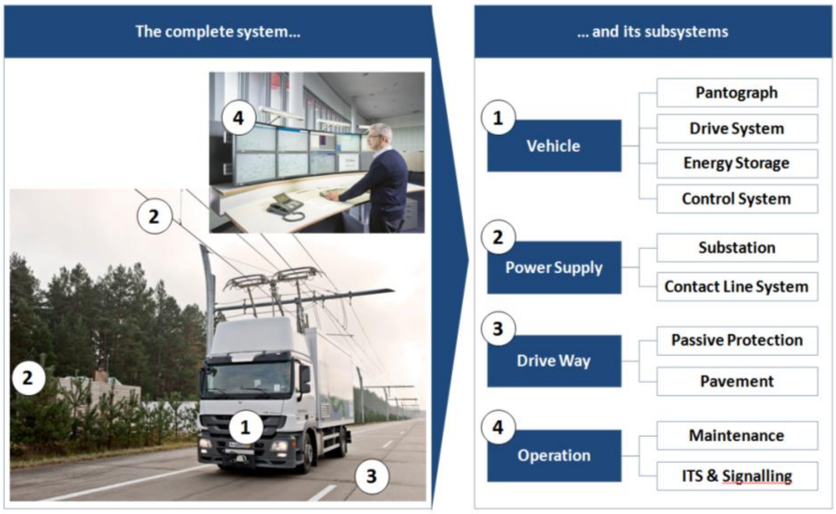

Fig. 1: The OCL-ERS and its sub-systems.

2.1 Electric infrastructure – from generation to distribution

The electric infrastructure of the OCL-ERS consists of substations supplying the traction power and an overhead contact line distributing the traction power to the consumers (trucks).

The electric infrastructure is erected alongside the road and has no direct interference with the road itself. Consequently there are no restrictions to mixed operation with other non-electrified vehicles. As the trucks are not guided by the system the wear and tear of the road is similar to conventionally used roads.

The substations include standard components as medium voltage and direct current (DC) switchgears, large-capacity power transformers and a rectifier. According to the Viktoria Swedish ICT [13] the distance between the substations varies from 1-3 kilometers depending on the power rating of the substations and the electric traffic assumptions. Furthermore the substations can be equipped with controlled inverters. Instead of generating waste heat while breaking the ERS-adapted trucks generate electric power. This process is called regenerative breaking and widely used in tramway and railway systems. By applying inverters this energy can flow back into the public grid via the overhead contact line and the substations. Even without the inverter technology, braking energy can be used to recharge on-board energy storage devices or to feed other trucks connected to the same substation contact line feeding section.

Similarly to trolley bus systems the OCL is designed as a bipolar system. This is due to the fact, that in contrast to rail bound systems, the roadway cannot be used as electric conductor for the return current. The contact line is suspended by single poles standing on both sides of the roadway, each of them carrying the contact line to supply one direction. This configuration can be adapted to the specific needs of the environment in which the system is integrated (e. g. use of portals).

The trucks are equipped with a current collector (pantograph) positioned above and behind the driver’s cabin (see section 2.2). Corresponding with the operational range of these current collectors the two parallel poles of the OCL are installed above the electrified lane. Each of the wire systems is providing one electric pole and consists of a contact wire and a messenger wire. The height of the system is designed to be above standard vehicle dimensions and clearances. The horizontal position of the OCL along the roadway is, amongst others, assured by tensioning devices installed inside or outside the masts supporting the overhead contact line system. This prevents sagging of the lines and ensures minimum wear of the carbon contact strips of the pantograph even at high speeds. At civil structures with limited clearances (such as e.g. bridges, tunnels) and to assure the required electrical safety distances the OCL can be interrupted or special constructions can be applied.

2.2 Trucks with intelligent pantograph and hybrid drive

The OCL-ERS technology is open for any electric vehicle that is equipped with a suitable pantograph and ready to operate in the installed electric system. Therefore different hybrid and full electric drive trains and propulsion systems can be used.

The key component which allows for combining the advantages of proven technologies from rail infrastructure and road systems is the newly developed pantograph. It enables the ability of safely connecting and disconnecting with the overhead contact line within the speed range of 0 to 90 km/h. Furthermore the pantograph actively compensates the lateral movement of the vehicle within the lane by using a system of sensors and actuators. Next to the mechanical and electrical design, intense research efforts have been invested in the detection of the contact line and the processing of the data provided by the integrated sensors. Additionally a human-machine-interface (HMI) and a diagnostic and configuration system were developed for the interaction with the driver.

The ERS-adapted truck runs in hybrid (e.g. diesel) mode on the “first mile” until reaching the electrified section of its route. After entering the electrified section the truck connects to the overhead contact line at any given speed. Upon connection, the hybrid drive (e.g. diesel engine) automatically switches off and the electric drive is directly supplied with energy from the contact line. When overtaking or driving into sections which are not electrified the vehicle is changing to hybrid drive propulsion mode without loss of traction force at any speed. Energy storage on the vehicle bridges the time required for restarting the diesel engine or allows for driving short passages (e.g. low bridges) without OCL or diesel operation. On-board electrical energy storage can be re-charged while driving under the OCL, so the vehicles leaving the OCL can be fully charged.

The wide range of drive train technologies that can be integrated with the Catenary Hybrid concept is shown in Figure 2. The pantograph and power electronics can be combined with a fossil fuel engine driven by diesel or natural gas in either a serial or parallel configuration, just as it allows for a full electric concept when combined with a battery, ultra-capacitor or fuel-cell power source. This allows the ERS concept to be tailored to different users’ demands, be it a port concerned with zero emissions or a mining operator desiring a strong diesel engine for use on the non-electrified sections in tough climatic environments.

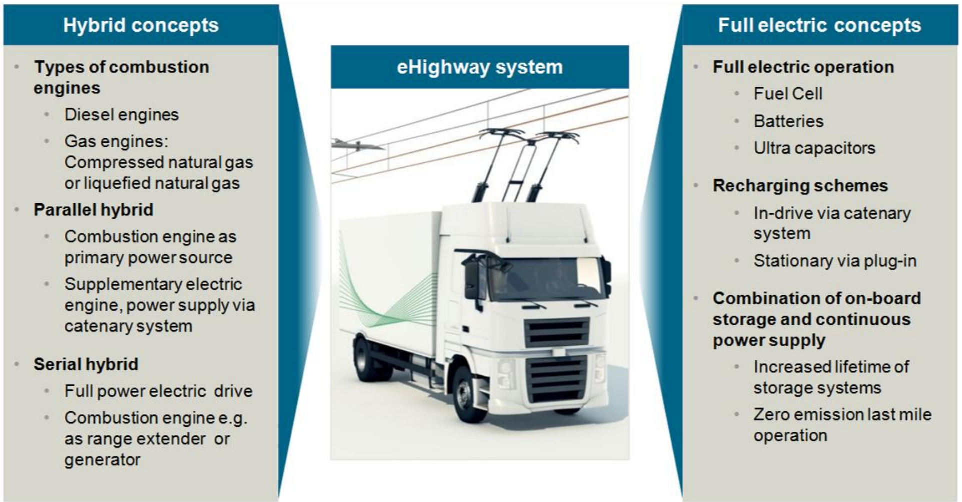

Fig. 2: Range of drive train integration possibility.

This flexibility also allows the ERS to be integrated with a range of different vehicles and vehicle manufacturers to accommodate specific demands.

2.3 Roadway

The technical concept was thoroughly evaluated in eleven workshops together with experts of the German Federal Highway Research Institute (BASt - Bundesanstalt für Straßenwesen). During this process detailed concepts for the following aspects were developed and evaluated:

Civil Infrastructure • Road Clearance and contact line construction at bridges • Heavy load transports with heights up to 4.5 m • Statics of contact line systems and poles • Statics of bridges • Requirements for road restraint systems • Visibility of road signs	**Construction, Operation & Maintenance** • Construction concept • Maintenance concept • Technical monitoring and authorisation • Incidence management • Ice loads and hazards (including mitigation)
Electrical Infrastructure • Integrated electrical safety concept for infrastructure and vehicles • Integrated EMC concept for infrastructure and vehicles • Emergency Energy Shut-Down	**Vehicle Technology** • Change of vehicle driving dynamics • Change of vehicle crash characteristics • Change of vehicle fire safety aspects • Limitations for hazardous loads • Increased vehicles lengths by 0,5 m to accommodate pantograph

Tab. 1: Workshop results concerning technical aspects

2.4 Operating System

The operation of the system is structured in three main elements: infrastructure, logistics and user management.

Similar to railway electrification infrastructure, the OCL-ERS infrastructure is operated via an operation and control center (OCC). From within the OCC the status of the system, substations and OCL, can be monitored and switching operations can be executed.

In terms of logistics, the system focuses on the traffic of vehicles rather than on the movement of individual goods. The initial process is the registration of the users, the trucks. This process can be supported by access control (e.g. via automatic number plate recognition gate entries) and law enforcement mechanisms. Wayside monitoring and signalling as well as centralized operation control allow for traffic optimization measures.

On-board and wayside metering of energy consumption provides the basis for processing of invoices, depending on the type of application. Differences may exist in a public and open set-up with individual customers or in a rather semi-private set-up with one owner of a larger fleet, e.g. in mining transport.

3 Reliability, Availability & Safety

The reliability and availability of any system is the result of the combination of the individual reliability and availability of its subsystems and components. The availability of the components is strongly influenced by the preventive and reactive maintenance applied. Here again the OCL-ERS benefits from the fact that it comprises of proven technologies from present rail and road systems.

The power supply infrastructure can be realized as a redundant system. In case of an outage of one substation feeding of the overhead contact line can be taken over by the neighbouring substation(s).

The contact line system can be equipped with intelligent monitoring devices that can detect contact failures. In the unlikely event of contact line failures these devices immediately trip the protection relays and switch off the power supply of the damaged section to assure electric safety. In case of an accident in the electrified section the OCL-ERS can be de-energized by the rescuing firemen or police staff. This is realized with a safe and self-explanatory measuring, switch-off and earthing unit located at the road for usage by rescuing staff. Signalling devices and enforcement functionalities (e.g. pantograph monitoring system) will increase the safety level.

As initially explained, the OCL-ERS does not directly interfere with the road infrastructure. Consequently the system has no impact on the reliability and availability of the road itself.

The ultimate purpose of the system remains to facilitate transport operation. In addition to the high degree of reliability, availability and safety of the infrastructure, the OCL-ERS safeguards the unhampered truck operation by the choice of drive system. Even in a case of infrastructure outage or malfunction of the pantograph the trucks remain fully operable and may proceed in hybrid drive mode.

4 Technical Maturity

In addition to careful analysis of system functionality as well as safety and reliability it is necessary to test the full system and obtain real world data.

A short design phase of only six months was followed by three months for construction of the infrastructure and integration of the pantograph into the hybrid truck. Afterwards all subsystems were thoroughly tested.

When evaluating the technologic maturity of the OCL-ERS the infrastructure components and the vehicle in general can be regarded to be proven technologies. The described infrastructure for substations and OCL is available and does not differ significantly from standard railway products. Moreover the trucks and the major on-board equipment are also available now. The key innovation of the OCL-ERS system is the pantograph. The pantograph has been tested extensively, see Table 2.

Test Run / Test Process	Amount/ Distance
Number of test runs	3000
Distance electrically driven on the test track	3000 km
Distance driven in diesel hybrid operation on the test track	4500 km
Distance driven in diesel hybrid operation on public roads	10000 km
Emergency breaking processes at various speeds	100
Test runs driving over obstacles of various sizes	200
Night drives	70
Test runs with trailer (total weight of truck: 40 metric ton)	700

Tab. 2: Overview of executed tests

The technical maturity of the OCL-ERS can be best described as follows:

Based on theoretical concepts, the pantograph design took shape in a process of extended laboratory tests and resulted in three prototypes which could be mechanically, electrically and control wise integrated in three test vehicles. Two standard 18 t trucks equipped with hybrid drive systems and loaded with ballast were used as test vehicles. The most recent tests are performed with a third vehicle in a truck and trailer set-up, see Figure 1. A test facility for the OCL-ERS was build up. After a short commissioning phase the pantograph and the OCL-ERS as a whole were tested intensely on the test track and proved to be working reliably under the given environmental and traffic conditions. Next to a series of test cases successfully performed, a multitude of demonstration runs were executed over the last years, see Table 2.

Based on the testing results under a large variety of traffic, loading and environmental conditions the general functionality of the OCL-ERS is proven.

The evaluation process helped to identify all relevant aspects to be considered for integration of the OCL-ERS infrastructure in public roads. Based on these findings design guidelines were derived. Furthermore the test facility was enhanced and now includes a curved section as well as additional infrastructure typical for German highways, such as road signs and gantries. Hereby it was successfully verified that the OCL-ERS infrastructure can be integrated into the existing road infrastructure.

5 System efficiency

As for all transport systems one of the most important characteristic values is the energy consumption. From in-feed at the substation to the wheel on the trucks, the OCL-ERS benefits from a high system efficiency ranging from 80 – 85 %, like other electric mass transit systems. This should be compared with standard diesel trucks, which are bound to the lower efficiencies of internal combustion engines ranging from 35 – 42 %. Additional benefits result from the ability of electric vehicles to recuperate energy while braking or cruising down-hill.

As part of the field testing comprehensive long-term measurements were conducted. Trucks at 50 % payload (i.e. 28 t) ran on more than 2,000 km of highway sections at different grades. Standard diesel trucks consume about 25 - 29 l / 100 km. This is equivalent to 2.6 - 3.0 kWh/km. The electric truck consumed 1.4 kWh/km and therefore proves the fundamental relation between drive train efficiency and energy consumption.

In addition to the improved air quality achieved by eliminating local emissions caused by diesel-engines, the IEA [6] has shown that the above demonstrated efficiency gains can also translate into global reductions of CO2; so long as the CO2-footprint of power generation is lower than 594 g CO2/ kWh the OCL-ERS will bring a net reduction in CO2 emissions. As power generation decarbonizes, the OCL-ERS allows those gains also to further bring down the emissions associated with heavy-duty road freight.

6 Ongoing Research and Outlook

Motivated by the positive results that prove the technical, economical and ecological feasibility of the OCL-ERS, the publically funded research work is continuing. Therefore the last part of the paper highlights:

- Focus fields of application
- International opportunities
- Cooperation with truck manufacturers

The OCL-ERS is an open system suitable for a variety of applications, amongst others:

- Shuttle service for bulk cargo transport with dedicated vehicles (e.g. connecting mines with shared facilities, intra- or interplant shuttle operation).
- Shuttle service for cargo transport (e.g. containers) with multiple operators (e.g. connecting ports with freight traffic centers).
- General application on public roads for long distance transports.

In the next step, the technology will be demonstrated on public roads. The first such case is likely to be in Sweden. There Trafikverket, the Swedish Transport Administration, has conducted a pre-commercial procurement process (PCP) for heavy-duty electric road demonstrations. The Trafikverket definition of “electric road” comprises any dynamic electric power transfer to vehicles, which can be done either continuously or in segments. Heavy-duty vehicles in this context can be either busses or trucks weighing at least 16 metric tons. The Swedish eHighway project takes places on a public road connecting the port city of Gävle with heavy industry facilities in the hinterland. A two-year long demonstration period was started in June 2016.

Another public road project is being funded by the South Coast Air Quality Management District (SCAQMD). That one mile project in Southern California was triggered by the report of Gladstein, Neandross & Associates [17] into the possibilities of Zero Emission transport between the ports and the rail yards. One of the trucks in that demonstration project will come from Mack, a U.S. subsidiary of the Volvo Group.

For the PCP project and for the second phase of the ENUBA research project Siemens has a development partnership with Scania, a European truck manufacturer that is part of the Volkswagen Group. The second development phase started in 2012 and still ongoing aimed at further system optimizations towards automotive product standards. The major task was to significantly reduce the pantograph dimensions and weight. The integration of the pantograph on the Scania truck was successfully executed and tests are being performed. An important future step will be to further standardize the interface between pantograph and vehicle, thus facilitating integration of pantograph on trucks from different OEMs.

In December 2014 the cabinet of the German federal government BMUB [18] and BMWI [19] approved plans including a field trial of the ENUBA system before the end of the legislative period, i.e. September 2017. A call was subsequently issued and as of July 20, 2016, the received proposals were under evaluation.

In conclusion, the ENUBA research project has successfully demonstrated that OCL-ERS is a realistic alternative for addressing the challenge of sustainable road freight. The next phase, consisting of bringing the system to public roads for further evaluation, is already under way.

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